United States
Environmental
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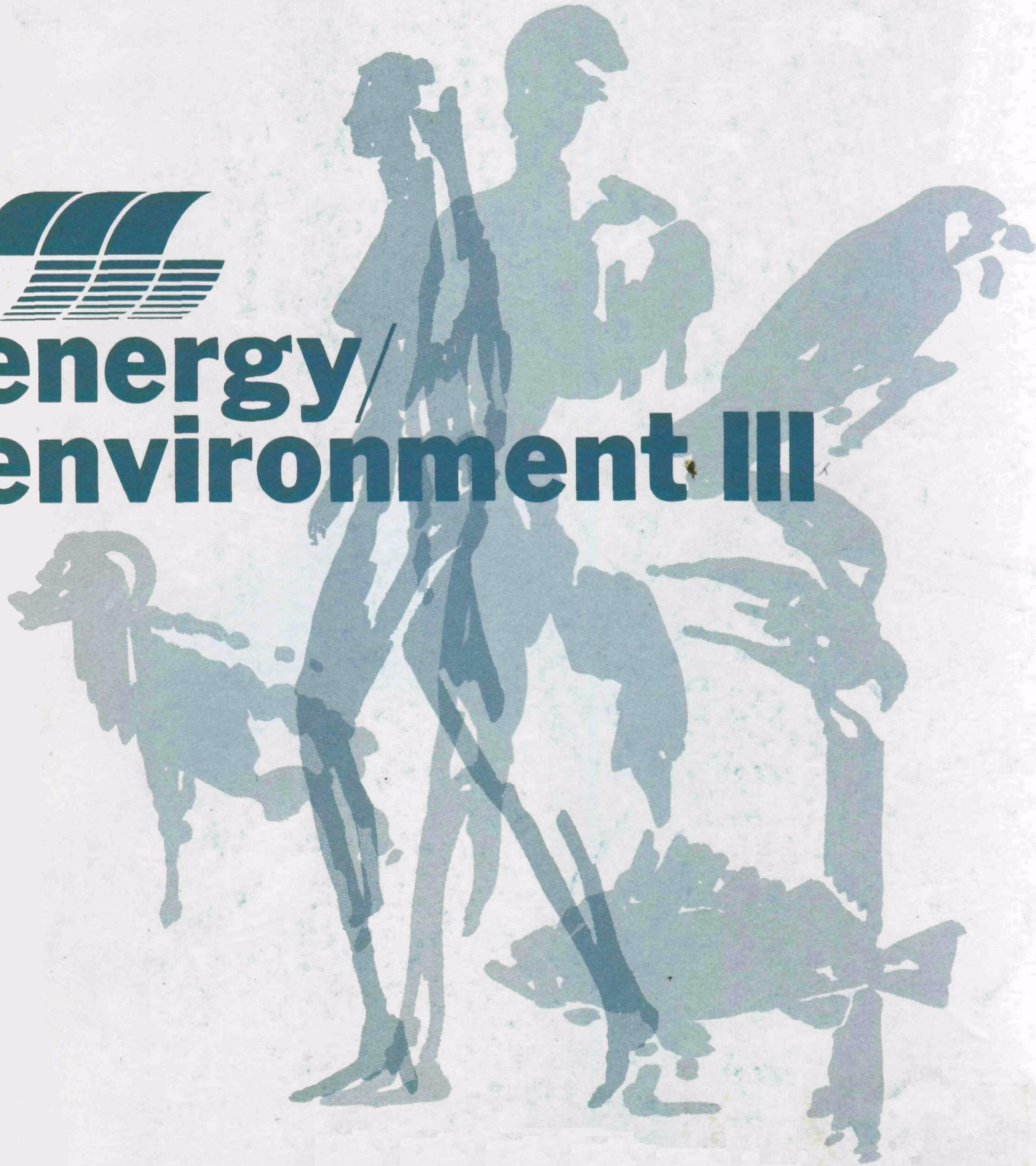
Office of
Research and
Development

EPA-600/9-78-022
October 1978

Energy, Minerals and Industry

EPA **Decision Series**



energy/ environment III

the energy/environment R&D decision series

This volume is part of the Energy/Environment R&D Decision Series. The series presents the key issues and findings of the Federal Interagency Energy/Environment Research and Development Program in a format conducive to efficient information transfer. Planned and coordinated by the Environmental Protection Agency (EPA), research projects supported by the program range from the analysis of health and environmental effects of energy systems to the development of environmental control technologies.

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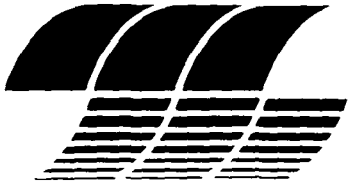

energy/ environment III

Third National Conference
on the Interagency R&D Program

June 1 and 2, 1978
Shoreham Americana Hotel
Washington, D.C.

U.S. Environmental Protection Agency
Region III Information Resource
Center (3PM52)
841 Chestnut Street
Philadelphia, PA 19107

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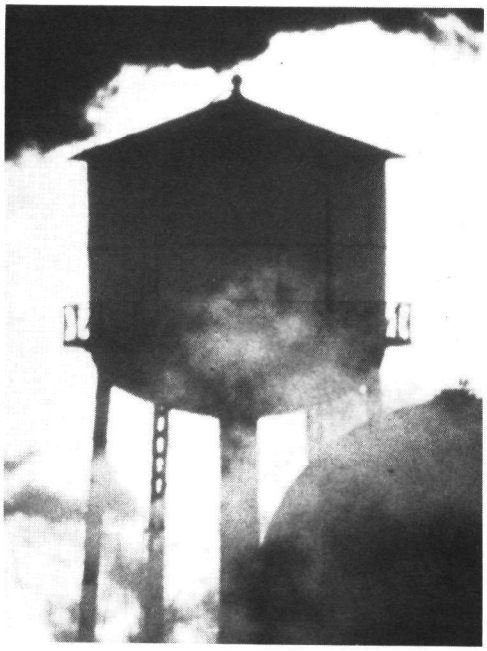
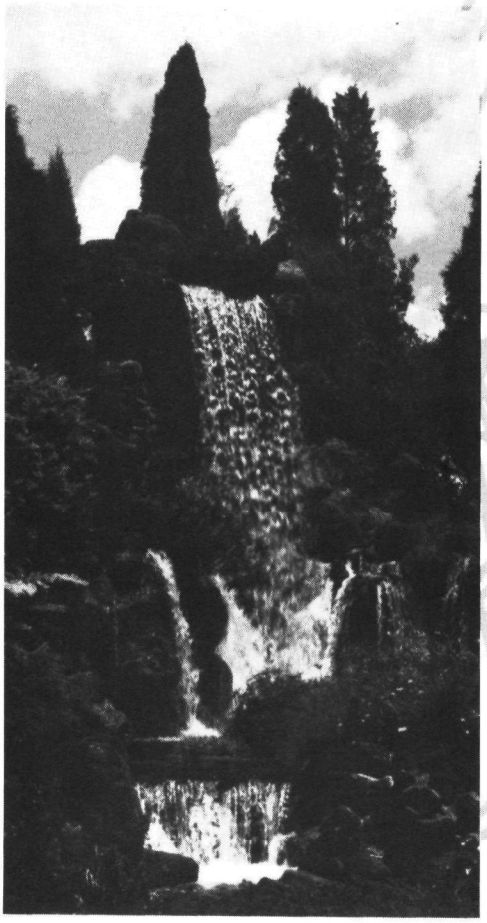


chapter 1

overview



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OVERVIEW

FOREWORD

Steven R. Reznek, Ph.D.
Office of Energy, Minerals and Industry
U.S. Environmental Protection Agency

The Interagency Energy/Environment R&D Program unites more than a dozen Federal agencies to ensure that unresolved environmental issues are not a barrier to timely and safe development of our domestic energy resources. To this end, the Office of Energy, Minerals and Industry within EPA's Office of Research and Development has, as coordinator, invested approximately $100 million a year in the Program since its inception in fiscal year 1975.

Substantial progress has been made toward achieving our goals. Selected achievements were reviewed at the Third National Conference on the Interagency Energy/Environment R&D Program, convened in Washington, D.C., on June 1 and 2, 1978. These Proceedings are a result of that Conference.

Energy/Environment III provides an update of Interagency research in particular areas, including health effects, transport processes and ecological effects, mining methods and reclamation, control technology, and integrated technology assessment. This report consists of the addresses, papers, and panel discussions of the Conference.

This report and conference, along with publications in our Energy/Environment Decision Series, such as the Who's Who in the Interagency Program and the Energy/Environment Fact Book, highlight one of the most important roles of our program—to link the people who need information to the people who have it. Most of us are becoming increasingly aware of a major change that is taking place within our economic and industrial institutions. Recent shortages and price hikes have brought home the fact that we cannot sustain a business-as-usual approach to our destiny.

We feel the need to act—but in what direction? More and more, our attempts to adjust one sector of our society run headlong into conflicting goals in other sectors. Environmental goals are being questioned on economic and energy-related grounds. Energy development efforts are challenged on environmental issues. Adjustments in the economy to discourage the waste of energy are confronted with arguments of equity and efforts at reducing unemployment.

It seems that we, as individuals and citizens within a democracy, have three valid responses to these conflicts. First, we can turn off—turn away from the discussion and occupy ourselves with our own concerns. Second, we can energetically enter the debate on the side of our own narrow self-interest. Third, we can seek to understand the issues involved and participate in the building of a new national consensus.

It is to this third response that our efforts here are dedicated. We, as scientists, engineers, and research managers, see it as our responsibility to provide the options. Whatever path the nation chooses, we will strive to supply both the knowledge and the technologies necessary to ensure that our energy supplies will be adequate and our environment will be healthy. In short, we will do our best to provide the ship of state with power, but there must be a wise hand on the helm.

We wish to express our thanks to all who, through their effort and participation, contributed to the success of this Third Conference and to the publication of these Proceedings. We are justifiably proud of the Program's achievements. We are, however, equally cognizant that there is much work yet to be done to ensure that our need to develop new and different energy sources and resources is compatible with concern for the integrity of our natural systems.

OPENING REMARKS

Stephen J. Gage, Ph.D.
Office of Research and Development
U.S. Environmental Protection Agency

ARAB OIL EMBARGO

The Interagency Energy R&D Program was created after the Arab oil embargo in the winter of 1974. Before the embargo, most Americans felt that energy supply was a public service that was available to meet nearly all possible demands at relatively low prices. After the embargo we became aware of the fact that oil and other fossil fuels are not available to meet our needs in whatever quantity we want. Economics reared its ugly head. For the average American the big car honeymoon was over, and consumers began looking for smaller cars that could save gasoline and money. That trend may have unfortunately been reversed in the last few years. The speakers at the first National Conference in 1976 reminded us that the Energy Crisis meant that our energy supply as a public service, almost as a free good, was ended.

ALTERNATIVE RESOURCES

It is a commonly understood axiom of our economic system that as demand increases and supply declines the price of a resource rises. Concomitant with this price rise is a leveling off of demand, supposedly, and a search for new resources. Mr. John O'Leary, who was our speaker at last year's Conference and is now the Under Secretary for Energy, reminded us that alternative resources, such as solar energy, nuclear energy and fossil fuels, are available to meet our energy needs, but at substantially higher prices than we have been paying for oil and natural gas. Nuclear power, coal, oil shale, and other technologies cost more than either oil or natural gas and have the potential for greater environmental consequences.

Therefore, as Mr. O'Leary pointed out, our nation faces rising costs for the replacement of energy supplies and also to protect environmental quality while these alternative sources are being used.

Before the energy embargo, pollution control and environmental protection were viewed as programs designed to help solve existing problems. By and large they were designed for the use of well-established control technologies on existing waste discharges.

After the energy embargo another view of environmental protection emerged that would steer the future course of our technological society. That future will see

limited supplies of higher grade ores and natural resources consumed. Technological innovation will allow the use of lowered grade ores and different resources or the use of the traditional resources in new and more efficient ways. An era of the world's history is rapidly coming to a close. We no longer believe that natural resources will be rewarded by a growing economy and that discharge cleanup will protect the environment. Although we have all witnessed some of the near-term economic, political, and environmental implications with the closing of the petroleum age, none of us can forecast accurately what the future has in store.

THE ENERGY CRISIS

The energy crisis could mean a protracted and gradual worsening economic recession, lack of opportunity for young people, and decreasing social mobility. It could mean a rapidly degrading environment, an exhaustion of our supplies of clean water, clean air, and productive land. On the other hand, the energy crisis may only mean that the cost of energy will rise to a point where widely available and more economically acceptable sources will be used to meet society's economic and social need. The exact course of our future cannot be predicted. The federal government is spending immense resources on research, development of demonstration projects to help shape that future.

INTERAGENCY PROGRAM

The Interagency Program is one of the major efforts to create the information and knowledge necessary for responsible decisionmaking not only by the federal establishment but by the individual American. Hopefully, our program has helped to clarify and define some of the environmental energy problems and to make that decisionmaking process a little less difficult. I say hopefully because I recently read a story about a consumer who was concerned about the use of nuclear power as an alternative energy source. At a stockholders' meeting of a major west coast utility, the shareholder told the company president that his neighbor was afraid that, if nuclear power came into widespread use, radiation might come leaking out of his wall socket. The utility company president, who was obviously a very bright man, said not to worry, that the neighbor really should be more concerned about important things—for instance, the utility was currently experimenting with cow manure as an alternative energy source.

Seriously, communication is what this Conference is all about, and I am looking forward to hearing about and discussing the major achievements of this past year.

COORDINATING THE ENERGY/ENVIRONMENT RESPONSE

The Honorable Frank Press
Office of Science and Technology Policy

CENTRAL CHALLENGE FOR AMERICANS

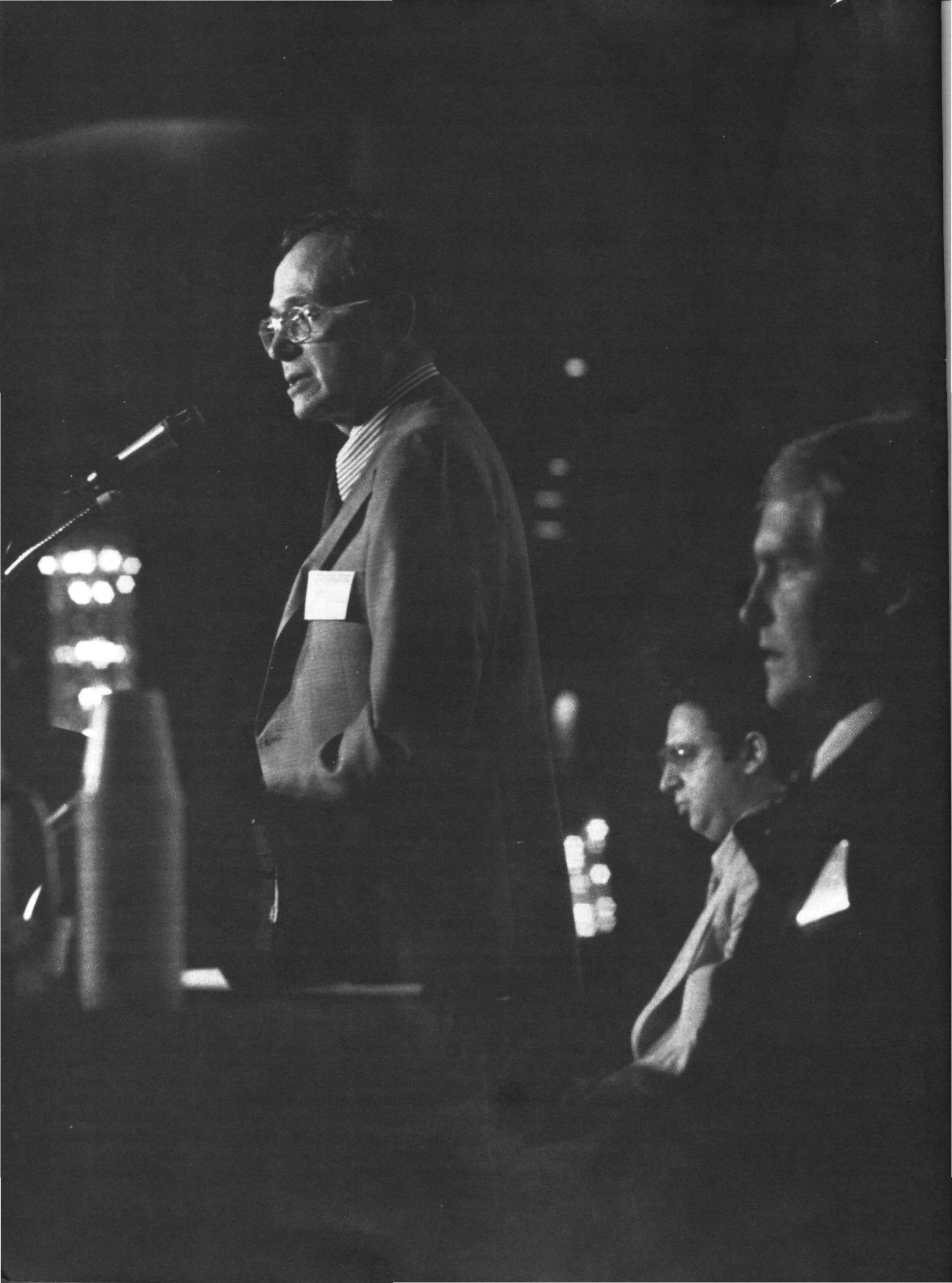
From a cursory study of our recent history, it appears that each generation of Americans is tested and tempered by a central challenge. In this century, for example, we had the First World War, the Depression, the Second World War, and the social and political revolution of the 1960's. The more we study the facts and the more we understand about the underpinnings of our society and way of life, the more clearly we see that the challenge of the rest of this century, barring some unforeseen calamity, will be to maintain our quality of life, in the face of global economic pressures and resource limitations. And by far the most important of our limited resources will be usable energy.

GROWING DEPENDENCE ON TECHNOLOGY

Science and technology have given us ever more powerful energy sources, and also a growing dependence on them. Individual Americans now have far more power to do work than could have been mustered by many of the most renowned rulers of the past, but in terms of the technologies that support our lives today, this energy use is all but essential. For example, if we live or work in a high-rise building, we are highly dependent on electricity to circulate the air we breathe and to operate the elevators we ride. Most of us live beyond practical walking distance to a market, and must have an automobile to get our food. And the very food we eat is the product of an energy-intensive agricultural technology and was probably frozen, pasteurized, and/or transported a thousand miles or more to reach our tables.

ENERGY-INTENSIVE LIFE-STYLE

Our entire society and economic infrastructure would face collapse if our energy supplies were suddenly cut short. In our bargain with technology to obtain a higher standard of living, we have become almost totally dependent upon that technology for the continued vitality of our culture. I am not speaking here in terms of the individual who chooses to go off into the wilderness, live off the land, and lead a life that is nearly self-sufficient in terms of energy. This may be possible for a handful of adventuresome people, but very few of us choose to commit ourselves to that option. Most of us are committed to an energy-intensive, modern life-style and all of its accoutrements.



BURDEN ON TECHNICAL COMMUNITY

Since science and technology brought us this life-style, people assume, quite understandably, that science and technology will continue to maintain and improve that life-style. This puts a tremendous burden on the scientific and technical community to make good on the expectations of our fellow citizens. Fortunately, it is a burden that, up to now, we have been able to meet with both resources and imagination. I assume that almost everyone in this room is today playing some role in this process of energy supply and its related problems.

There are two parts to this effort, without either one of which we would be hard-pressed to show any progress. The first part involves science and technology—science to provide us with sufficient understanding of the complex problems involved in accelerating domestic energy development, and technology to translate that understanding into reality. The second, and equally important, part of the solution is not technical at all—it is institutional. Above and beyond our scientific endeavors, there are social, economic, and political forces that must be factored into the equation. It is these forces that provide us with the funds to do our research and development, and it is these forces that determine whether or not our research results and technologies will be sufficiently relevant to the problems at hand.

BREAKTHROUGHS—IMPOSSIBLE TO SCHEDULE

I am not saying that if we technologists were left alone, we would surely come up with a solution to the energy crisis. Far from it. Unfortunately, the continued faith that Americans have in science and technology is often accompanied by a tendency to look upon scientists and technologists as the unfailing solvers of all problems. We scientists know that this is hardly the case. We suffer our share of failures—many of them—and we have all learned the hard way that major breakthroughs are impossible to schedule. Sometimes it appears that breakthroughs are harder than ever to achieve now—just as more problems seem difficult to resolve fully these days. Residual problems or related impacts are always cropping up. There seems to be a lot of truth in a cartoon that appeared in the Wall Street Journal recently. It showed one man at a bar commenting to another, "Remember the good old days, when problems had solutions?"

In view of this, I believe it is as much our responsibility to inform the decisionmaking community of what we cannot do as it is to tell them what we can do. We should also be able to point out where alternatives to technical solutions may be available. And it is just as much our role, as technologists, to point out to the decisionmaking community where economic, social, or political situations offer significant opportunities for progress as it is the role of the socioeconomic and political communities to establish our overall research priorities.

RESEARCH PRIORITIES

In the light of these dual responsibilities, the current debate over which path our Nation should follow to find the energy it needs becomes a little more complex and a little less obvious. The most simplified version of the debate pits the "hard" energy suppliers against the "soft" energy conservers—the coal and nuclear power supporters against the conservation and renewable-resources advocates. The labels we choose for these alternative paths are not important. What is important is that there is a tendency to polarize our energy/environment philosophies. One side advocates expanded use of our existing fossil fuel and nuclear resources; they argue that we can rely on our existing oil, gas, coal, and uranium reserves for as many years as it takes to solve the economic, technological, and social problems associated with nuclear and advanced power systems. Others see a future in which we rely solely on our renewable resources—solar, water, and geothermal. These latter energy sources have great appeal, because they appear to be relatively less polluting than our coal and nuclear resources.

ENERGY PATH

I see problems with either path, if chosen at the expense of the other. Where would we be, for example, in the year 2000 if our Nation had been traveling the coal-nuclear path exclusively for more than 20 years? What would be our alternative if we had not yet solved the plutonium or radioactive waste problems, or had discovered serious health or environmental hazards from electricity transmission grids, or had determined that CO_2 was causing our atmospheric temperature to rise? It would already be too late to say we should have placed greater emphasis on geothermal research and development (R&D), or the Federal Government should

have accelerated its support of the construction of solar collecting units, or should have encouraged more intensive conservation efforts. By the year 2000, our best efforts at shifting priorities would be "too little, too late."

CONSERVATION PATH

Or let's consider the other direction—the conservation renewable-resources path. If, for the next two decades, we were to concentrate entirely on solar technologies, where would we be if our conservation hopes proved somewhat idealistic and highly impractical? We would have spent tremendous amounts of money and, even more important, precious and irretrievable time on solar R&D at the expense of other promising technologies. We would not have the technologies to burn coal cleanly and efficiently, and our nuclear problems would remain unsolved. Again, we would have painted ourselves into a corner and lost the energy gamble—a precarious position for a highly industrialized nation such as ours.

It is for this reason that we must avoid taking polarized viewpoints toward our energy future. Compromise is necessary to ensure that both short- and long-term energy requirements are met in such a way that our Nation's economic growth is not inhibited by an energy shortage due to poor technological planning.

President Carter made clear, in the National Energy Plan, his intention to take a balanced approach towards development. This Adminstration is committed to increasing our use of coal under stringent environmental controls while, at the same time, reducing our dependence on foreign oil and gas reserves.

AIR QUALITY STANDARDS

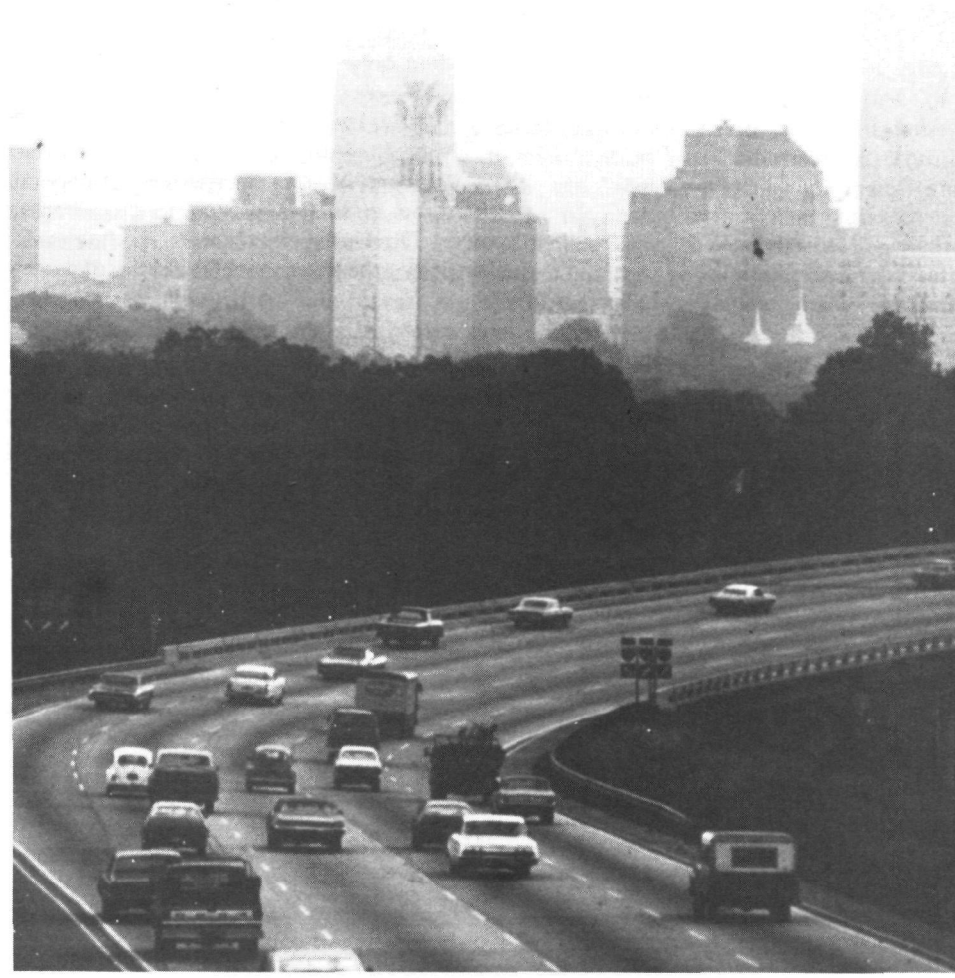
To ensure that air quality standards are not sacrificed as we convert to coal, the Administration has supported and encouraged the R&D performed by the Department of Energy, and other Federal agencies, and has given added emphasis to the Interagency Energy/Environment Program. Initiated in late 1974, the interagency program has invested more than $430 million to date, most of it to support coal-related efforts. Direct burning of coal is required in the short- and mid-term, until the more advanced technologies, such as fluidized-bed combustion and coal gasification, can be commercialized. Flue gas desulfurization systems, or scrubbers, are now in commercial use as a result of the quality research performed under the interagency program, which is planned and coordinated by the Environmental Protection Agency. The plans of the utility industry call for a large portion of coal-fired power plants to be equipped with scrubbers within the next decade.

In the short- and mid-term, coal, conservation, and nuclear fission are our most promising approaches to achieving a reliable energy supply. However, we should keep in mind that we are only buying time until our solar, nuclear fusion, and other renewable-resource technologies are sufficiently advanced to take over as primary energy sources.

Federal solar R&D has greatly increased in the past 3 years, and I expect this trend to continue. Just as Earth Day was the harbinger of the environmental era, so Sun Day should mark the beginning of an age when we as a nation become seriously committed to the development of practical efficient solar technologies. But we must not confuse commitment with accomplishment. Our drive toward the development of solar energy technologies must be tempered with realism concerning the time it takes to make a major energy transition. In an energy-dependent society such as ours, a severe energy shortage could be disastrous.

EMPHASIS ON SAFETY AND WASTE MANAGEMENT

For this reason, along with solar energy development, the development of our nuclear resources is essential. The necessity for nuclear-related environmental R&D is also readily apparent. Plutonium's extreme toxicity, together with the fact that it may be used to manufacture nuclear weapons, requires us to look very closely for alternative nuclear technologies. In April of last year, the President made clear the Administration's policy on this subject by presenting detailed plans to restrict the use of plutonium as a fuel source. While we look for alternative nuclear fuel cycles—those that will not involve the production of plutonium—the United States will have to rely increasingly on light-water reactor technologies. The R&D community will, therefore, have to place greater emphasis on solving the safety and waste-management problems associated with this type of reactor.



COMBINATION OF TECHNOLOGIES

In the long-term, it is difficult to say what technologies will emerge as the most environmentally and economically practical. Whether it be nuclear fusion, solar, advanced fossil fuel technologies, or, more probably, a combination of these, our present balanced approach will provide us the time necessary to ensure thoughtful, organized alternatives.

The problem is not simply one of technology or science. It is also one of politics, institutions, economics, and social attitudes. Let me illustrate this point with some examples. The United States is committed to the automobile as its major form of transporting people. Our highway system, parking facilities, fuel supply network, urban and suburban population patterns, and distribution systems represent a capital investment of half a trillion dollars or more. And it is an investment which gives us a significant advantage over most of the other nations of the world in terms of social mobility and opportunity for personal freedom.

But we pay a high price for this advantage. The automobile is responsible for a large portion of our nearly $50 billion per year foreign oil debt. It is, for all practical purposes, the key factor in enforcing our continued dependence upon foreign oil. And yet, if anyone were to propose that all automobiles be required to achieve twice the fuel efficiency that they do today, there would be an uproar. Here the problem has little to do with technology, and even less to do with basic science. It has to do with a firmly established set of institutional interests and the economic and social patterns that have been generated over a period of years.

COGENERATION

Another case where institutional barriers outweigh technical ones is in the area of cogeneration—the simultaneous production of industrial process steam and electricity. Until about 25 to 30 years ago, a great deal of electricity was produced in this country by factories and industries. In fact, at one time, cogeneration facilities were providing 15 percent of our electricity. The availability of relatively inexpensive oil in the post-World War II period discouraged the burning of coal, and various institutional problems have, over the years, acted to discourage the use of this potentially important source of electricity. At the present time, cogeneration is providing only 4 percent of U.S. electricity.

Partly because of State and Federal Government regulation, utilities make little or no profit from the purchase of electricity from an industrial firm. There is also the problem of rate incentives. Utility rate schedules have, for many years, been structured in such a way as to discourage a potential industrial user from generating power. Obviously, if there is no financial incentive for a firm to generate its own electricity, the economic feasibility of cogeneration facilities is in question.

To promote cogeneration, President Carter has proposed exempting industries using cogeneration from State and Federal public utility regulation. Additional proposed incentives are intended to ensure that industries which generate electricity receive reasonable rates from utilities. I am confident that, as the American people become aware of the advantages of cogeneration and are informed of the barriers blocking its implementation, they will work with us to convince the appropriate governmental organizations of the necessity for change.

PROBLEMS AT PERSONAL LEVEL

In addition to these broad-scale institutional problems, there are others at a more human and personal level. To install and maintain solar-powered heating systems, for example, requires additional training and experience for the local plumber and contractor. Solar water heaters cannot be installed with an imprecise attitude of "if it doesn't leak, it's just fine." The proper materials must be selected and proper techniques used to ensure efficacy, maintainability, and durability over an extremely long—30 to 50 years or more—system life. We are at a formative point in the development of solar-powered systems. Technical specifications and performance criteria must be set quickly, or the public will soon grow wary of inferior solar-powered systems. On the other hand, room must be left for initiative and inventiveness so that future progress is not hindered by oppressive technical specifications or excessive and slow bureaucratic processes.

Another major institutional barrier to the full realization of scientific creativity is the legalistic contract mechanism. For example, to obtain any significant level of contract support for a new idea or technology in today's environment takes *at least one year*, if not more. And it requires such an explicit description of what is to be accomplished—and proof that it can be accomplished—that it often appears necessary to do most of the research before even submitting the contract proposal. These delays and excessively demanding scopes of work are, it appears, intended to ensure that Federal research money is not wasted on experiments or technologies that may fail.

This whole approach contradicts the entire scientific research method. If an experiment fails to produce a commercially practical product, that does not mean that it has failed to provide the key information necessary to produce that product at some future time. We often learn more from our failures than from our successes. Unfortunately, the Federal contracting procedure allows too little flexibility to deal with funding high-risk research. And this lack of flexibility is not saving Federal money—it is wasting it by allowing promising ideas to go untested. Contracting procedures at the Federal level should rely more heavily upon the judgment of the scientific or technical project officer as to what constitutes adequate justification for a contract. The project officer is paid to exercise that judgment, but all too often the exercise becomes an interminable and frustrating process of wordsmithing.

PROBLEMS OF COMMUNICATION

It seems to me that a great many of our institutional barriers—and some of our technological ones—are actually problems of communication. I cannot count the number of times I have heard my peers complain about the poorly informed

technical decisions being made at the policy levels. However, the responsibility for keeping the policy levels well-informed can be no other than ours. And we can do better.

There are two key communications links which must be formed in order to make our efforts both relevant and more efficient. The first link is within the research community itself; the second is between that community and the policy level decisionmakers and interested public.

CORNERSTONE TO R&D PROGRAM

Communicating within the research community is the cornerstone of a coordinated research program. In such a broad area as the health and environmental effects of energy systems, the problem of coordination is a real challenge. Through reports, seminars, and conferences such as this, the interagency program brings together the key actors in various aspects of energy/environment research and development. Such direct contact is an effective way to coordinate the Federal research effort and to avoid unnecessary duplication of, or misdirection of, research. No matter how often we reorganize, there will always remain many important topical areas which cut across organizational and agency lines.

But if coordinating research and development within government is important, perhaps of even greater importance is the coordination of R&D between government and industry—between the federally and privately funded sectors. The roles of Federal and private R&D communities are, in many respects, naturally defined. Industry is somewhat reluctant to engage in major exploratory basic research because of the length of time it takes for the payback—sometimes 25 years. Additionally, basic research is difficult to keep secret, especially from one's competitors. Hence, some sectors of industry see little financial incentive in basic research. On the other hand, the private sector will engage in a high-technology research area where the return on investment is more secure.

These are all matters that are going to be examined in some depth, with a view toward creating new policies to deal with them, in a new interagency study of industrial innovation. The President announced this major study a few weeks ago and is looking forward to the policy options it will bring him.

INDUSTRIAL INNOVATION

The principal motivation for the study is the idea that industrial innovation is central to the economic well-being of the country. It is seen as providing a basis for economic growth and as intimately related to such important concerns as productivity, inflation, unemployment, and the competitiveness of U.S. products in both domestic and world markets. There are a number of observations that underscore Federal concern over industrial innovation. Among them are industry's underinvestment in innovation; increased private-sector R&D on low-risk, short-term projects directed at incremental product change, rather than longer-term research that could lead to new products and processes; declining international competitiveness; lagging productivity; and difficulties on the part of small, high-technology firms in obtaining venture capital. There is also the matter of industry's recent diversion in innovation, from a focus on new products to meeting other goals, such as the requirements of environmental quality or consumer safety. Efforts must go into so-called defensive research, rather than into exploratory work that might break some totally new ground.

In the past year I have met with a number of vice presidents for industrial R&D to discuss these matters. A common feeling running through these meetings was that excessive Federal regulation hampered innovation, creating a climate of uncertainty that inhibited exploratory R&D. Industry was forced to spend a substantial portion of its R&D money in so-called defensive activities in order to comply with the many overly strict and ever-changing environmental and consumer safety regulations.

They were especially critical of the inflexible and zero-risk criteria built into some of the regulations. This type of regulation, they felt, drove exploratory research and product development overseas. I rarely heard any arguments in favor of the regulations, though such arguments do exist.

Before the new rules, many products were not adequately tested and evaluated for environmental and consumer safety before marketing. Therefore much of the regulation was demanded by the public. New evidence was continually being developed, and scientific uncertainty or inconclusiveness prompted conservatism in considering risks.

GOVERNMENT'S ROLE

At the time when most of the rules were promulgated, the public consensus was in favor of conservatism. It is the Government's role and responsibility to protect the public and to consider the social costs, the broad effects on the environment, and the public health, which were once external to the business community. Most of the regulations were therefore based on legislation following extensive investigation and hearings.

One way we can advance our R&D and the process of innovation is to improve information transfer between the technical community and the decision-makers and the public. It is the responsibility of the technical community to ensure that the policymakers and concerned citizens are provided with enough information to be able to make intelligent decisions that will then guide our research efforts. It is also our responsibility to provide that information in a form which can be easily

understood by the intended audience. It is not enough simply to produce massive volumes of technical data and scientific papers—this we do for our peers and not for the decisionmakers. We must also endeavor to translate our findings into a form which can be used to directly influence the decisionmaking process.

BUILDING A CONSENSUS

As we communicate, as we coordinate our efforts, we build a consensus. A consensus is nothing more than a common judgment arrived at by the majority of a concerned group. By helping to build a consensus as to what path we should take to assure a future with adequate energy, we clarify and redefine the problems facing us. We should realize that effective decisionmaking requires a definition of the problem and then a solution—not vice versa. Interagency programs are, then, part of an important effort to clarify and define problems and to offer viable solutions through a communication process. It is this process which builds the consensus, and upon this consensus depends our ability to act.

You are here to help in achieving that consensus and in improving the coordination of our energy and environmental programs. In those most important tasks, I wish you the very best of success.

TO HELL WITH IT: NAVIGATING A SEA OF ENVIRONMENTAL HAZARDS

The Honorable Charles Warren
Council on Environmental Quality

Some years ago, the *New Yorker* published a cartoon that depicted a woman reporting the disappearance of her husband to the Bureau of Missing Persons. A police officer at the desk was taking down his description. "He's 43 years old," the bereaved wife said; "he's about 5 feet, 5 inches tall, has prematurely gray hair, sort of a nondescript face, and a receding chin." At that point the woman paused, thought about the description she had just given, and then said to the police officer, "Oh, to hell with it."

HAMBURGERS CARCINOGENIC?

I was reminded of this cartoon a couple of weeks ago when Dr. Barry Commoner revealed that the humble hamburger, as it is usually fried, might prove carcinogenic. Over the years, we have had indications that cyclamates, saccharine, red dye No. 2, and the aerosol used to propel deodorants might all harm our health or our biosphere. More recently, Americans who are into consciousness-expanding techniques have become alarmed about the use of the herbicide paraquat for spraying Mexican marijuana. If any frosting were needed on this environmental cake, we might consider Dr. Commoner's consoling observation that hamburgers are all right if you fix them in a microwave oven. From other quarters, however, come allegations that prolonged exposure to radiation from microwave ovens can harm the eyes.

IS NOTHING SAFE?

Considering the multiplicity of environmental problems today, many an American might conclude that nothing is safe. If melanoma cancer from reduction of the ozone shield by fluorocarbons doesn't get you, cancer of the stomach from a Big Mac will. If you decide neither to smell nice nor to eat well, but to go to bed early and light up a joint, your pajamas may catch fire while you twist with intestinal agonies caused by an herbicide designed to eradicate a Mexican plant. After reviewing the environmental hazards past and present, I am frankly surprised that our people have not decided that environmental protection is more trouble than it's worth, or concluded, with the lady in the *New Yorker*, "To hell with it."

But they have not. On the contrary, judging by the opinion polls, public support for environmental protection is not merely holding firm but is actually

growing. I was astonished by a Lou Harris poll of last March which indicated that, by a majority of 71 percent to 18 percent, American people would rather live "in an environment that is clean, rather than an area with a lot of jobs."

HARD CHOICES VS. WISH LISTS

That kind of support is heartening to those of us who have professional obligations as well as personal commitment to environmental protection. Yet I question the true strength of that public support. It is sincere, but it has not yet been severely tested in a real-life situation that forces one to make hard choices. It is one thing, for example, to favor a clean environment over job-creation when you already *have* a job. It is quite another to support such a choice when you *don't* have a job, and when a proposed energy project would create one for you. It is one thing to be skeptical of further nuclear development when your house is heated; it is quite another to oppose such development when the oil runs out. Lacking the necessity for making a genuine choice whose consequences each individual, personally and directly, will have to bear, public opinion polls tend to be "wish lists." As Mr. Harris himself concluded after summarizing opinion on environment-energy issues, "The people . . . believe deeply in the system and its capacity to perform miracles and to do the impossible."

In sum, despite the arguments that rage over specific environmental policies, we have enjoyed a kind of honeymoon with the public over the last decade. We had better make the best use of it, because the heady bliss of these early days will not continue indefinitely. Only when the hard choices start—when serious conflicts arise—can one decide whether the honeymoon will deepen into marriage or wither toward divorce.

HONEYMOON WITH THE PUBLIC

In no other area of environment-related policy is there a greater possibility for conflict than there is in the energy field. Nor does any other aspect of environmental protection affect so many people. It is these characteristics that give such urgency to our work, for, by the time the honeymoon ends, we must not only be able to meet our energy needs; we must be able to do so safely and in an environmentally acceptable manner. Prudent public policy demands we do no less.

Two examples of the need for the environmentally prudent course in energy policy development have recently emerged from specialized research to become interesting subjects for conversation among informed laymen—acid rain and carbon dioxide buildup. These, of course, provide much more than interesting conversation. Both have the potential for massive damage. Both point up, moreover, the irritating unknowns that make environmental protection such a frustrating profession.

One of the basic tenets of President Carter's National Energy Plan is a greater dependence on the use of coal—through direct combustion in boilers, for the immediate future, and through liquefaction and gasification in the more distant future. Neither of these approaches is free of damaging side effects. Consequently, President Carter directed that a study be undertaken by a committee of nationally recognized experts to assess the potential impacts of increased coal combustion upon public health and the environment generally. The urgency of charting a sane course for national energy development required an intense and concise appraisal of a very complex issue. The study, completed in January of this year, is called the Rall Study, after the chairman of the study group, Dr. David Rall, Director of HEW's National Institute of Environmental Health Sciences. As several members of that committee are on the agenda for this conference, I will treat the study only briefly.

RALL STUDY

The charter for the Rall Study focused on the environmental impacts of *increased* coal combustion. Soon after beginning work, however, the committee found several problems that would require attention even if there were no increase at all in the combustion of coal and other fossil fuels. Two of those problems are acid rain and carbon dioxide buildup.

Although a few U.S. scientists have conducted research on acid rain, Scandinavian scientists were first to gain widespread attention for the problem. To avoid the local impacts of sulfur and nitric oxides, past and present practice in Europe has been to diffuse such pollution by discharging it from tall stacks. This worked fine for the locals, but prevailing weather patterns carried it northward, into

Norway and Sweden, and deposited it in quite different form. Through combination with moisture, the SO_x and NO_x fell back to earth as dilute acids.

PH UNITS

Acidity can be expressed in pH units, on a scale from 0 to 14. A pH of 7 or below is acidic. Normal rainfall is slightly acidic, owing to normal background constituents such as carbon dioxide; it has a pH of 5.7. In parts of southern Norway and Sweden, however, the annual average acidity of rainfall has fallen below 4.3. That may not sound like a particularly drastic change; however, owing to the peculiar mathematics of the pH calculation, such rainfall is *25 times* as acidic as normal.

Some soils can buffer this acidity, but Scandinavian soils are deficient in this respect, and runoff following acid rains has been heightening the acidity of lakes and streams. About 5,000 lakes in Sweden are estimated to have been acidified below a pH of 5.0, and fish populations in some lakes have been exterminated. Norwegian scientists estimate that 20 percent of the fish in their southern bodies of water have been similarly affected, and the annual loss in the catch of Scandinavian salmon alone is estimated at $10 million.

EXPANDING U.S. ACID RAIN BELT

We have observed the same trend in the acidity of rainfall in the northeastern United States. In some places, such as the Philadelphia-Wilmington area, the current average pH of rainfall is as low as 4.0, and values in the range of 3.6 to 2.1 have been observed in single storms. This is 100 to 4,000 times—*repeat, 4,000 times*—more acidic than normal. Further, the "acid rain belt" in the U.S. has greatly expanded. In the mid-1950's, the pH of rainfall over roughly half of the area east of the Mississippi River averaged below 5.0; now such an acidity level is found in rain over the *entire* eastern United States.

LONG-TERM THREAT

The systems most strongly affected by acid rains tend to be high-altitude forests, streams, and lakes-which suggests a serious long-term threat to many national parks and forests. Of the mountain lakes in the Adirondacks located above the 600-meter line, 50 percent now have a pH of less than 5.0; and 90 percent of those are totally devoid of fish. By comparison, only 4 percent of the lakes were in this condition in the 1930's.

CO_2 ADVERSE EFFECTS

The chain of causality here is not precisely defined. I recently saw a report which claimed that the toxic effect on fish resulted not from the acid rain directly, but from increased amounts of aluminum in soil runoff triggered by the rains. In any case, acid rains are implicated, and the effects on fish have been demonstrated. Other adverse effects, according to studies from Europe, Canada, the Soviet Union, and the U.S., may include:

- Decreases in agricultural and forest yields
- Depletion of nutrients from soils or aquatic systems
- Inactivation of important microorganisms
- Corrosion or deterioration of materials.

Because evidence on this issue is so incomplete, it is premature to assume that a crash control effort is needed. On the other hand, it is certainly *not* premature to plan a comprehensive assessment of the acid rain problem. Such an assessment would determine the relationship between emissions and levels of acid rain through monitoring and modeling, determine current effects through field investigations, and determine the potential future effects through laboratory and controlled field studies. With the results of that assessment in hand, we could understand the dimensions of the problem—whether, for example, the effects of acid rain are reversible or not, determine how much of it the environment can tolerate, and then develop control strategies for the excess.

CO_2 BUILDUP

The second energy-related problem has received vastly more publicity than acid rains, undoubtedly because of its purported doomsday consequences. In fact, a popular novel of the "disaster" category has already been written about CO_2 buildup possibly leading to the "greenhouse effect." Carbon dioxide levels in the atmosphere have been on the rise at least since the start of the Industrial Revolution and have increased by 5 percent in the last 20 years. CO_2 in the atmosphere helps to control the earth's heat balance by preventing part of the sun's reflected energy from returning back to space. As the CO_2 level increases, therefore, more energy is retained and atmospheric temperatures rise.

CAUSE-EFFECT NOT UNDERSTOOD

As with acid rains, the cause-effect relationship here is not well understood, at least not well enough for us to exercise long-range policy judgments. Most scientists who have studied the matter believe that the increases observed during the last century were caused by rising consumption of fossil fuels; some others believe that massive deforestation has contributed equally.

If current models describe the phenomenon with reasonable accuracy, rapid use of the world's fossil fuel reserves could produce a seven-fold increase in the CO_2 level by the year 2200. A doubling of the level could occur in 50 years. Such a doubling, it is estimated, could cause an average temperature increase of 2 to 3 degrees Celsius, a change that would pose a major environmental threat. To illustrate, in the last 6,000 years, average mid-latitude temperatures in the Northern Hemisphere have not varied by more than 1 degree above or below 15 Celsius.

Although the full consequences of a 2-degree warming are highly speculative, some obvious social and economic disruptions can be predicted. Agricultural belts would shift toward the poles, and the melting of the ice caps could raise the sea level. On the positive side, increases in rainfall and in CO_2 might enhance photosynthesis. We simply cannot anticipate all the implications of CO_2 buildup at this point, but we must learn, not only because the possible consequences are so grave, but because we must develop some sense of the decisions that may have to be made to deal with or avoid those consequences.

COMPREHENSIVE ASSESSMENT

Here we return to the same place where acid rain deposited us: the need for a *comprehensive assessment* of the problem. In the case of CO_2 buildup, we have more time to perform the assessment, but the costs will be greater: the larger the environmental system, the more complex and costly the study requirements.

MID-COURSE ENERGY POLICY CORRECTIONS

In his National Energy Plan, President Carter stated the need for such an assessment and assigned responsibility for it to the Department of Energy. DOE has already developed a research plan and will invest about $4 million on the study in the next 2 years. The results should give us the information on which to base necessary mid-course corrections in *international* energy policies; the U.S. cannot solve either the acid rain or CO_2 problems without the cooperation of other countries.

SOLAR ENERGY

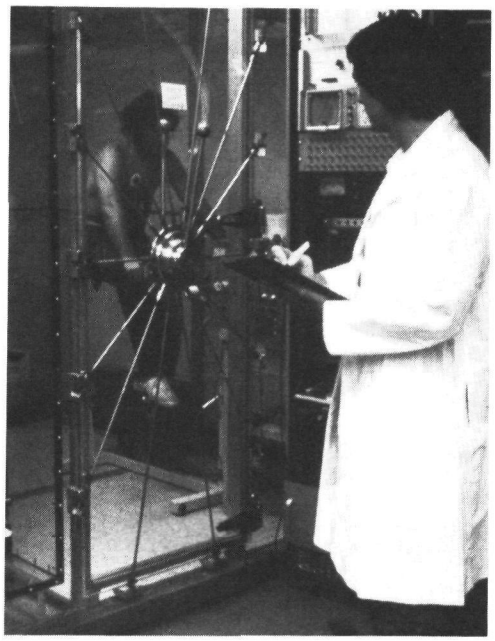
The existence of these threats should also accelerate our development of energy technologies that do not depend on fossil fuels, in particular, solar energy. At present, most solar technologies are not cost competitive with fossil fuels. But if our assessment of the acid rain and CO_2 problems proves them as serious as scientific inference suggests, the economic as well as environmental costs of increased fossil-fuel consumption might well transform solar energy into an overnight bargain.

You here are charged with conducting the research and development we need to ensure that energy development proceeds without disrupting the natural systems that support our lives. Certainly, the two problems I have outlined today are capable of massive ecological disruption and unpredictable economic harm. They also illustrate a most irritating aspect of environmental protection: as soon as we begin to get a handle on one problem, a newcomer that we didn't even dream of appears. Although we *have* been making progress on one environmental problem after another, it is hard to convey that impression convincingly—especially to the lay citizen—when we seem to be navigating a sea of environmental hazards, with no shore in sight.

A RACE BETWEEN CIVILIZATION AND DISASTER

Henry Adams once described education as "a race between civilization and disaster." In our time, and in view of the potential conflicts between energy development and human well-being, that description seems even more true of your research. So far, our citizens are with us. We must honor their trust by squeezing the maximum of environmental protection from every dollar and every month they give us. We must give substance to their expressed conviction that we can have a healthy economy and a healthy environment at the same time. Unless we do, the seemingly endless variety of environmental concerns may cause those who support us to lapse into apathy.

We can't say "To hell with it." We have a race to win.



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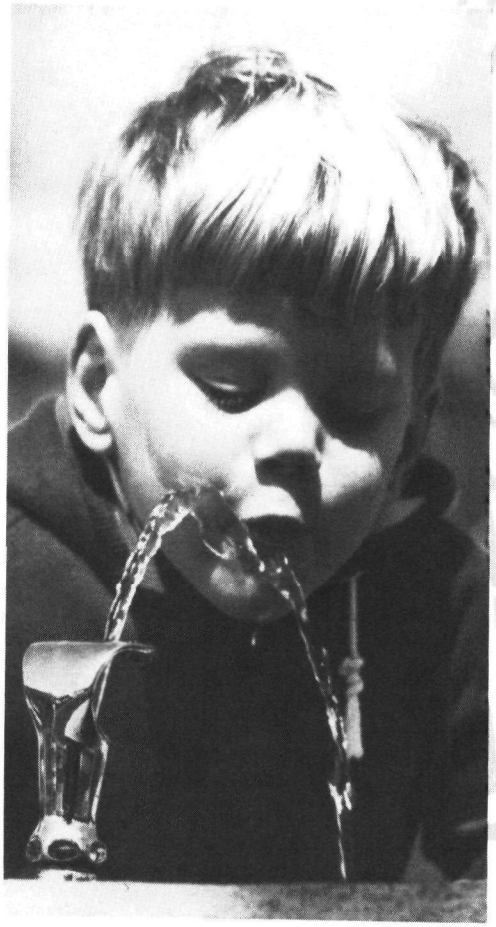

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STATUS OF BIOSCREENING OF EMISSIONS AND EFFLUENTS FROM ENERGY TECHNOLOGIES

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PROBLEM SOURCES

The National Energy Plan has affirmed that "The United States and the world are at the early stage of an energy transition." This transition and the future reliance on multiple sources of energy have provided the problem and the challenge to "bioscreening" for health and ecological effects.

During the next 10 years, the major contribution to energy-related emissions and effluents will be of a conventional nature. We will see increased combustion of coal by conventional methods together with the gradually increased utilization of alternative procedures such as fluidized-bed combustion. It is unlikely that the newer technologies such as the gasification of coal, shale oil production, solar energy, and nuclear fusion will have a major impact before the middle of 1980 (1).

Therefore, our bioassay methods must be geared to the evaluation of conventional sources as well as to the newly evolving energy conversion technologies. We have made significant progress in both areas as described in the proceedings of the Second National Conference (2) but much remains to be accomplished.

SHORT-TERM BIOASSAYS

Although our concern is with health as well as ecological effects, it is the purpose of this presentation to examine the current status of short-term bioassays which are applicable in studies of potential health effects of energy-related technologies.

Short-term bioassays are being applied effectively in the detection and evaluation of potentially hazardous emissions and effluents from conventional and developmental energy sources, but, as yet, to a limited extent.

Biological screening tests such as the Ames *Salmonella* microsome assay (3) have demonstrated their utility: 1) as indicators of potential long-term health effects such as mutagenesis and carcinogenesis, 2) as a means to direct the fractionation and identification of hazardous biological agents in complex mixtures, 3) as a measure of relative biological activity to be correlated with changes in process conditions, and 4) to establish priorities for further confirmatory short-term bioassays, testing in whole animals, and more definitive chemical analysis and monitoring.

Clearly, however, these tests do not circumvent the need for conventional toxicological, clinical, and epidemiological evaluation. Likewise it is not possible to divorce our vested concern for human health effects from a more basic concern for the welfare of the ecological environment.

ENVIRONMENTAL MEDIA

The introduction of emissions and effluents into the environment from energy related technologies creates a multifaceted toxicological problem. The problem is a function of the environmental media—i.e., air, water, food-and of the routes of exposure. Indeed, mechanisms of toxic effects may be highly media or route specific. Most exposures to hazardous agents in the environment are multiexposures; that is, there are very few instances in which a singular substance or a single

exposure is solely responsible for adverse health or environmental effects. Table 1 lists some general classes of chemicals with significant human exposure. Each of these exposure factors must be taken into account in assessing the potential health effects of energy related technologies.

ENVIRONMENTAL EFFECTS

Man is but a part of a total ecosystem. His well-being is utlimately dependent upon the well-being of the system as a whole. Hence, it is critical to evaluate health effects in man in the light of relevent and significant perturbations of the ecosystem, especially those which directly influence exposure media including food, water, and air.

Environmental effects may be slow to manifest themselves. Thus, our current methods of disposal and recycling of toxic wastes and by-products may ultimately compound the health and ecological effects of substances introduced into the environment. We need to have detailed knowledge of the transport and fate of environmental toxicants. Careful consideration of these factors is as important as measuring the toxicity of the industrial discharge waste stream and must ultimately be included in the assessment of the environmental impact of new technologies.

APPROACHES TO THE PROBLEM

We have considered the components of the process of environmental assessment in the broadest sense, i.e., the total impact of new technology on man and his environment. The development of a rapid, effective, and inexpensive means for evaluating the potential health hazards associated with emissions and effluents from energy related technologies is a critical step in this process. Short-term bioassays provide a means to this end but do not offer an independent solution to the assessment problem.

CHEMICAL AND BIOLOGICAL ANALYSIS

It is clear that chemical and biological analysis have a dual role in the process of environmental assessment. Each of these disciplinary approaches has its advantages and limitations. Chemical analysis, while indicative, cannot provide sufficient data for complete evaluation of potential pollutant effects, because the biological activity of complex samples cannot be consistently predicted. Although bioassays can indicate the biological activity of a given sample, they cannot specifiy which components of a crude sample are responsible for the observed toxicity. A cost-effective approach in screening involves the use of short-term bioassays to determine which samples are biologically active together with chemical fractionation and analysis to ascertain which agents are responsible for the observed effects. This was the theme of the

TABLE 1
General classes of chemicals with human exposure: potential environmental mutagens/carcinogens

DRUGS	INDUSTRIAL PRODUCTS AND EFFLUENTS
• MEDICINAL	ENERGY-RELATED EFFLUENTS
• VETERINARY	• ENERGY PRODUCTION
COSMETICS	• ENERGY CONVERSION
PESTICIDES	• ENERGY USE
STIMULANTS	
FOOD	NATURAL PRODUCTS
• ADDITIVES	• TOBACCO
• DYES	• SOOT
• PRESERVATIVES	
• SWEETENERS	FLAME RETARDANTS

Adapted from Epler, et al., *Environmental Health Perspectives,* 1978.

recent Williamsburg Symposium (4) sponsored by the EPA Office of Energy, Minerals and Industry through the Biochemistry Branch at EPA's Health Effects Research Laboratory, Research Triangle Park, NC. The conference demonstrated that short-term bioassay techniques can be used effectively to assess the biological activity of complex samples and their components. Assays for toxicity, mutagenesis, oncogenic transformation and related effects have been applied to an array of complex samples including ambient air, water and food, automotive emissions, industrial emissions, coal and its combustion products, and natural and synthetic oil products. A major part of one of the Williamsburg papers is included in this report as an example of the combined use of state-of-the-art biological and chemical methodology.

METHODOLOGY

In considering the application of analytical chemical methodology it is important to realize that the presence or absence of a known toxic component within a complex sample neither indicates nor precludes a relationship between that component and the biological activity of the sample. To avoid the possibility of overlooking unanticipated biologically active components chemical analysis should not be restricted to determination of preselected known toxic compounds or suspected hazardous components of a complex sample. Indeed, it may be technically overwhelming to analyse for all of the known or suspected hazardous components in a large number of complex samples. For this reason and for cost effectiveness, it can be argued that a phased approach involving stepwise application of biological and chemical methodology is appropriate in evaluating the potential health hazard of complex mixtures.

ASSESSMENT APPROACH

The Industrial Environmental Research Laboratory of the Environmental Protection Agency, Research Triangle Park, North Carolina (IERL-RTP), has delineated a three-phased approach to performing an environmental source assessment, i.e., the evaluation of feed and waste streams of industrial processes in order to determine the need for control technology. Each of the three phases involves a separate sampling and analytical procedure.

According to the plan outlined by IERL-RTP, (5-7) "The first level: 1) provides preliminary environmental assessment data, 2) identifies problem areas, and 3) generates the data needed for the prioritization of energy and industrial processes, streams within a process, and components within a stream for further consideration in the overall assessment. The Level 2 sampling and analysis effort is designed to provide additional information that will confirm and expand the information gathered in Level 1. Level 1 results serve to focus Level 2 efforts. The Level 2 results provide a more detailed characterization of biological effects of the toxic streams, define control technology needs, and may, in some cases, give the probable or exact cause of a given problem. Level 3, utilizes Level 2 or better sampling and analysis methodology in order to monitor the specific problems identified in Level 2 so that the toxic or inhibitory components in a stream can be determined exactly as a function of time and process variation for control device development. Chronic, sublethal effects are also monitored in Level 3.

FINAL OBJECTIVE

"To meet the environmental source assessment requirement of comprehensiveness, the IERL-RTP phased approach provides for physical, chemical, and biological tests. Physical and chemical characterization of environmental emissions is critical to the definition of need for and design of control technology. However, the final objective of the Industrial Environmental Research Laboratory's environmental assessment is the control of industrial emissions to meet environmental or ambient goals that limit the release of substances that cause harmful biological (health and ecological) effects. Consequently, the testing of industrial feed and waste streams for biological effects is needed to complement the physical and chemical data and ensure that the assessment is comprehensive."

This effort is cited as an example of a large scale phased application of short-term bioassays and chemical analytical techniques to the analysis of complex environmental samples. It represents an important beginning in an area of research and application that will require continued intensive collaboration between engineers, chemists and biologists if success is to be achieved. The results of Level 1 pilot studies on samples from fluidized-bed combustion and coal gasification processes are

still being analyzed; a number of conclusions, however, can be drawn from the results obtained thus far:

- In general, chemical analytical techniques are quantitatively more sensitive than are the health effects bioassays.
- Biological activity, especially genetic activity, may be masked by toxicity and may require chemical fractionation to become demonstrable.
- In some cases, tests for potential ecological effects may be more sensitive and more critical than tests for potential health effects.
- The prediction of relative toxicity on the basis of chemical analysis alone is subject to error.
- Results of biological and chemical tests are complementary considered together the two types of tests provide useful information not obtainable when considered separately.

HEALTH EFFECTS BIOTESTING

There now exists a matrix of short-term health effects bioassays which can be applied in a phased or stepwise manner in the biological analysis of energy related samples. As with the IERL-RTP example, any program aimed at identifying and reducing release of hazardous emissions or effluents requires the utilization of inexpensive short-term bioassays to prioritize samples for further evaluation by conventional toxicological procedures. However, it should be noted that some short-term bioassays are known to be insensitive to specific chemicals or classes of chemicals. Indeed, no single bioassay is adequate to monitor all types of chemical and biological activity. The problem of potential false negatives may be alleviated by the use of a required core battery of tests and by the identification, prior to biological testing, of those samples which contain chemicals structurally or physicochemically similar to known false negative agents or classes of agents. Such agents or fractions of complex samples might then be selected for higher level testing without the need for preliminary screening.

MUTAGENICITY/CARCINOGENICITY TESTING

In the areas of mutagenicity and carcinogenicity testing, several variations of the tiered or phased approach have been discussed in the literature (8)(10). However, there is a considerable agreement on the essential point of emphasis at each level of evaluation and on the need to employ a battery of tests to detect various genotoxic effects, i.e., those effects involving damage to the genetic material.

For purposes of illustration and example we have organized a number of the existing bioassays into a three-phased matrix based primarily on the endpoint measured, cost and complexity. While the short-term bioassays that will be mentioned are not to be considered exclusive, they do represent state-of-the-art methodology. The refinement and implementation of many of these systems has been a direct result of funding under the Interagency Energy/Environment R&D Program.

PHASED APPROACH

A phased approach to bioscreening for environmental health effects emphasizing kinds of bioassays is illustrated in figure 1. This is a three-step matrix with a battery of tests at each level. The emphasis in the Phase 1 test battery is on the *detection* of acute toxicity using mammalian cells in culture and intact animals, genotoxic effects including point mutation and primary DNA damage in microbial species, and chromosomal alterations in mammalian cells in culture. The Phase 2 battery is designed to *verify* the results from Phase 1 tests by employing higher level toxicity tests involving mammalian cells in culture and intact mammals and genotoxicity assays using plants, insects, and mammals. Genotoxicity assays at Phase 2 are separated into tests for mutagenicity *per se* and specific tests for carcinogenic potential. Phase 3 testing is devoted to quantitative *risk assessment*, using conventional toxicological methods. For the purpose of defining a probable negative result for genotoxicity, the core battery of short-term tests is most important.

For the reason stated previously that no single test is capable of indicating all of the various types of biological activity which may be relevant to the processes of

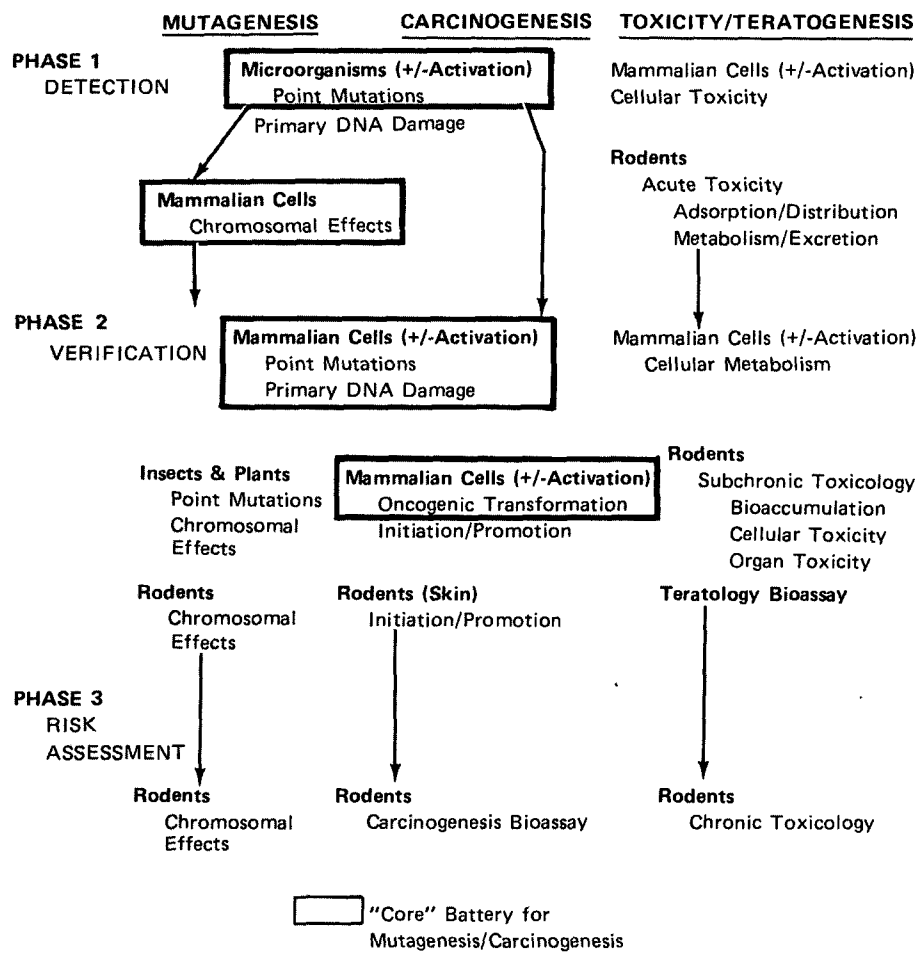


FIGURE 1—*A phased approach to bioscreening for environmental health effects*

GENOTOXIC EFFECTS TESTS

mutagenesis and carcinogenesis, it is generally held that a battery of short-term tests should be performed. The battery approach is intended to reduce false negatives to a minimum and thus assure reasonable protection of human health. Batteries of tests have been proposed in the development of EPA's Pesticide Guidelines for Mutagenicity Testing and in the Consumer Product Safety Commission's "Principles and Procedures for Evaluating the Toxicity of Household Substances" (11). These documents reflect the thinking expressed in the Committee 17 Report on Environmental Mutagenic Hazards (12) and in the report of the working group of the DHEW Subcommittee on Environmental Mutagenesis "Mutagenic Properties of Chemicals: Risk to Future Generations" (13). There is considerable agreement that a core battery of tests for mutagenic and carcinogenic effects should include, as minimum, tests for point mutation in microorganisms and mammalian cells in culture; a test for chromosomal alterations, preferably in *in vivo* test; a test for primary damage to DNA using mammalian, preferably human, cells in culture and a test for oncogenic transformation *in vitro*. Such a battery of tests might be considered to represent the core or the most essential of the genotoxicity tests in the phased evaluation process. Redundancy in the test battery is considered desirable until a more complete data base of test results has been assembled. Also, to aid in interpretation, it is necessary to ascertain the influence of cellular toxicity in these tests. The following is a description of the kinds of biological activity detectable in short-term tests comprising the core battery.

POINT MUTATION

Point mutations are alterations which affect single genes. These alterations include base pair substitutions, and frameshift mutations as well as other small deletions and insertions. Applicable test systems include both forward and reverse

mutation assays in bacteria, yeast, and mammalian cells in culture. Most of these assays employ an exogenous source of metabolic activation provided by a mammalian liver microsomal preparation. It has become apparent that a majority of the genotoxins are procarcinogens or promutagens which must be converted into their reactive forms before their effects can be evaluated. The metabolic conversion is believed to be mediated by oxidative enzymes and to involve the formation of reactive electrophilic metabolites which bind covalently to DNA. Gene mutation assays which incorporate whole animal metabolic activation (e.g., urine screening) are very desirable since it is not possible to ensure metabolic fidelity in entirely *in vitro* systems. One must employ intact animals to demonstrate the heritability of mutational effects.

CHROMOSOMAL ALTERATIONS

Chromosomal alterations include the loss or gain of entire chromosomes, chromosome breaks, non-disjunctions and translocations. Short-term tests for these abnormalities involve searching for chromosomal aberrations in somatic and germinal cells usually from insects and mammals. Chromosomal aberrations observed in germinal tissues of intact animals provide important evidence of the accessibility of the test chemical to the reproductive organs.

Damage and repair bioassays do not measure mutation directly but do measure the direct damage to DNA and other macromolecules by chemical agents and its subsequent repair. Bioassays to detect macromolecular damage and repair are available, using bacteria, yeast, mammalian cells, and whole animals. Except for the whole animal bioassays, these systems generally employ an exogenous source of metabolic activation.

Oncogenic transformation is the process whereby normal cells grown in culture are converted into malignant cells after treatment with a carcinogen. The demonstration of malignancy (tumor formation) can be observed by injecting the transformed cells into whole animals, although this is not an obligatory requisite for oncogenic transformation. A number of mammalian oncogenic transformation bioassays utilizing cells derived from different rodent species are currently available. Some of these cell systems have the endogenous capability to activate procarcinogens while with others exogenous microsomal activation has been used successfully.

TOXICITY *IN VITRO*

An initial requirement in mammalian cell mutagenesis and oncogenesis bioassays is the determination of the lethal toxicity of each test agent. This information may be used to establish the range of concentrations to be employed in the mutagenesis or oncogenesis assays and to quantify the observed mutation or transformation frequency in terms of the number of cells surviving the treatment.

Two critical questions are: How good are these genotoxicity tests and what do they mean?

CARCINOGENESIS

At the present time, microbial mutagenesis test systems are most widely used to prescreen substances for potential oncogenicity. Tests for gene or point mutations in microorganisms, as for example those involving the *Salmonella typhimurium*/microsome system, have been found to be highly predictive of oncogenic potential (14). Most chemical mutagens which have been adequately tested have been found to be oncogenic in whole animal bioassays. It is well established that most but not all oncogens are mutagens when appropriate metabolic activation is provided in the short-term tests. Research on test systems which permit sequential evaluation of mutagenesis and oncogenic transformation has enhanced our understanding of the relationship between these two phenomena.

Oncogenic transformation *in vitro* is considered to be directly relevant to the process of tumor formation in the intact animal. Few, if any, false positives are detected using this methodology (15). However, because of the laborious nature of cell transformation assays, it may not be feasible because of time or fiscal constraints or the availability of facilities to immediately put a very large number of samples through such testing procedures. It is for reasons such as these that oncogenic transformation assays are generally considered to be higher level tests.

When more fully developed, human cell bioassays for oncogenic transformation may afford a final short-term test for substances found positive in phylogenetically lower organisms. This will be true especially if epithelial cell systems can be developed which retain their metabolic activation capability. Those chemicals which produce positive responses in human cell systems might be given highest priority for evaluation in conventional whole animal oncogenesis bioassays.

MUTAGENESIS

The fundamental concern in mutagenesis testing is the risk to future generations. Alterations of the genetic material in germinal cells are rarely expressed in the exposed individuals. These alterations may not become apparent for several generations but they contribute to an increased genetic burden in the exposed population. The observation and quantitation of these mutational effects in germinal tissues requires the use of intact animals, e.g., the sex-linked recessive lethal test in the insect *Drosophila* (16). It would be highly desirable to include such a test in the core battery if significant human exposure is anticipated to a suspect mutagen.

The usefulness of cells other than germinal cells as a predictive tool is judged to be high for certain kinds of genetic alterations. Microbial cells are widely used to detect point mutagens. Many of these systems have been genetically engineered to enhance their sensitivity as detection systems. Mammalian and human cells in culture can provide more relevant information on the ability of the substance to induce both point mutations and chromosomal alterations. It is important to evaluate both types of potential genetic activity. Chromosomal alterations are best evaluated in intact animals but inexpensive whole animal tests for point mutagens are lacking.

ANCILLARY EFFECTS

Tests which detect primary damage to informational cellular macromolecules (e.g., DNA) have been found to show moderate to high correlation with mutagenic and oncogenic potential as indicated by animal bioassays (17,18). Microbial tests in this category are extremely rapid and inexpensive and offer the possibility of examining various manifestations of macromolecular damage. Mammalian and human cell culture bioassays for primary DNA damage offer the possibility of detecting macromolecular damage in tests which have demonstrated promising correlations with mutagenic and oncogenic potential as evaluated using experimental animals (19). Several of these systems permit concomitant measurement of primary DNA damage, point mutation, chromosomal effects and cellular toxicity. The Interagency R&D Program is continuing to support developmental research of this kind.

As indicated previously, a phased mode of application has been favored as a cost effective approach to the bioscreening of large numbers of complex environmental samples and their components.

BIOASSAY STRATEGY

A strategy for the employment of short-term bioassays based on biological activity, cost and complexity may be delineated as follows:

In Phase 1, tests representing each kind of biological activity would be performed. The extent of redundancy in testing within a category of biological activity would be dictated by a number of factors including production volume, anticipated human exposure, and known hazards of feed stocks. If any of these tests proved positive, the appropriate follow up tests would be pursued in Phase 2 and, if required, in Phase 3 depending upon the degree of associated risk. If those tests were to prove negative, no further testing would be performed unless there were overriding considerations as mentioned previously. In such cases a core battery of tests for genotoxicity would be completed with negative results before short-term testing would cease. Extensive health risk could entail further long-term testing to define a negative result. This approach would facilitate a cost effective utilization of limited testing resources and would at the same time provide protection for human health in proportion to the anticipated risk involved.

Specific tests may be organized within the test matrix as follows:

PHASE 1 BIOASSAYS

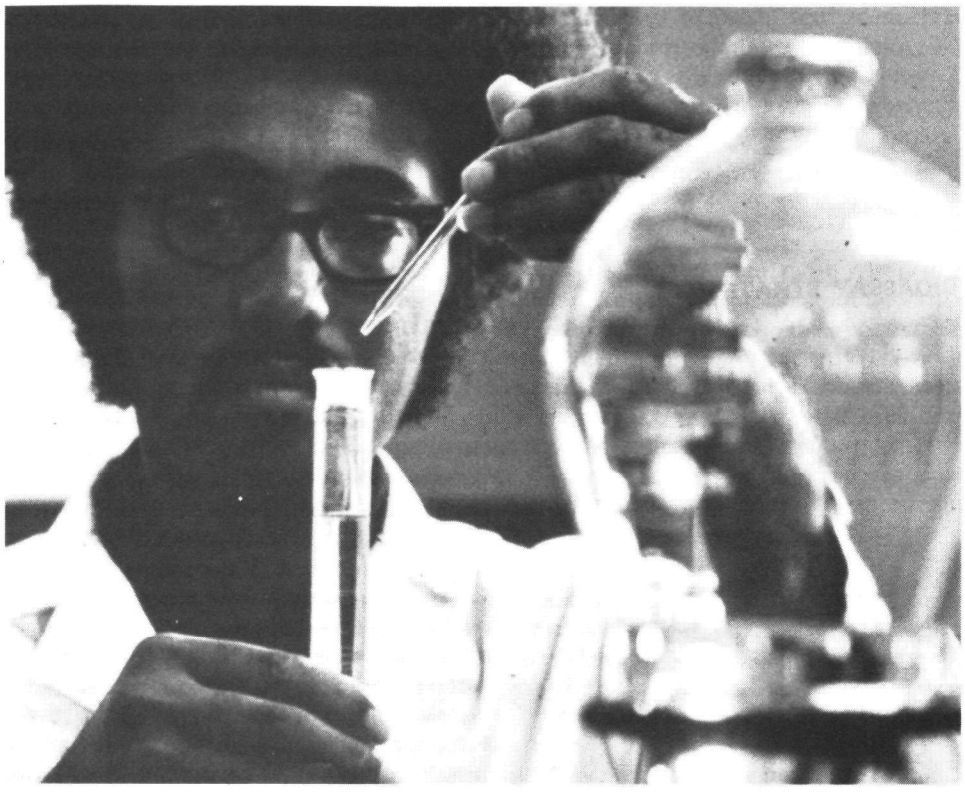
A battery of short-term tests for this phase is illustrated in figure 2. As mentioned previously, the emphasis at this level of testing is on *detection* of mutagens, potential carcinogens and acutely toxic chemicals in a battery of *in vitro* and *in vivo* tests. The results obtained from Phase 1 tests are used to assign priorities for further testing in appropriate confirmatory bioassays at Phase 2. The *in vitro* end points that are considered, based upon expense, complexity, and the current level of development of bioassay systems, are point mutations, chromosomal alterations, primary DNA damage, and cellular toxicity. All bioassays are performed with and without mammalian metabolic activation systems where feasible. Conventional rodent acute toxicity tests are considered essential at Phase 1 in view of the limitations of cytotoxicity screening tests. The latter tests cannot represent intact animals but provide useful preliminary information about the relative cellular toxicity of selected samples (e.g. airborne particulate materials (20). In addition, rodent acute toxicity tests can provide a source of body fluids and tissues to be examined for the presence of active mutagens and carcinogens by the use of short-term genotoxicity bioassays.

PHASE 2 BIOASSAYS

As mentioned previously, Phase 2 tests illustrated in figure 3 are designed to verify the results obtained in Phase 1. The test systems are selected to provide confirmatory information on point mutations, chromosomal alterations, primary DNA damage and repair, and cellular oncogenic transformation. The latter test provides more explicit information on the carcinogenic potential of a sample. The test organisms are mammalian cells in culture supplemented with exogenous metabolic activation, plants, insects, and intact mammals. These systems are considered to provide more relevant and definitive information in the continuing process of health hazard evaluation, especially where intact organisms are employed.

PHASE 3 BIOASSAYS

Phase 3 testing involves the use of conventional whole animal methods. The emphasis here is on quantitative risk assessment. Experimentation with intact mammals is needed to provide information on the presence, concentration, and biological activity of toxins in the target tissues. In addition, information on pharmacokinetics involving absorption, distribution, metabolic transformation, and excretion cannot be obtained without studies using intact mammals.



POINT MUTATIONS

- SALMONELLA/MICROSOME (AMES) REVERSE MUTATION, PROTOTROPHY TO HISTIDINE
- ESCHERICHIA COLI-WP2/MICROSOME REVERSE MUTATION, PROTOTROPHY TO TRYPTOPHANE
- SACCHAROMYCES CEREVISCIAE REVERSE AND FORWARD MUTATION

CHROMOSOMAL EFFECTS

- *IN VITRO* CYTOGENTICS
  CHINESE HAMSTER OVARY CELLS
  WI-38 HUMAN FIBROBLASTS

PRIMARY DNA DAMAGE

- ESCHERICHIA COLI POL A⁻ REPAIR DEFICIENT STRAINS
- BACILLUS SUBTILLIS, REC⁻ REPAIR DEFICIENT STRAINS
- SACCHAROMYCES CEREVISCIAE GENE CONVERSION AND MITOTIC RECOMBINATION

CYTOTOXICITY

- RABBIT ALVEOLAR MACROPHAGE (FOR PARTICULATES)
- CHINESE HAMSTER OVARY CELLS
- WI-38 HUMAN LUNG FIBROBLASTS

RODENT ACUTE TOXICITY

FIGURE 2–*Phase 1 short-term bioassays for mutagenesis/carcinogenesis/toxicity*

POINT MUTATIONS

- MAMMALIAN CELLS IN CULTURE (CHO, L5178Y, V79)
- INSECTS-DROSOPHILA
- PLANT-TRADESCANTIA AND MAIZE

CHROMOSOMAL EFFECTS

- *IN VIVO* CYTOGENETICS – LEUCOCYTE CULTURE AND BONE MARROW CELLS

PRIMARY DNA DAMAGE

- UNSCHEDULED DNA SYNTHESIS (WI-38)
- SISTER-CHROMATED EXCHANGE FORMATION *(IN VITRO* AND *IN VIVO)*

NEOPLASTIC TRANSFORMATION

- SYRIAN HAMSTER EMBRYO CELLS
- MOUSE FIBROBLAST CELL LINES (C3H10T1/2 AND BALB/c 3T3)

CELLULAR METABOLISM

- PRIMARY LIVER CELLS

(RODENT SUBCHRONIC TOXICOLOGY)

(TERATOLOGY)

FIGURE 3–*Phase 2 short term bioassays for mutagenesis/carcinogenesis/toxicity*

The resource implications of a mutagenicity/carcinogenicity bioscreening program are shown in table 2. It is evident that most of the short-term bioassays designed to detect point mutation, chromosomal alterations *in vitro* and primary DNA damage and repair are relatively rapid, inexpensive, and require small amounts of test material. Together with cytotoxicity bioassays for selected applications and rodent acute toxicity tests these bioassays constitute effective screens for toxic and genotoxic effects of energy related emissions and effluents.

SYNTHETIC FUEL PRODUCTS BIOASSAY

As we have reported previously (2), a number of mutagenicity/carcinogenicity bioscreening efforts related to energy technologies are now underway. In work conducted at Oak Ridge National Laboratory, the feasibility of using short-term mutagenicity assays to predict the potential biohazard of various crude and complex test materials has been examined in a coupled chemical and biological approach. The research program was not deliberately structured according to the three-phased matrix outlined above. However, it does provide an appropriate example of the stepwide application of bioscreening methodology to energy related samples and provides some documentation of comparative mutagenesis responses to such samples.

This work has emphasized test materials available from the developing synthetic fuel technologies (21). However, the procedures are applicable to a wide variety of industrial and natural products, environmental effluents, and body fluids.

The principal focus of the research has been preliminary chemical characterization and preparation for bioassay, followed by testing in the *Salmonella* histidine reversion assay described by Ames (3).

The general applicability of microbial test systems has already been demonstrated, for example, by the use of the assay as a prescreen for potential genetic hazards of complex environmental effluents or products, e.g., tobacco smoke condensates (22) natural products (23,24) hair dyes, (25) soot from city air, (26) fly ash, (27) and synthetic fuel technologies, oils, and aqueous wastes (28,29).

To study the application of mutagenicity testing to environmental effluents and crude products from the synthetic fuels technology, preliminary screening was performed with the highly sensitive Ames histidine-reversion strains known to respond to a wide variety of proven mutagens/carcinogens (26). The working hypothesis was that sensitive detection of potential mutagens in *fractionated* complex mixtures could be used to isolate and identify the biohazard. In addition, the information could be helpful in establishing priorities for further testing, either with other mutagenesis assays or with carcinogenesis assays.

BIOASSAY METHOD

Fractions and/or control compounds to be tested were suspended in dimethyl sulfoxide to concentrations in the range of 10-20 mg/ml solids. The potential mutagen was in some cases assayed for general toxicity (bacterial survival) with strain TA1537. Normally, the fraction was tested with the plate assay over at least a 1000-fold concentration range with the tester strains TA98 and TA100. Revertant colonies were counted after a 48-hour incubation. Data were recorded and plotted versus added concentration, and the slopes of the induction curves were determined. It is assumed that the slope of the linear dose-response range reflects the mutagenic activity. Positive or questionable results were retested with a narrower range of concentrations. All studies were carried out with parallel series of plates with and without the rat-liver enzyme preparation (24) for metabolic activation. Routine controls demonstrating the sterility of samples, enzyme or rat-liver S-9 preparations, and reagents were included. Positive controls with known mutagens were also included in order to recheck strain response and enzyme preparations. All solvents used were nonmutagenic in the bacterial test system.

TABLE 2
Resource implications of carcinogenicity/mutagenicity bioscreening program

Test	$ Cost*	Study Time †	Quantity of Material Required
	Gene (Point) Mutations		
Bacteria (Ames plate test)	350 – 600	2–4 weeks	2 g
Bacteria (liquid suspension)	1,000 – 2,000	2–4 weeks	2 g
Eukaryotic micro-organisms (yeast)	200 – 500	2–4 weeks	2 g
Insects *(Drosophila,* recessive lethal)	6,000 – 7,500	4–6 months	10 g
Mammalian somatic cells in culture (mouse lymphoma)	2,500 – 4,800	1–2 months	2 g
Mouse specific locus	20,000+	1 year	25 g
	Chromosomal Mutations		
In Vitro cytogenetics	1,000 – 2,000	2–4 weeks	2 g
In Vitro cytogenetics	3,000 – 6,500	6–8 weeks	20 g
Insects, heritable Chromosomal effects	3,000 – 6,500	4–6 weeks	10 g
(Drosophila) non-disjunction	3,000	1–3 months	
Dominant lethal in rodents	6,000 – 10,000	3 months	20–25 g
Heritable translocation in rodents	40,000 – 67,000	12–18 months	25 g
	Primary DNA Damage		
DNA repair in bacteria	200 – 500	2–4 weeks	2 g
Unscheduled DNA synthesis	350 – 2,000	4–6 weeks	2–5 g
Mitotic recombination and/or gene conversion in yeast	200 – 500	4–6 weeks	2–5 g
Sister chromitid exchange	1,000 – 1,200	4–6 weeks	2–5 g
	Oncogenic Transformation *In Vitro*		
Chemically induced transformation	6,500 – 7,500	10–12 weeks	2–5 g

* Cost of these tests has varied and can be expected to vary until test requirements are stabilized.
† This time period covers the experimental time and report preparation.

TABLE 3
Distribution of mutagenic activity of synthetic oil* (Synfuel A-2)

Fraction†	Relative Weight (% of total)	Specific Activity (rev/mg)‡	Weighted Activity (rev/mg)§
1. $NaOH_I$	20.9	1700	356
2. WA_I	2.2	180	4
3. WA_E	4.9	1260	62
4. SA_I	<0.1	30	0
5. SA_E	0.4	130	1
6. SA_W	0.4	120	1
7. B_{Ia}	6.8	38700	2633
8. B_{Ib}	0.1	1270	1
9. B_E	2.0	36200	725
10. B_W	0.6	570	3
Neutral	69.2	583 (570)**	403
Total	107.6		4189
Neutral Subfractions			
Hexane	72.7	340	244
Hexane/benzene	5.0	710	35
Benzene/ether	19.8	1360	270
Methanol	2.3	1460	34
Subtotal	99.8		583
Initial sample, g	26.166		
Chromatographed, g	10.664		

* All assays carried out in the presence of crude liver S-9 from rats induced with Aroclor 1254.

† I = insoluble (fractions a and b), E = ether soluble, W = water soluble, WA = weak acid, SA = strong acid, B = base.

‡ rev/mg = revertants/mg, the number of histidine revertants from *Salmonella* strain TA98 determined by use of the plate assay with 2×10^8 bacteria per plate. Values are derived from the slope of the induction curve extrapolated to a milligram value.

§ Weighted activity of each fraction relative to the starting material is the product of columns 2 and 3. The sum of these products is given as a measure of the total mutagenic potential of each material.

** Comparable to "specific activity", but based on the activity of the total neutral fraction rather than on the summation of the individual fractions.

SAMPLES

Samples that have been tested and their sources are listed in tables 3 and 4. The authors recognize the possibility that these samples may bear no relationship to the process as it may exist in the future, nor should it be construed that these materials are representative of all natural crudes or synthetic or shale-oil processes. They are used here simply as appropriate and available materials for the research.

The bulk of the samples listed above were subjected to the fractionation scheme described by Swain et al., (30) as modified by Bell et al. (31). The scheme is described in detail as applied to oils in Rubin et al. (32). As an example, a

summary of the results from a sample of Synfuel A-2 (ref. 28) is given in table 3. Subfractionation results are shown with the neutral fraction chromatographed on a Florisil column. The column was eluted with the solvents shown and, with this sample, collected in one fraction. The data include the analytical weight analysis of the sample (column 2) and the specific mutagenic activity (slope of the dose-response curve) of each fraction (column 3). The product of these (column 4) represents a weighted value of each fraction relative to the contribution to the starting test material. Mutagenic activity is seen in both the acidic and basic fractions as well as in the neutral subfractions. However, the major contributors to the mutagenicity appear to occur in the basic fractions, with activities also consistently present in the neutral materials.

ACTIVITIES COMPARISON

A comparison of these activities and the total mutagenic potential of the various oil and aqueous samples is given in table 4. Reasonable reproducibility is seen in similar samples, e.g., Synfuel A-1 and A-2; Synfuel B-1 and B-2. Synfuel A-3 represents the same material without prior centrifugation of the solids. The consistency of activities seen in all oils considered is illustrated. On a relative scale, the synthetic fuels show more mutagenic activity than the natural crude control samples shown. Shale oil appears to be only slightly higher than the natural crudes. References are given to the complete published compilations on these samples.

Each determination represents the slope of the dose-response curve. All testing was carried out in the presence of the rat-liver microsomal activation system. Slight mutagenic activity without enzyme treatment was occasionally noted.

ROUTINE SCREENING

The routine screening utilized strains TA100 (missense) and TA98 (frameshift); however, complete strain-specificity tests were carried out with selected materials. Fractions giving a positive response with strain TA98 were, in general, also positive with the other frameshift strains, TA1537 and TA1538. Positive results were routinely noted with the sensitive missense strain TA100; however, reversion of the

TABLE 4
Summary of mutagenicity testing results with synthetic oils and aqueous samples–class fractionation scheme*

	SA_W		B_E		Neutral			
Sample	Relative Weight (%)	Specific Activity (rev/mg)	Relative Weight (%)	Specific Activity (rev/mg)	Relative Weight (%)	Specific Activity (rev/mg)	Total Weighted Activity (rev/mg)	Reference
Composite crude-1	0.1	400	0.2	150	84.2	277	241	9
Composite crude-2	0.1	750	0.2	500	84.2	166	147	10
La.-Miss. crude	0.1	240	0.2	180	80.7	90	76	9
Shale oil	0.6	160	7.1	952	86.7	112	178	10
Synfuel A-1	0.3	240	2.0	28900	73.6	517	4032	9
Synfuel A-2	0.4	120	2.0	36200	69.2	583	4189	9
Synfuel A-3	0.3	1010	3.1	43300	56.4	1094	7308	9
Synfuel B-1	0.4	0	2.6	1500	82.3	560	516	9
Synfuel B-2	1.6	0	1.8	3800	89.3	465	484	9
Separator Liquor, 1.3 w/v%	53.9	0	0.5	850	1.5	0	17	unpublished
Gasifier condensate, 0.9 w/v%	30.8	0	0.5	4000	1.9	100	211	14
Process water (shale oil), 1.0 w/v%	65.0	0	2.7	1575	2.4	52	68	10

*Strain TA98 metabolically activated with Aroclor-induced preparation

missense strain TA1535 was rare. TA98 appeared to be the best general indicator of mutagenic activity of these materials. Furthermore, liver preparations from rats induced with Aroclor 1254 showed the best *general* applicability. However, individual differences in effectiveness do occur, for example, variously induced preparations show obvious differences between basic fractions and, e.g., the neutral/methanol fraction (28). An Aroclor-induced preparation reacts best with the neutral fraction (polynuclear aromatic hydrocarbons?), while a phenobarbital-induced preparation works more efficiently with the basic fraction (heterocyclic nitrogen compounds?).

Primary candidates for the mutagens (and carcinogens?) responsible for activity in the basic fractions include quinoline, substituted quinolines, alkyl pyridines, acridine, naphthylamines, aza-arenes, benzacridines, and aromatic amines; in the neutral fractions, potential threats may be benzanthracenes, dibenzanthracenes, substituted anthracenes, benzopyrenes, benzofluorenes, pyrene, substituted pyrenes, and chrysenes (33,34). Thus, work with these pure compounds is being carried out concurrently.

VALIDATION

Reproducibility of results was shown by comparison of data from similar samples. Although discrepancies exist from fraction to fraction, the general trend is apparent and the sum of activities appears to be roughly reproducible. Again, when the major-component, neutral fraction is assayable, as with the Synfuel A, the summation of the subfraction values of the neutrals reflects the approximate additivity of the individual mutagenic determinations. For example, 570 revertants/mg with a direct assay of the neutrals from Synfuel A-2 compares with 583 revertants/mg based on the summation (table 3).

An overview of the results points to a number of consistencies: 1) all crudes and Synfuels showed some mutagenic potential; 2) the neutral and basic fractions showed activities regardless of the source of the sample; and 3) the relative total mutagenic potentials varied over two orders of magnitude. Whether these results reflect a comparative biohazard of processes still under development is not the point in question here. The results simply show that biological testing—genetic reversion assays in this case—can be carried out with the newly developed tester systems, but only when coupled with the appropriate analytical separation schemes. Conceivably, the use of this approach could rapidly provide information concerning health effects.

AQUEOUS SAMPLES

Table 4 also lists sample results from a group of aqueous samples subjected to the class fractionation procedure (Stedman procedure). In general, greater activity is seen in the more polar, more water-soluble fractions rather than in the nonpolar neutral materials. Caution must be used in work with any aqueous material because of the high potential for instability. Although we have used organic extraction here, techniques with resin concentration, e.g., XAD-2, may prove useful with aqueous samples (35,36). Only in exceptional cases is the mutagenic activity directly observable in an unconcentrated sample.

In the initial studies with coal-liquefaction products, the crude oils were fractionated by the use of the scheme originally developed for cigarette smoke condensates (Stedman procedure). The scheme yields class separations based on the relative acid-base properties of the components. The samples are partitioned between ethyl ether and 1 N NaOH in a single-stage, continuous procedure to yield an aqueous acid fraction and organic-phase base and neutral fractions. The organic fraction is extracted with 1 N HCl to yield an aqueous basic fraction, an organic basic fraction, and an organic neutral fraction. The neutral material is subsequently subfractionated on a Florisil column. These primary subfractions are then subjected to mutagenicity testing.

OTHER METHODS

Realizing the potential for modification of the components inherent in this procedure, consideration was given to a number of other fractionation methods. The fractionation procedures using Sephadex LH-20 can provide a gentle and large-scale class separation for (initially) crude oils from shale-oil and coal-liquefaction processes. The procedure involves three steps, using the gel in different modes: 1) lipophilic-hydrophilic partitioning, 2) molecular size separation, and 3)

TABLE 5
Sephadex LH-20 fractionation of shale oil coupled with mutagenicity testing

Test Material	Percent of Total	Specific Activity* (rev/mg)
Crude oil	100	233
Hydrophilic	6	1300
Lipophilic	93	196
Polymer	5	54
Hydrogen-bonding	5	1040
Sieved	84	100
Polymer	1	0
Aliphatics	60	180
Aromatics		
1 and 2 rings	14	24
3 and 4 rings	5	132
Polynuclear	4	1220

*Slope of dose-response curve with *Salmonella* strain TA98 plus liver preparation from rats induced with Aroclor 1254.

aliphatic-aromatic separation. The procedure (37,38) was designed by Jones, Guerin, and Clark of the Analytical Chemistry Division, ORNL. Using fractions prepared as above, we have started a comparison of this procedure and the Stedman procedure for usefulness in preparation for bioassay. The preliminary mutagenicity studies confirm the suitability and utility of the method. Table 5 summarizes some of the results from shale oil. The method appears to be generally applicable to complex organic mixtures and achieves the goal of providing a gentle and rapid separation scheme which is useful with large-scale samples.

SUBFRACTIONATION

Again, considering the results with class fractionation procedures, a procedure (39) was developed specifically designed for subfractionation of the basic materials, now realized to be a major contributor to mutagenic activity. An elution sequence using alumina and Sephadex LH-20 gel with a combination of solvents isolates 90 percent of the mutagenic activity from basic compounds into a 0.5 wt percent fraction of crude oil.

A basic alumina column eluted first with benzene and then ethanol isolates the mutagenic compounds of the ether-soluble base fractions of synthetic crude oils into a fraction of about 25 wt percent of the ether-soluble base. A further separation is achieved by eluting the ethanol isolate through a Sephadex LH-20 gel column with isopropanol followed by acetone. About 90 percent of the basic mutagenic activity is recovered in the acetone subfraction, which comprises ~ 0.5 wt percent of the crude oil. Development of this separation scheme was made possible by use of the Ames microbial mutagenesis assay as the detector during exploratory liquid-chromatographic separations.

COMPARATIVE MUTAGENESIS

To validate and compare the results accumulated in the Ames system with complex test materials from synthetic fuel technologies, specific fractions or subfractions were selected on the basis of their activity in the histidine-reversion assay for further testing in the various other assays designed to detect mutagenicity. Preliminary results have been published in the Proceedings of the Second

TABLE 6
Comparative mutagenesis of fractions from synthetic crude oils*

Test system	Assay	Basic Fraction	Neutral Fraction	Crude Synfuel†
Salmonella	$his^- \rightarrow his^+$	+	+	+
E. coli	$arg^- \rightarrow arg^+$	+	+	NT
	$gal^- \rightarrow gal^+$	+	+	NT
Yeast	$his^- \rightarrow his^+$	+	+	NT
	$CAN^S \rightarrow can^R$	+	+	NT
Drosophila	sex-linked recessive lethal	+	–	NT
CHO cells	6-thioguanine resistance	+	NT	NT
Human leucocytes	chromatid aberrations	P	+?	NT
	sister chromatid exchange	+	+?	NT
Mouse	dominant lethals‡	–	P	+
	skin painting§ (carcinogenesis)	P	P	P

* For references to published work or work in progress see text. The fractions utilized were generally those from Synfuel A-3 or Synfuel B-2. + = mutagenic; – = nonmutagenic; NT = not tested; P = in progress.

† Crude synfuels are generally too toxic to test in most systems.

‡ Work or W. M. Generoso, ORNL, in progress.

§ Work of J. M. Holland, ORNL, in progress.

International Conference on Environmental Mutagens, Edinburgh, 1977 (40). The results are given in table 6 for qualitative comparison. The selected fractions or subfractions utilized were basic and neutral isolates from synthetic crude oils from coal-liquefaction processes—Synfuel A and B as described in Epler et al (11). For *Drosophila* (41) and for the mammalian cell gene mutation assay (40), detection has been a function of newly developed fractionation schemes, (e.g., the use of LH_{20}) (37,39) that result in higher-specific-activity (more highly purified) mutagenic subfractions. In general, the results validate the initial screening carried out in the *Salmonella* assay, but these other systems have not as yet been used to exhaustively test materials that are negative in the Ames system. Note, also, however, that the preliminary results of Generoso (personal communication) show that the crude synthetic fuel does induce dominant lethals in mice, although the *basic* fraction alone appears to be negative.

SYNFUEL FRACTIONS

For the comparative studies with microbial systems given here, four Synfuel fractions were selected. The results with the metabolically activated frameshift strain TA98 were considered. Fractions #6 (SA_W), #7 (B_{Ia}), #9 (B_E), and neutrals/methanol were selected on the basis of their ability to revert the Ames strains. To validate the mutagenicity results obtained from the *Salmonella* histidine-reversion system, we extended the treatment with the selected test fractions to the *E. coli* 343/113 system of Mohn (43). The results obtained in the forward- (gal^+) and reverse-mutation (arg^+) assays with *E. coli* support the results obtained with *Salmonella*. Both the basic fraction (#9) and the neutral/methanol subfraction are mutagenic upon metabolic activation with Aroclor-induced rat-liver homogenate (S-9).

FURTHER VALIDATION

Further validation of the bacterial results was obtained by assaying for both forward and reverse mutation in the yeast system (40,44). The Synfuel A fractions tested were weakly mutagenic and were effective without metabolic activation. Some antagonistic effects were encountered when metabolic activation was incorporated. The most active fraction, B_E, also reverted the putative frameshift marker, hom3-10. This fraction may contain acridines and other nitrogen heterocyclics. Unpublished results from our group point to similar effectiveness without activation in the *Salmonella* system when suspension tests rather than plate assays are used with crude mixtures.

Selected test fractions from Synfuel B were assayed in the *Drosophila* sex-linked recessive lethal system. The acetone fraction from the basic material is effective as a mutagen for *Drosophila* at the higher concentrations fed (41).

SUMMARY

In summary, short-term tests with bacterial and yeast mutagenicity assays appear to detect effectively the mutagenic potential of complex environmental or industrial effluents; however, chemical fractionation is necessary to reduce toxicity and concentrate hazardous materials. Extension of the results to higher organisms, i.e., mammalian cells, *Drosophila*, and the mouse, appears to be valid but needs more testing.

In these initial feasibility studies, the purpose has not been to reflect on whether a relative biohazard exists in comparison with other materials or processes. The results show that biological testing within the limits of the specific system used can be carried out with complex organic materials, but perhaps only when coupled with the appropriate analytical separation schemes. An extrapolation to relative biohazard at this point would be, at least, premature. The primary use that such combined chemical and biological work may serve is to aid in isolating and identifying the specific classes or components involved. A number of precautions are listed below.

The detection or perhaps the generation of mutagenic activity may well be a function of the chemical fractionation scheme utilized. The inability to recover specific chemical classes or the formation of artifacts by the treatment could well corrupt the results obtained, as could an inability to detect the specific biological end point chosen. Along with the obvious bias that could accompany the choice of samples and their solubility or the time and method of storage, a number of biological discrepancies could also enter into the determinations. For example, concomitant bacterial toxicity could nullify any genetic damage assay that might be carried out; the choice of inducer for the liver enzymes involved could be wrong for selected compounds; the choice of strain could be inappropriate for selected compounds. Furthermore, the applicability of the generally used *Salmonella* test to other genetic end points and the validation of the apparent correlation between mutagenicity and carcinogenicity still needs validation through sufficient fundamental research. The short-term assays chronically show negative results with certain substances, e.g., heavy metals and certain classes of organics. Similarly, compounds involved in or requiring co-carcinogenic phenomena would presumably go undetected.

However, as a prescreen to aid the investigators in ordering their priorities, the short-term testing appears to be a valid testing approach with complex mixtures. Overinterpretation at this stage of research, especially with respect to relative hazard or negative results, should be avoided.

CONCLUSIONS

Several general conclusions may be reached on the basis of the foregoing discussion:

- Short term bioassays are being applied effectively to energy related samples as indicators of potential health effects.
- These tests facilitate rapid prioritization of samples for further evaluation by conventional biological and chemical methodologies.
- The bioassays are useful as a means to direct the chemical fractionation and identification of hazardous components of complex mixtures.

- Chemical fractionation may be required for the demonstration of genetic or genotoxic activity in complex mixtures which contain interfering toxic components.

- The prediction of relative toxicity on the basis of chemical analytical results is subject to error.

- However, chemical analyses are, in general, quantitatively more sensitive than are the health effects bioassays.

- The results of chemical and biological analysis are complementary and together provide useful information not obtainable when the two approaches are applied separately.

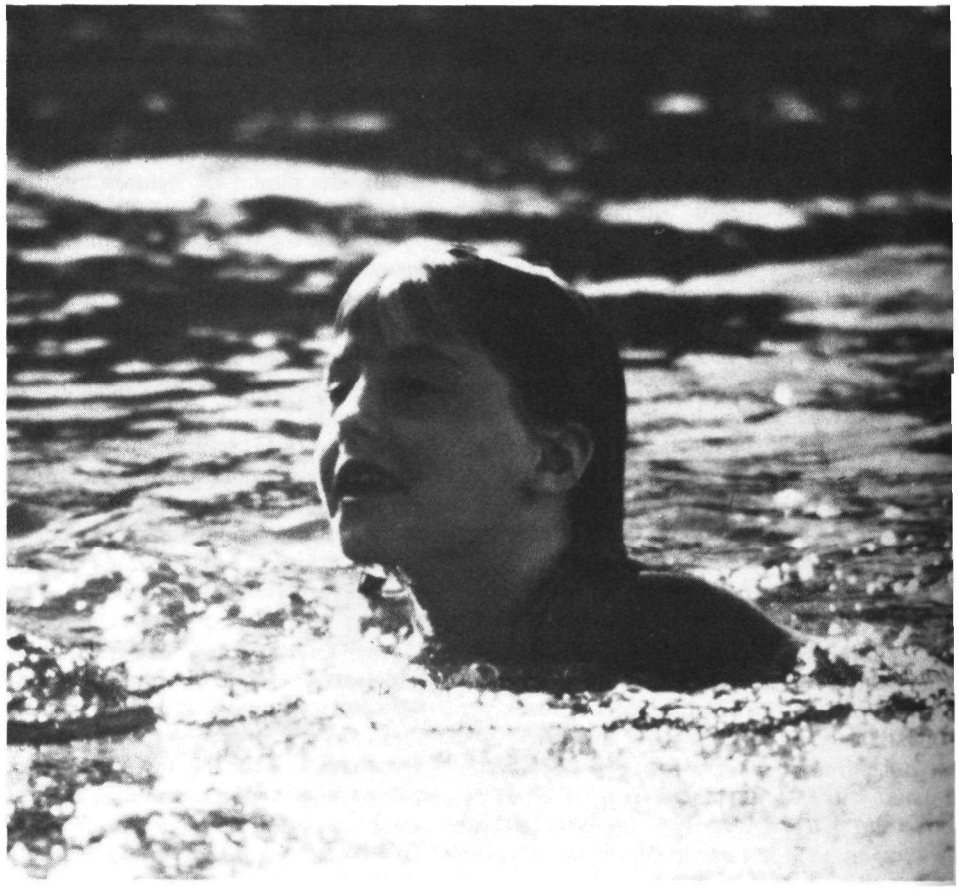
ACKNOWLEDGMENTS

Research supported through the Environmental Protection Agency, Office of Energy, Minerals and Industry.

Research jointly sponsored by the Environmental Protection Agency (IAG-D5-E681; Interagency Agreement 40-516-75) and the Division of Biological and Environmental Research, U.S. Department of Energy, under contract W-7045-eng-26 with the Union Carbide Corporation.

The authors thank the staff at the Pittsburgh Energy Research Center and the Laramie Energy Research Center for their cooperation in providing samples.

The authors acknowledge the extensive participation of their colleagues in this work. The authors thank the staff of the Biochemistry Branch, Health Effects Research Laboratory, and the Industrial Environmental Research Laboratory, Environmental Protection Agency, Research Triangle Park, North Carolina; the Biology Division and the Analytical Chemistry Division of the Oak Ridge National Laboratory for providing data, both published and unpublished.



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THE EFFECTS OF H_2SO_4 ON MEN AND H_2SO_4 AND O_3 ON LABORATORY ANIMALS

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STUDIES SO FAR INCONCLUSIVE

Although sulfuric acid is known to be a strong irritant, the results obtained through toxicological studies on animals and limited exposure studies on humans have so far been inconclusive. The greatest problems and uncertainties are in quantitating the health effects induced by submicron sulfuric acid mist in concentrations below $100\mu g/m^3$. The assessment of the potential health effects of sulfuric acid is further complicated by uncertainties as to the extent of the interaction with various ambient, physical, and physiological factors as well as chemical agents. Variables such as relative humidity, ambient temperature, level of breath ammonia, or frequency and depth of breathing, may modify considerably the response to sulfuric acid and are probably the major causes of the diversity observed between studies. Because of the inherent problems associated with studying the effects of pollutants on the human respiratory system, animal model systems have been developed to investigate various hypotheses that can later, through appropriate epidemiological surveys, be tested in man. The animal model for the microbe-host interaction system must be a sensitive one for measuring the subtle effects resulting from inhalation of toxic substances. The model should therefore reflect a summation of the varied responses of the respiratory tract, which may include edema, cellular disruption, reduced macrophage function, inflammation, and immunosuppression.

HUMAN STUDIES

Eighteen healthy, young, nonsmoking male volunteers were studied. Before being selected for inclusion in the study, all subjects were given a physical examination, a detailed history was obtained, and a psychological Minnesota Multiphasic Personality Inventory taken by the investigator physician. Subjects were carefully questioned to exclude those taking any medications, those with any recent pulmonary infections, allergies, and so forth. In addition, blood was drawn for standard blood tests; and temperature, blood pressure, and pulse were recorded before starting the experiment. Consent was obtained from each subject prior to the study. Each subject was exposed for three consecutive days to either clean air or H_2SO_4. On days 1 and 3 each was exposed to clean air and on day 2 to H_2SO_4. The 2-hour exposure protocol was the same for all 3 days. Since the subjects alternated 15 minutes of exercise (500 W) with 15 minutes of rest, pulmonary function tests were done 10 minutes after the end of each exercise during the resting periods. The environmental conditions in the chamber were continuously monitored for temperature, relative humidity, aerosol concentration, and particle size. The temperature was maintained at $74^\circ \pm 3^\circ$, relative humidity at 46% ± 10%, peak particle size at 0.075 μm, and 0.055 mean mass diameter. The aerosol was generated using the modified fuming sulfuric acid technique developed by Scaringelli and Rehme. The particle size distribution was monitored by the Electrical Aerosol Size Analyzer Mod. 3000 (Thermosystems, Inc) and the concentration of acid was determined by chemical analysis of samples collected on Fluoropore filters (Millipore Corporation).

THREE GROUPS OF CONCENTRATION

Subjects were divided into three groups, depending on the concentration they were exposed to. Group I consisted of four subjects exposed to 66 ± $\mu g/m^3$. Group II had 10 subjects exposed to an average of 100 ± 14 $\mu g/m^3$ and Group III had 4

subjects exposed to an average of 195 ± 35 $\mu g/m^3$. Pulmonary function parameters between 8 and 18 were measured at various time intervals during the experimental period.

MOST SENSITIVE TO H_2SO_4

Group I seemed to be the most sensitive to H_2SO_4. However, only 3 out of 18 parameters became significantly changed with H_2SO_4 exposure. The FEV 2 (forced exposure volume at 2 seconds) decreased an average of 190 ml, which was a 3.3% decrease from the control after 2 hours of exposure. Airway resistance (RAW; plethysmographic method) increased by 3.5% (figure 1) and the functional residual capacity (FRC) increased by 470 ml, or a 10.9% increase over control.

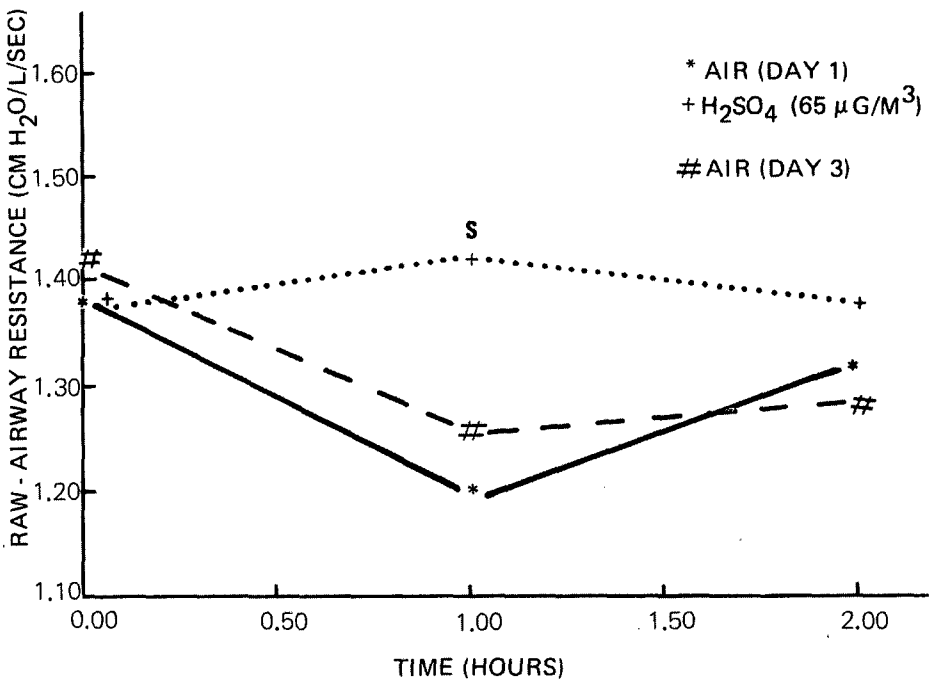


FIGURE 1—*Group I H_2SO_4 concentration (66 ±$\mu g/m^3$)*

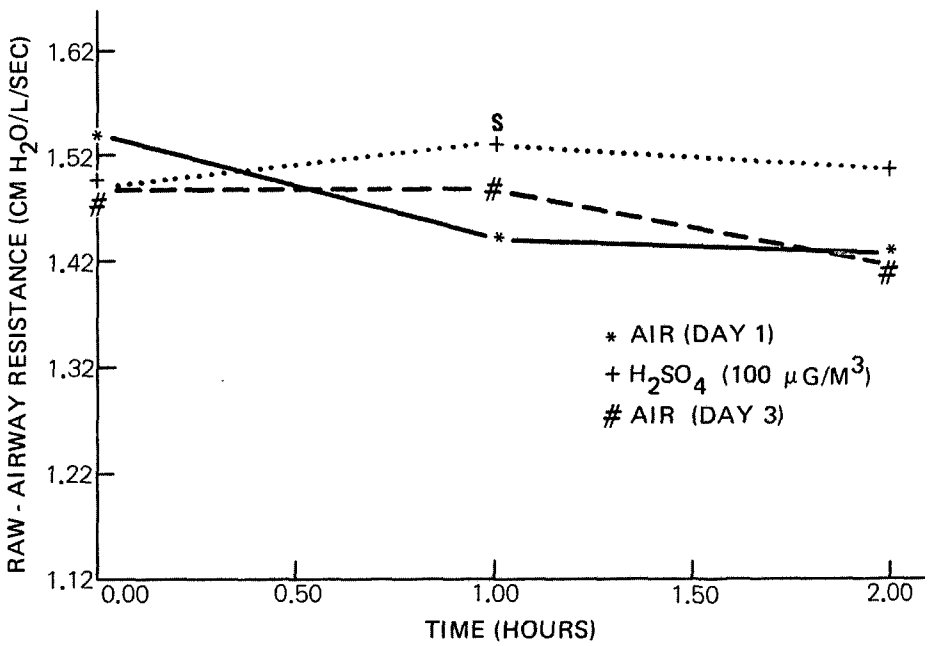


FIGURE 2—*Group II H_2SO_4 concentration (100 ±14 $\mu g/m^3$)*

INSIGNIFICANT CHANGES

Despite a higher acid concentration and a larger number of subjects, Group II showed fewer changes than Group I in lung function. Again, only FEV 2 (0.5%) and RAW (figure 2) showed statistically significant changes. About half of the remaining parameters showed some degree of improvement during acid exposure day when compared with control day.

Group III was exposed to the highest average concentration and showed the least effect. Not a single test was significantly affected at this concentration. About two-thirds of all lung function tests showed some degree of improvement over the control day. Airway resistance was increased significantly after 1 hour of exposure. In the two previous groups it deviated very little from the air days (figure 3). Similarly, for other functions, air-day results were not significantly different from the acid-day data. Moreover, although it is well documented that irritant substances when inhaled will modify the ventilatory pattern, we were not able to detect any changes in either respiratory rate or tidal volume (figures 4 and 5).

RESULT CONTRARY TO EXPECTATIONS

The review of our data indicates that subjects exposed to low concentration of H_2SO_4 showed greater changes in various lung function parameters than subjects exposed to higher concentrations. This is contrary to our expectation—that the higher acid concentrations should have elicited a greater response. A plausible cause of such an inverse relationship may be a shift in the size distribution curve to the right towards larger particles. It is well documented that the relative deposition and retention of particles in various compartments of the respiratory tract is a function of particle size and a flow regime. The warm humid air of the airways will certainly accelerate the growth of particles, and the higher the acid concentration, the greater the shift will be. Consequently, the most sensitive part of the lung to injury, the small peripheral airways, will be less compromised by the aerosol because the larger particles will be deposited in the larger upper airways. As discussed earlier, the pulmonary function tests showed some degree of impairment; however, the clinical significance of these changes is unclear. Additional studies using a greater number of subjects as well as more sensitive and specific tests are needed to give us a clearer picture of the subtle changes in pulmonary function induced by acid aerosol.

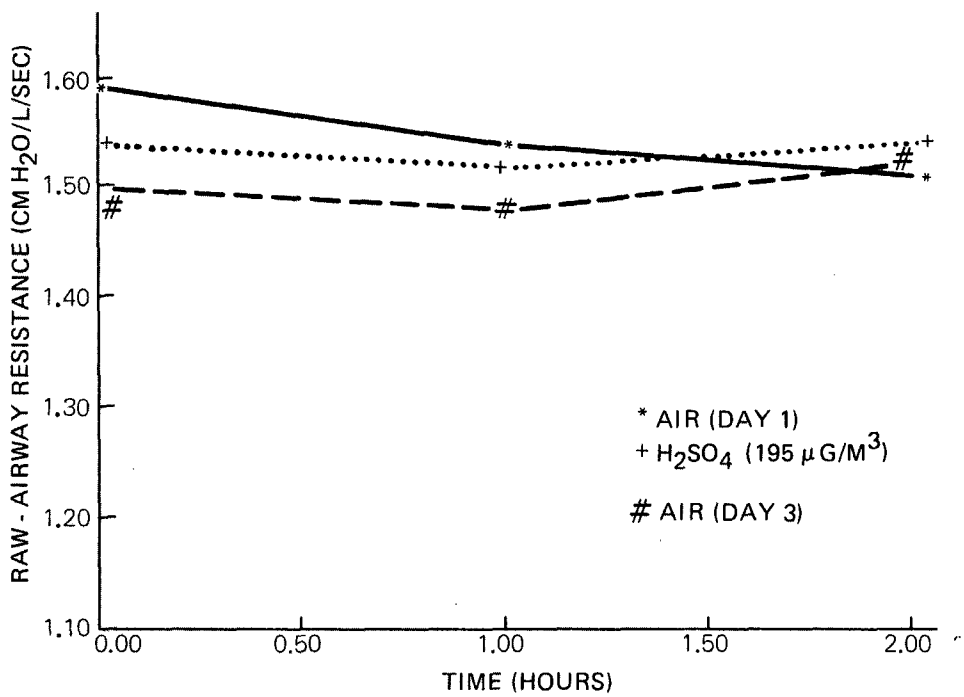


FIGURE 3—*Group III H_2SO_4 concentration (195 ±35 µg/m^3)*

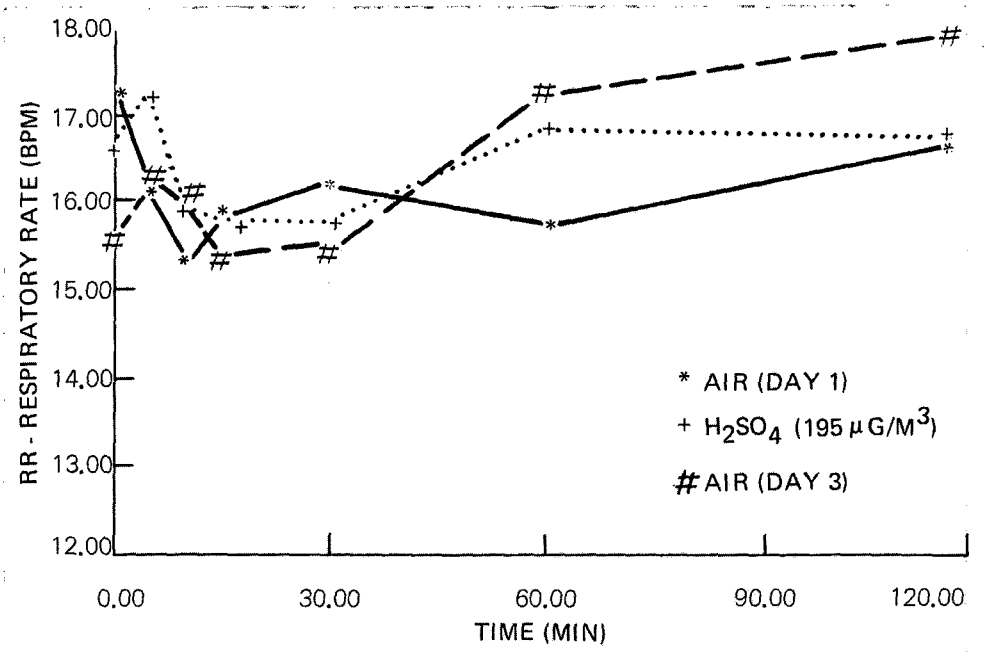


FIGURE 4—*Respiratory rate*

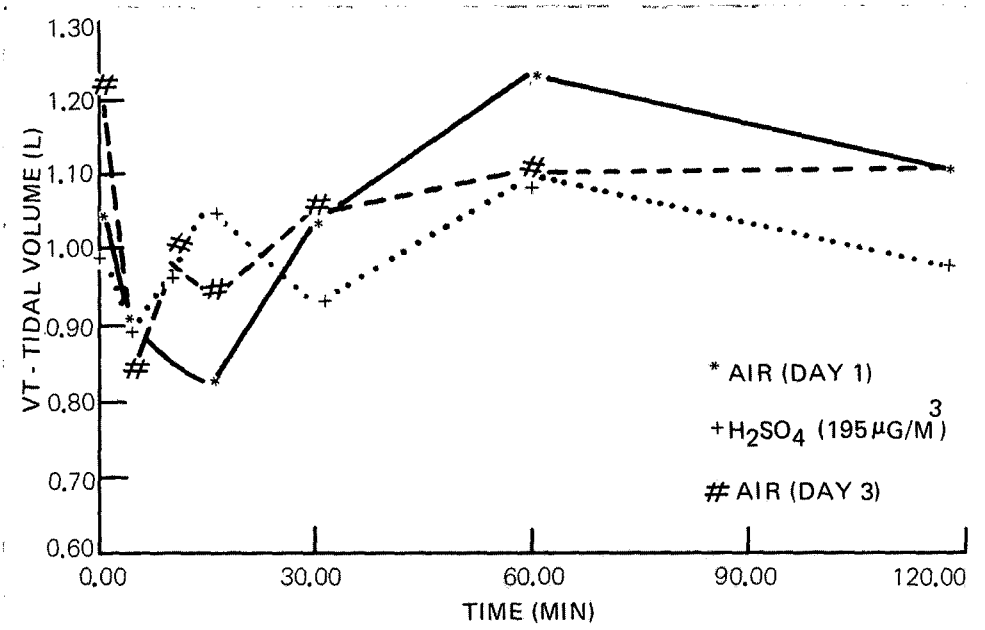


FIGURE 5—*Tidal volume*

ANIMAL TOXIOLOGICAL STUDIES

A number of different experimental approaches have been used to demonstrate the potential of chemical agents for altering host susceptibility to respiratory infectious agents. One of the most sensitive methods used by laboratories, including ours, is called the infectivity model. Briefly, animals are randomly selected for exposure either to filtered room air or to the test substance. After the cessation of this exposure, the animals from both chambers are combined into a third chamber where they are exposed for approximately 15 minutes to an aerosol of viable microorganisms, *Streptococcus pyogenes,* Group C. At the termination of this exposure, some animals from each group are sacrificed, and, using standard microbiological techniques, the number of inhaled microorganisms is determined. The

remainder of the animals are returned to clean filtered room air, and the rate of mortality in the two groups is determined during a 15-day holding period. The control mortality, which reflects the natural resistance of the host to the infectious agent, is approximately 15% to 20%.

CILIARY BEATING FREQUENCY

Assays of ciliary beating frequency were performed following in vivo exposure of Syrian Golden hamsters. The tracheas were excised asceptically and cut into rings approximately 1 mm thick and the ciliary beating frequency determined using an electronic stroboscope.

The acid aerosol was generated by heating concentrated H_2SO_4 to 120°C and passing 5 1/min of dry air over the liquid. The resulting droplet-vapor mixture was passed through heated lines to an impactor to remove the largest particles and then discharged into a mixing flask where 20 1/min of dry air was added. This mixture was merged with the air stream supplying the animal exposure chamber at a rate sufficient to provide approximately one chamber vol/min.

AEROSOL SAMPLES

Aerosol samples were collected on 47 mm diameter Fluoropore filters (Millipore Corporation) and analyzed for strong acid, ammonium ion, and soluble sulfate ion. The sulfate concentration was 900 $\mu g/m^3$ ± 90 SD, with approximately one-third being associated with ammonium ions. The aerosol had a volume median diameter of 0.23 μm ± 2.4 SD (geometric) as determined by an Electrical Aerosol Analyzer (Thermo-Systems, Incorporated). Temperature (25.8°C ± 0.9 SD) and relative humidity (38% ± 16 SD) in the chamber were monitored by a thermistor and dew point hygrometer (EG&G, Incorporated).

OZONE GENERATED

Ozone was generated by passing oxygen through a neon-tube silent arc generator. The resultant effluent was mixed with filtered room air to equal a total flow rate of 11.4 cu ft/min and conveyed into a stainless steel chamber with a volume of 11.4 cubic feet exclusive of funnels. Ozone was monitored by the chemiluminescence method.

EXPERIMENTAL RESULTS

The experimental results can best be described in three different phases. The first phase of these studies consisted of general range-finding experiments which were necessary to provide information on what concentration of acid mist alone, without the infectious challenge, would cause an increase in mortality in mice after a single 3-hour exposure. Mice appeared to be very resistant to the acid aerosol alone. In these studies, a significant mortality (25-50%) was observed only after exposure to 600 mg/m^3 but not exposure to 400 mg/m^3. By combining carbon particles (5 mg/m^3) to 400 mg/m^3 of H_2SO_4, a 17% mortality rate was produced; but, at any lower concentration of acid, the addition of the carbon did not alter the effect of the acid alone.

In the initial infectivity studies, the concentration of acid mist tested was 100 mg/m^3 for 3 hours before administering the bacterial challenge *(Streptococcus pyogenes*, Group C). In this series of experiments, there was no difference in mortality between the animals exposed to acid aerosol and the control air animals.

Based on these types of studies, it became evident that if the inhalation of H_2SO_4 were to alter the host's defense system against infectious agents, it would have to through its interaction with some other environmental pollutant or stress. Thus, the second phase of these experiments was designed to study the effects of the sequential exposure to H_2SO_4 with ozone (O_3).

EXPERIMENTAL DESIGN

The exposure regimens for the experimental design are presented in figure 6. Female mice (CD-1, COBS^R, Charles River Breeding Laboratory, Wilmington, Mass.) weighing 25 grams were randomly assigned to various treatment groups, and each group contained 20 animals. The test groups represent all combinations of sequential exposure to two of the three following test substances: O_3, H_2SO_4, and filtered air. The total exposure length was 5 hours for each treatment group. All exposures to

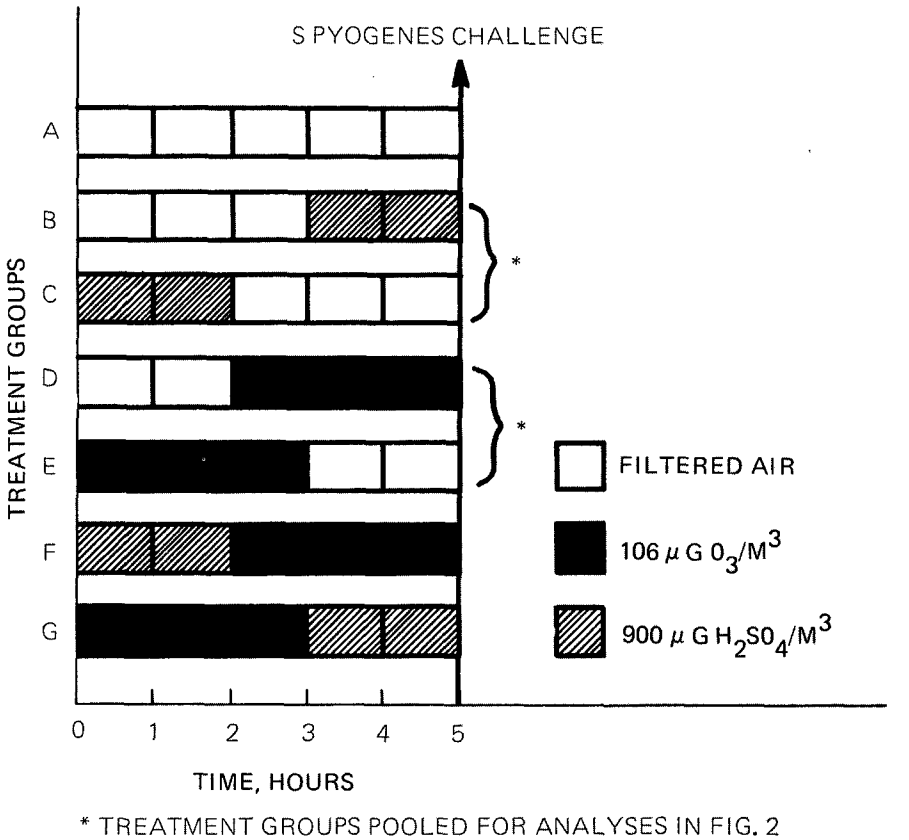


FIGURE 6—*Exposure regimens*

FILTERED AIR EXPOSURES

196 μg O_3/m^3 (0.1 ppm) were for 3 hours and exposures to 900 μg H_2SO_4/m^3 were for 2 hours. Filtered air exposures of sufficient duration were added to treatment groups (groups B through E, figure 6) to maintain the total test period at 5 hours. Control animals (A) were exposed for 5 hours to only filtered air. After exposure, the test animals were combined and challenged with a viable aerosol of *Streptococcus pyogenes* (C). The animals were again separated into their respective treatment groups and the incidence of mortality observed over a 15-day period.

Neither pollutant alone (B-E) caused a significant increase in mortality, as compared with clean air controls (A). Statistical analysis indicated that the two H_2SO_4 groups (B and C) were not significantly different and were therefore pooled for subsequent analyses. Likewise, the two O_3 groups (D and E) were not different and were also pooled.

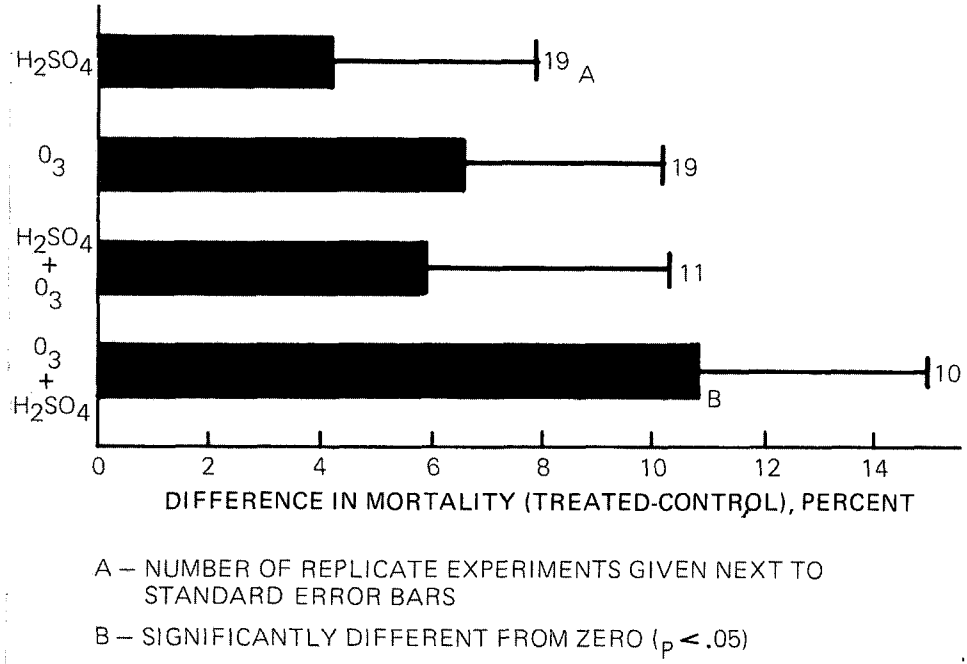


FIGURE 7—*Increase in mortality for treatment groups and combined pollutant exposure test groups.*

COMBINED POLLUTANT EXPOSURES

Figure 7 shows the increase in mortality for these pooled treatment groups, as well as for the test groups representing the combined pollutant exposures. In those studies involving the combined action of the two pollutants, there was a statistically significant increase ($p < 0.05$) in respiratory infections in the treated group over controls (indicated by percent mortality) only when the exposure to the oxidant gas immediately preceded that of the acid. For this increase, the observed mortality was equal to the additive effect of the individual pollutants. The two combined exposure groups were not significantly different. When the data of these groups were pooled, the resulting mean was still statistically different ($p < 0.05$) from the control mean.

An additional experiment was conducted wherein the concentration of ozone was 0.1 ppm but the concentration of H_2SO_4 was lowered to 500 $\mu g/m^3$ and the two pollutants were administered simultaneously for a period of 3 hours. A statistically significant increase in mortality over control of 7.5% was observed for this treatment group (figure 8). H_2SO_4 alone at this level showed no increase in mortality.

CILIARY ACTIVITY

The effects of in vivo exposure to ozone and H_2SO_4 on ciliary activity were investigated (figure 9). Immediately after a 2-hour exposure to 900 μg H_2SO_4/m^3, a significant decrease in ciliary activity from control of approximately 320 beats/min

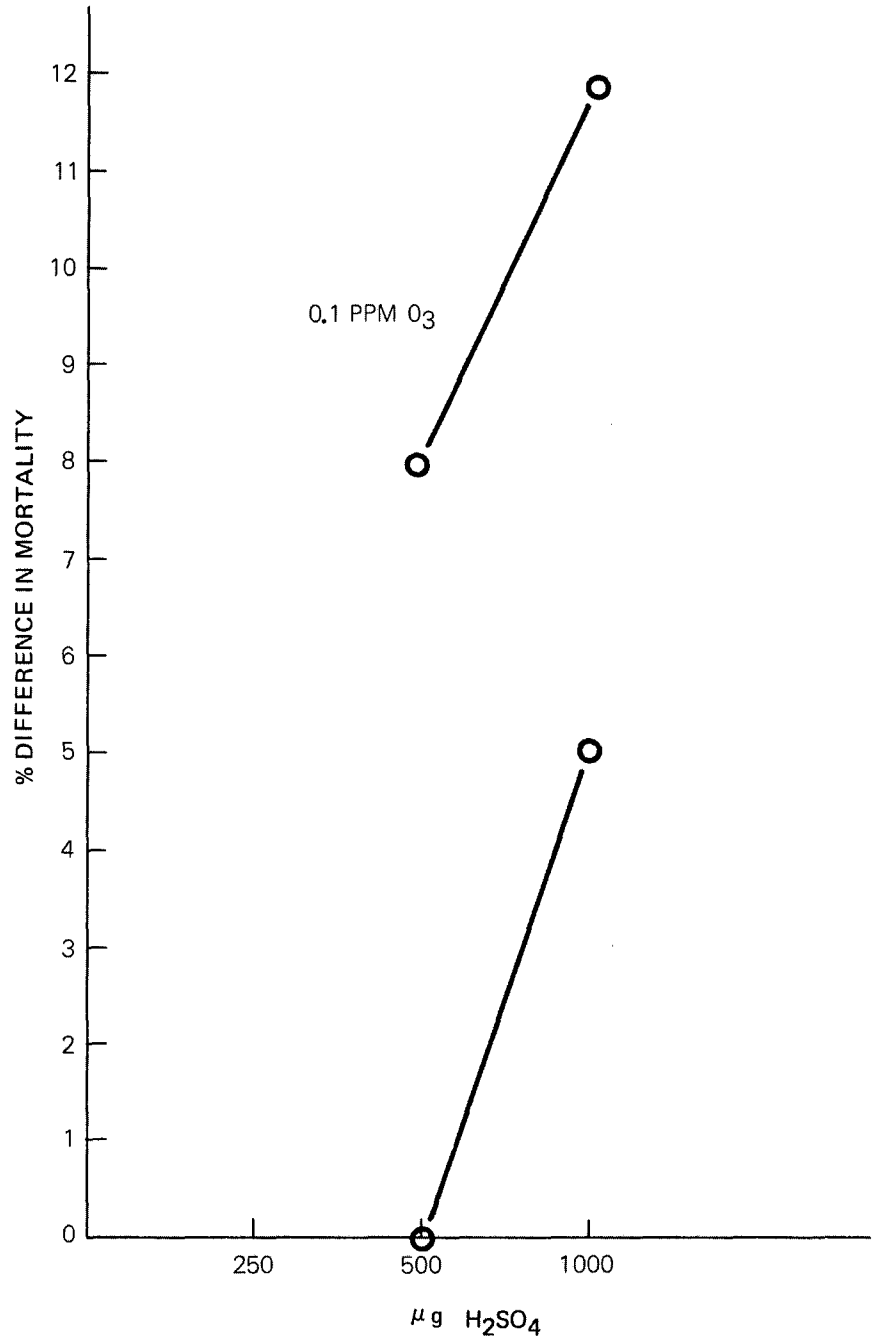
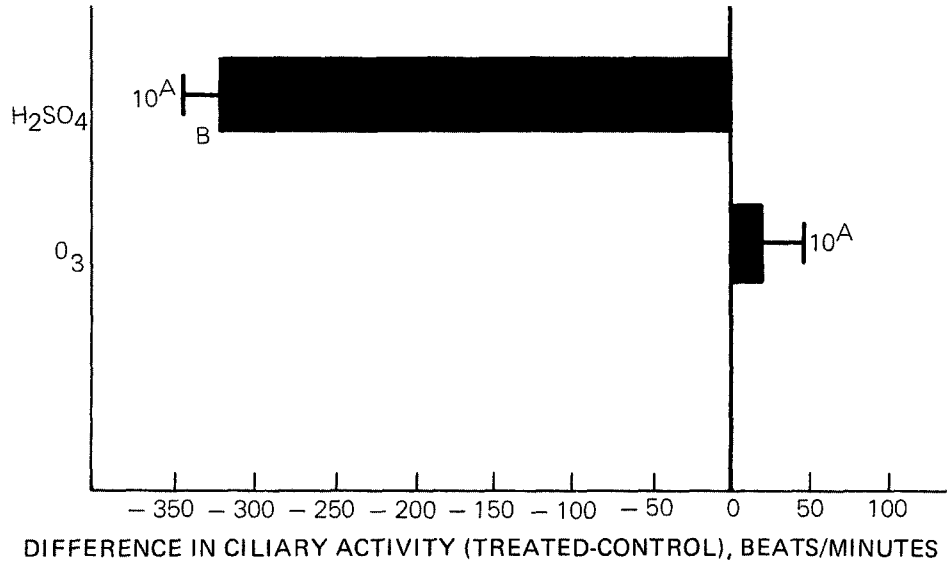
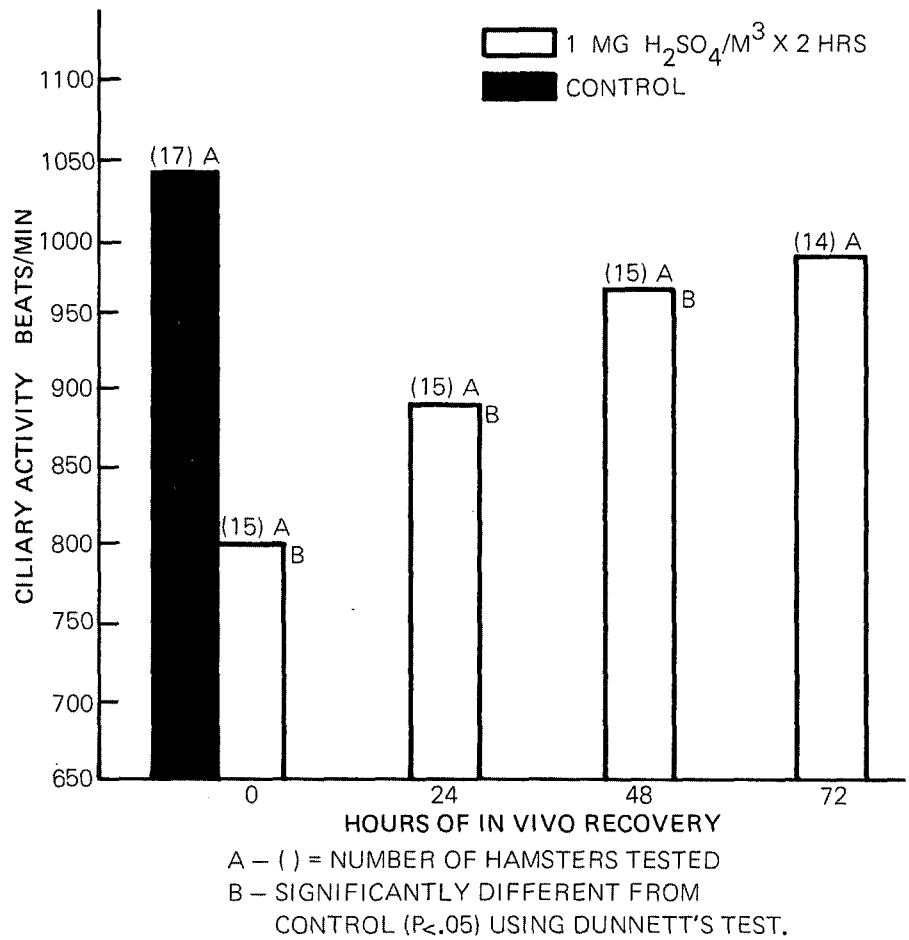


FIGURE 8–*Ozone and H_2SO_4 administered simultaneously*



A – NUMBER OF HAMSTERS.
B – SIGNIFICANTLY DIFFERENT FROM ZERO (P<.05).

FIGURE 9–*Effects of exposure to ozone and H_2SO_4 on ciliary activity*



A – ( ) = NUMBER OF HAMSTERS TESTED
B – SIGNIFICANTLY DIFFERENT FROM CONTROL (P<.05) USING DUNNETT'S TEST.

FIGURE 10–*Persistence of depression in ciliary activity with H_2SO_4 exposure*

was observed. Exposure to 196 μg O_3/m^3 (0.1 ppm) for 3 hours resulted in no significant difference from control. Experiments designed to study the sequential effects of O_3 followed by H_2SO_4 also indicated a significant decrease in ciliary activity of exposed animals comparable to the decrease observed with exposure to H_2SO_4 alone.

Experiments were also conducted to determine the persistence of depression in ciliary activity that was observed with exposure to H_2SO_4. For these studies, animals were exposed to 1 mg of H_2SO_4/m^3 for 2 hours and then allowed to recover in clean air for various lengths of time. The results given in figure 10 show that, even up to 48 hours after exposure, there is still a significant depression in ciliary activity, compared with control, which by 72 hours had returned to within the normal range.

COMBINATION STUDIES

Since the atmosphere contains numerous chemicals, combined action studies are extremely relevant in determining the toxicity of pollution. With individual pollutant exposures at low levels, slight alterations in the biological response are likely to occur that are both difficult to interpret and to detect as being statistically significant. However, combination or sequential exposures at low levels may result in an additive or synergistic action of the pollutants which may be sufficient to evoke a significant response. The additive effect observed in this study with exposure to O_3 and H_2SO_4, which alone did not produce an effect, clearly demonstrates the importance of combination studies in environmental toxicology.

panel discussion

HEALTH EFFECTS PANEL DISCUSSION

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U.S. Department of Health, Education and Welfare

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Institute of Environmental Medicine
New York University Medical Center

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U.S. Department of Health, Education and Welfare

William W. Burr, Jr., M.D.
Division of Biomedical and Environmental Research
Department of Energy

Roy E. Albert, Ph.D.
Carcinogenic Assessment Group
U.S. Environmental Protection Agency

(Additional comments by presentation speakers Dr. Waters, Dr. Epler, Dr. Gardner, and Dr. Hazucha.)

DR. RALL: One general question arises from hearing the presentations this morning. The last two presentations dealt primarily with sulfuric acid, which may be only one of a number of derivative pollutants from the major originating one, sulfur dioxide. The effort spent to get some indication of the relative quantitative risk from inhaling sulfur dioxide, SO_x, H_2SO_4, while probably not extensive enough, has certainly been extensive. Drs. Epler and Waters are dealing with possibly hundreds of different pollutants. What of the future? To what extent can we look at the myriad pollutants from some of these complex fuel conversion processes? Can we look at them one at a time, or must we develop broad screening systems which will deal with groups of pollutants simultaneously?

DR. NELSON: The presentations were, for this very reason, extremely interesting, presenting as they did a broad exploration of a wide variety of very diverse compounds with a new, simple, and extremely attractive procedure; a very meticulous examination of a restricted set of questions in humans and whole animals. It seems to me that this is the way in which we will have to proceed.

Although the Ames system is very attractive, it is not going to answer all questions. There are obviously areas where it will not. The Ames system is, however, extremely powerful. It is very ingeniously contrived, and it can give us some very sharp answers. In many instances, we are going to have to fall back on much more meticulous procedures. Sometimes they are going to have to involve people, as well as the whole animal. One of the things we have not really thought about sufficiently, but which we have to think about, is the necessary strategy.

I am really not overwhelmed by the number of serious problems; I am overwhelmed by the relatively modest number of very serious problems, but I am not going to be awed into settling for a third-rate approach to these very serious problems because of the multiplicity of possible nasty compounds in the environment. We need a strategy right now perhaps as much as we need the hard science approach to these issues. We need to face the fact that we cannot give equal attention to everything. We need, therefore, to devise a scientific approach, using the best science we can assemble. We must isolate the hard questions and focus attention on them. We must also isolate the very soft questions. Certainly we will make some mistakes, especially in the screening process. Other techniques, ranging from structure activity relationships to short-term screening tests, will be needed to help sort these out. We will have to use the accumulated wisdom of people in the medical and scientific professions who have lived with these problems to help sort out the hard questions from the easy ones. We should not depend on any one set of backup techniques for this sorting process.

The gong I would like to sound right now is the urgency of developing not one but a battery of strategies to sort out the problems that we need to focus on. We must attempt to sort out the less consequential issues, issues not necessarily to be wholly shelved, but those which we can put slightly toward the rear of the cupboard to be pulled out next month. And we must be prepared to find we have made some mistakes in these decisions.

DR. BRIDBORD: The area of interactions is particularly important and cannot be overemphasized. Two good examples not confined to the energy-related area, although certainly impacting on that area, can be cited from my own personal experience. One deals with the interaction between asbestos and cigarette smoke. Exposure of a smoking individual to asbestos results in a risk of lung cancer roughly 90 times as great as that of someone not exposed to asbestos and not smoking. Another interesting example of the importance of interactions comes from studies supported by the National Institute for Occupational Safety and Health, studies of the interaction between a drug, Dilsulfram, commonly used in alcohol control programs, and exposure to ethylene dibromide, a very important chemical intermediate, which, incidentally, is a scavenger for lead additives in gasoline. The combined exposure produced a significant increase in cancer in multiple sites, including angiosarcoma of the liver, whereas in this particular model system the single exposures did not result in similar effects. We must keep in mind, therefore,

that the environment is complex. We need to be concerned not only about combined exposure to multiple chemicals in a single medium, such as air, water, or food, but also about the complex interactions between chemicals, drugs, alcohol, and cigarettes. We have barely begun to scratch the surface in our understanding of this aspect.

I would like to make a special point about the need for concern with the health and safety of the worker in the design of energy technologies. There has been appropriate emphasis on environmental effects, both for human health and ecology, but in this discussion the health and safety problems of the worker have frequently gotten lost. It is particularly important to note that the workers are often at greatest risk of exposure to toxic chemicals. I make a special plea to have the biological scientists speak to the engineers. My undergraduate training, before my medical training, was in the area of chemical engineering. We have not adequately sensitized the engineering community to the need to ask certain hard questions about health and safety in the design of chemical plants and engineering facilities. Were the engineers sensitive to this need, they would begin to ask the questions and to develop modifications of engineering design and applicability of control technologies before facilities became "cast in concrete." I think we can make substantial progress and perhaps encourage ingenious approaches to basic product development. I am optimistic that this can happen, but it is important to get that cross-fertilization between the various study disciplines.

DR. BURR: Communication is improving, at least in the Department of Energy. We do talk with the engineers. We do talk to the technologists. We are improving this bridge. As far as strategies are concerned, one presented this morning is the same as the experimental strategy we are using at DOE in support of the work we are doing in this area.

Keep in mind that this is not the only approach. We certainly need the epidemiology. DOE has human health studies, as do other agencies. As an experimental strategy, we process specific materials, looking at chemical and biological characterization, preferably using simple biological systems. We then go on to animal validation as necessary, preferably, again, in short-term animal studies. Next, we conduct dose-response studies. We then address the problem of extrapolating the data to the actual species of concern, the human. In general, that is the experimental strategy we are presently following. It may not be the only one that we should be following. In view of all the other kinds of approaches, such as epidemiology, that also go on, I don't think it is.

DR. ALBERT: Perhaps, in the studies of pulmonary airway resistance by Dr. Hazucha and ciliary function by Dr. Gardner, they may be overlooking the effect of sulfuric acid on clearance, mucociliary transport. Data emerging now show that, at the levels Dr. Hazucha used, there is a substantial stimulation of the clearing mechanism from the bronchial tree without any real effects on airway resistance. Perhaps Dr. Gardner did not see it because he used a rather high level of sulfuric acid exposure.

The presentations by Drs. Waters and Epler echo the question about the practical use of these data in real life. The scheme which is neat, elegant, and well organized is most useful for a preliminary characterization of where the mutants and carcinogens might be in the various industrial processes, but it will not help much at the other end of the spectrum—namely, the risk assessment which leads to the strategies of regulatory control—other than to identify where the major problems are. The one thing missing is the kind of work that deals with comparative magnitudes of effect.

For example, take the case of the diesel exhaust. This is an issue of emerging importance with respect to conservation of energy because diesel engine automobiles are more economical, but unlike conventional automobiles, they put out particulates. One can use the tests to show that these exhaust particles have mutagenic and carcinogenic properties, but any combustion process would exhibit such properties. If you burn leaves in your backyard, you are producing carcinogens and mutagens. The central issue in a risk assessment is the question of how carcinogenic these materials are in relationship to other things that we encounter. This involves assessment of the carcinogenic and mutagenic potencies. In terms of carcinogenic potencies, clearly the mutagenesis assays, although they correlate very nicely with carcinogenesis, don't correlate when it comes to the quantitative aspect of how nasty the agent is. In determining what we are going to do about things such as the carcinogens from diesel exhaust, the issue is, how harmful is the material that is being studied with respect to other materials that we deal with, such as ordinary particulates in urban atmospheres or the particulates that come out of coke oven plants in the steel industry? How bad are these particulates in relation to the particulates from cigarette smoke, a major form of indoor pollution as well as the pollution of the users. In actually doing a risk assessment, in formulating regulatory strategy, one needs to get much closer to the issues that relate to the real life hazard, and the screening techniques, displayed here this morning, although exceedingly useful, are but one step in that process. Here one really needs comparative studies.

DR. WATERS: Perhaps, I did not convey in my presentation that what we are, in fact, talking about with respect to the utilization of short-term tests is just what is being suggested—detection. This is the place that the tests can be used best at this time. At this point they certainly are not quantitative. However, there is considerable effort going into studies on mutagenic and carcinogenic potency, and efforts to understand the correlations, or lack of correlations, for large numbers of compounds. I hope you did not get the impression that the short-term tests alone are the answer. That is certainly not the case.

DR. EPLER: Our central theme with respect to mutagenicity is a comparative approach, exactly what is being suggested; moving on from microbial testing into higher organisms, and then finally, on to the mouse, as close as we can get to man in the laboratory. That is with respect to the end points of both mutagenesis and carcinogenesis. The complicating factor is that we are working perhaps for the first time with these assays with complex mixtures rather than pure compounds. Both types of assays need to be carried out.

DR. GARDNER: Some very fine work is being done by Dr. Lipman and colleagues at New York University on clearance mechanisms with H_2SO_4. Also Dr. Gerry Lass at Davis, California, has been looking at acid alone and acid with ozone and finding increase in mucus production with it. These all fit together in a total package.

DR. HAZUCHA: Increased mucous production would cause some of the changes we observed. For example, changes in functional residue of capacity certainly were caused at least partly by increased production of mucus. It is unfortunate that we have only three to five laboratories in the nation working on problems with air pollution. We are just touching the tip of the iceberg. We don't know how healthy older subjects will react, for example, to various pollutants. We are studying only 18- to 25-year-olds, the young athletes one might say. We don't know how children will react. And I am not speaking about the diseased population. There is a lot of work to be done.

questions & answers

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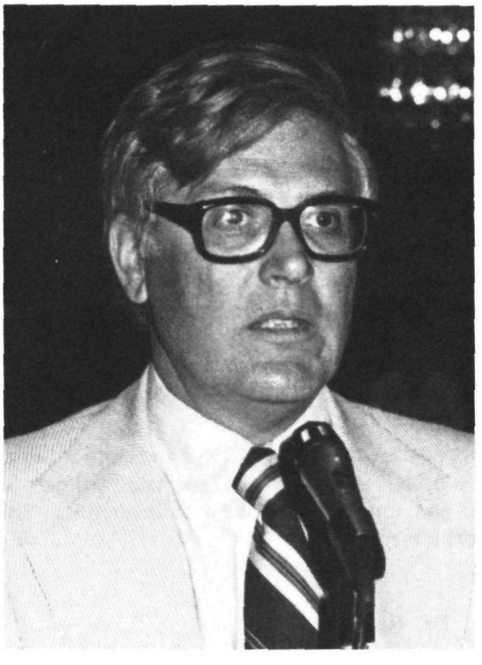
Tom Culley
University of Maryland

Philip S. Tow
Sacramento County Air Pollution Control District

Dr. Krishna P. Misra
Food and Drug Administration

Robert L. Goldberg
Environmental Defense Fund



QUESTION

How will the environmental results discussed determine the effects on human beings?

RESPONSE: Dr. James L. Epler (Oak Ridge National Laboratory)

We are beginning to learn how the short-term tests interrelate. We now realize that no one test is sufficient; we need a battery of tests. We really don't yet know how they can be extrapolated to man. We need more research and development, to look at more compounds and then extrapolate to whole-animal testing, for both mutagenesis and carcinogenesis, before we can answer that question. The general answer is going to have significant impact in determining the effects on man, but the scientist must learn much more before decisions can be made.

QUESTION

What is the lung volume at which you measured airway resistance (RAW)? RAW does vary with lung volume. Another way to express it is specific airway conductance (SCAW).

RESPONSE: Dr. Milan Hazucha (EPA)

I have slides for both functional residual capacity (FRC) and DGE total gas volume at which airway resistance was measured, but to save time, I did not show them. Functional residual capacity increased sig-

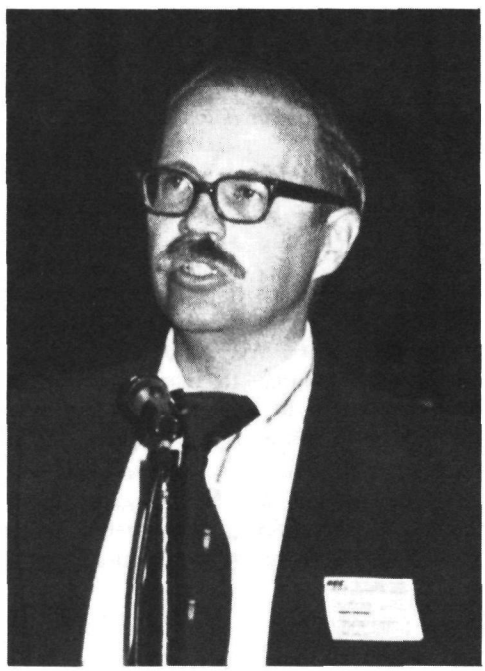
nificantly at low concentration, 0.66 micrograms. It also increased significantly at 100 micrograms, but the change was considerably less. At 200 micrograms no changes were observed. So, certainly these two tests are, as you said, interrelated.

QUESTION

The test animal for teratogenesis studies was a mouse. Are you planning any primate studies on teratogenesis? We are all familiar with the thalidomide problem.

RESPONSE: Dr. Michael D. Waters (EPA)

Yes, it would be necessary to use primates at higher levels of evaluation. In almost any short-term test, we will miss chemicals with unique metabolism. It is essential to proceed by steps, as Dr. Epler indicated, to gain additional information on a number of compounds to understand these metabolic differences. They are critical, and we just don't have all the answers.



QUESTION

How do you relate acute exposure experiments using normal healthy subjects to experiments using subjects with severe respiratory problems?

RESPONSE: Dr. Donald E. Gardner (EPA)

We are now testing H_2SO_4 and other inhaled particulate matter, using normal animals, animals with emphysema, and animals with chronic bronchitis. This is a very important step.

RESPONSE: Dr. Hazucha

All the subjects were young and healthy and very well screened. The results were unexpected even to us. With high concentration, we did not see any effect, and it is almost impossible to say what effects we will observe on other subjects or subjects with permanent disease. Preliminary studies of asthmatics showed little effect from ozone, for example, although the general expectation was that asthmatics would react strongly.

QUESTION

We are exposed to pathogens at the same time we are exposed to pollutants, and we are exposed to ozone at the same time that we are exposed to sulfuric acid. Why aren't these conditions simulated in your studies with mice? Why aren't they exposed at the same time to those combinations?

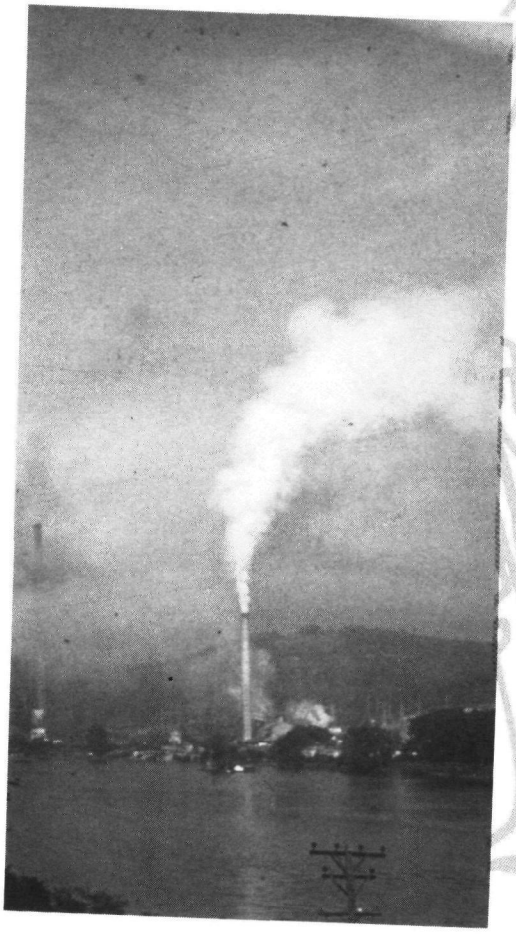
RESPONSE: Dr. Gardner

We are exposing the animals to a combination of ozone and acid at the same time, and we are getting a similar synergistic effect. Our problem comes when we lower the acid concentration to about 500 micrograms and ozone to 0.1 parts per million. Because of the buildup of ammonia of the animals during the 2- or 3-hour exposure, we are no longer getting acid. We get ammonium sulfate because these are whole-body exposures. So, we are limited. We will correct this by first going to head-only exposures.

The sensitivity of the model system is increased if given bacteria at the same time. In fact, it increases with ozone. For these studies, the number of streptococcus pyogenes inhaled and deposited in the lung at zero time is approximately 400.

chapter 3

transport processes and ecological effects



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TRANSPORT PROCESSES AND ECOLOGICAL EFFECTS

REPORT ON THE INTERNATIONAL SYMPOSIUM ON SULFATES IN THE ATMOSPHERE

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It is envisioned that the energy air pollution relationship is a closed loop system driven by man's urge to increase his well-being, and eroding some of the quality of life through the environmental impact of his actions (figure 1).

CLOSED LOOP SYSTEM

The increasing economic activity has been met in the past by the combustion of fossil fuels. The air pollutant emissions from fossil fuel combustion are linked to ambient concentrations through the atmospheric transmission processes (transport, transformation, and removal). The potential environmental and health effects are the consequences of atmospheric concentrations or deposition, while the overall harm caused by primary or secondary air pollutants is determined by the potential effects as well as the receptor sensitivity. The loop is closed by the harm of air pollution eroding some of the well-being or quality of life that has been gained through the utilization of energy.

As in any chain, the closed loop is only as strong as its weakest link. The International Symposium on Sulfur in the Atmosphere (ISSA) was organized to strengthen the link between the sources and receptors of sulfur compounds (figure 2).

Where does all the sulfur go? How long will it reside in the atmosphere and what happens during the transport? A particular concern today is what fraction of SO_2 passes through the environmentally more harmful aerosol phase before removal. The residence time and the transport distance of sulfur compounds in the atmosphere are determined by the competing rates of chemical transformations and dry and wet removal.

TOPIC CONTENT OF SYMPOSIUM

For sake of scientific rigor and depth, the symposium was confined to transport, transformation, and removal processes as well as to the properties and measurements of sulfur compounds in the atmosphere. Neither the effects nor control techniques were discussed in detail.

The symposium was co-sponsored by the United Nations Environment Programme (UNEP), Electric Power Research Institute (EPRI), the Environmental Protection Agency (Interagency Energy/Environment R&D Program), Department of

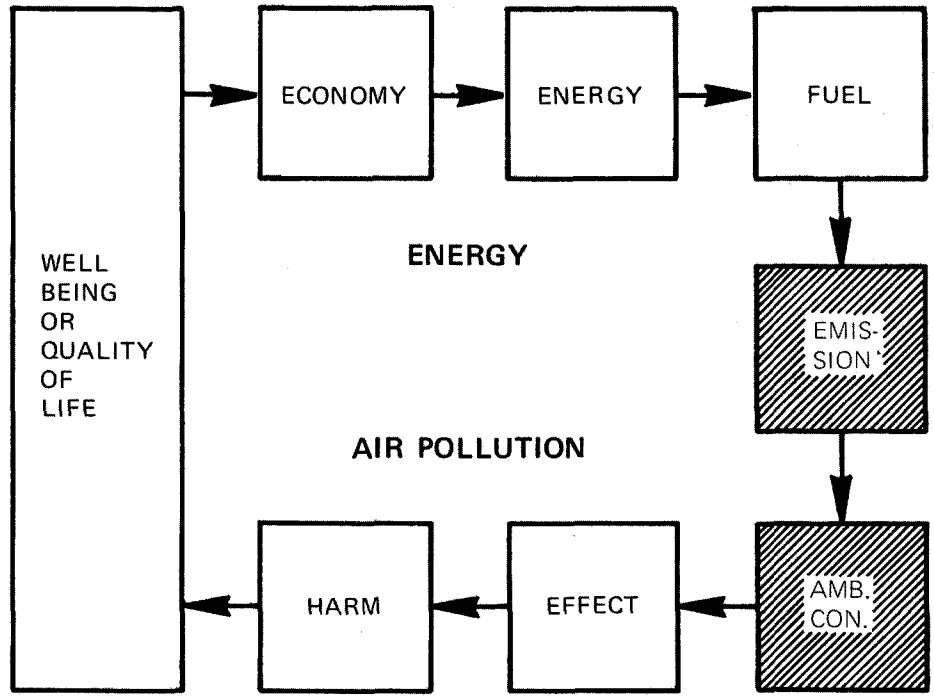


FIGURE 1—*The energy-air pollution system*

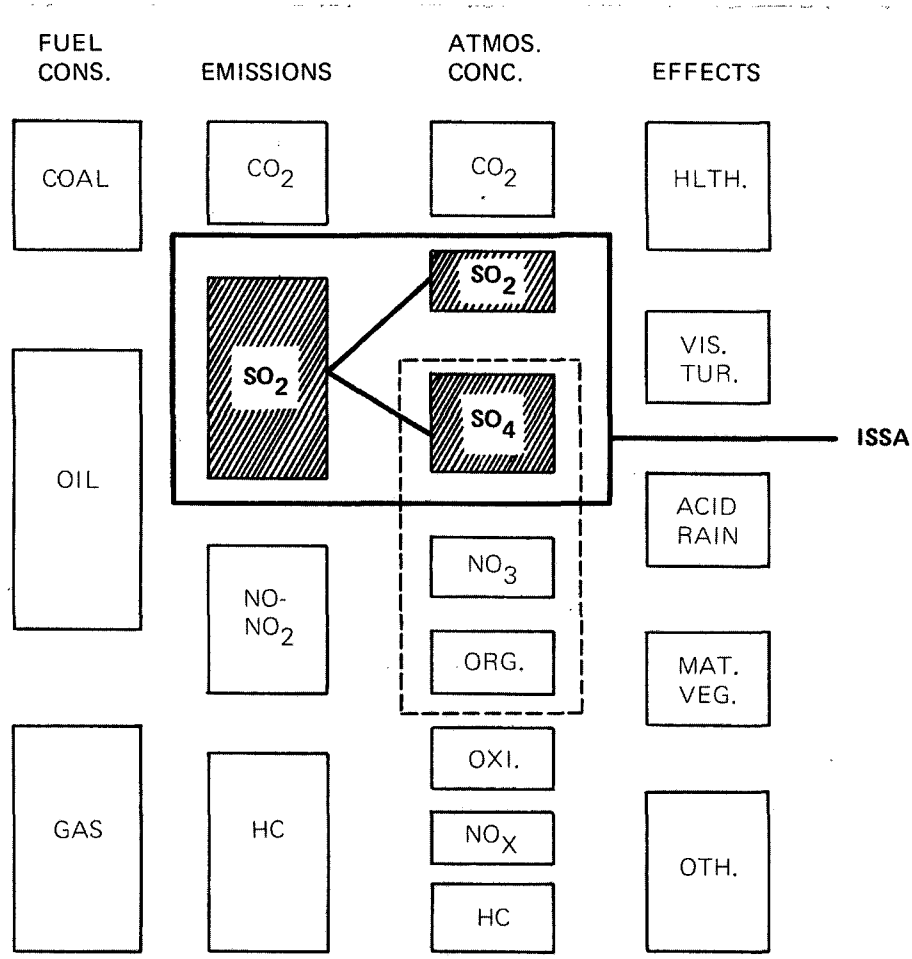


FIGURE 2—*The scope of ISSA*

Energy (DOE, formerly ERDA) and the American Meteorological Society, and it was under the auspices of the Yugoslav Academy of Arts and Sciences.

SYMPOSIUM PARTICIPANTS

Some 160 participants from 22 countries, mostly from Europe and North America, participated in the 7-day symposium, held in Dubrovnik, Yugoslavia, September 7-14, 1977. Following the presentation of 85 invited and contributed papers, the participants gathered in smaller workshops to develop a scientific concensus among the differing viewpoints expressed mainly by the European and North American participants. The symposium proceedings along with workshop summaries are now published in the journal *ATMOSPHERIC ENVIRONMENT*, Volume 12 (1978), pp 1-796. The book version of the proceedings is also available from Pergamon Press. What follows is a reflection of the key symposium results.

The current estimate for natural volatile sulfur emissions, such as H_2S and DMS, is about 35 million tons per year (Granat et al 1976). This represents a downward adjustment from about 60-100 million tons per year of natural emissions which was estimated in earlier global budgets (Eriksson 1960, Junge 1963, Robinson and Robbins 1970, Kellogg 1972, Friend 1973).

Man-made emissions, which are primarily in the form of SO_2, account for about 65 million tons per year as SO_2 (or about 65% of the global emissions). However, the bulk of the man-made emissions are confined to regional hot spots (covering less than 2% of the global area) over North Central Europe and the industrialized regions of Northeastern America. In the United States, for instance, SO_2 emission is about 1 pound per capita per day.

TRANSFORMATIONS OF SULFUR DIOXIDE

Sulfur dioxide, a primary pollutant, undergoes chemical reactions in the atmosphere that lead to a change in its oxidation state, most commonly to SO_4. The change is accompanied by a gas-to-particle conversion process having particulate sulfur, a secondary pollutant, as an end product.

Evidence is accumulating that the major effects of sulfur oxides (those on health, terrestrial and aquatic ecosystems, visibility, and weather and climate) are associated more with the reaction products than with sulfur dioxide itself. For this reason, an appreciable fraction of current sulfur research is focused on the sulfur dioxide transformation. The questions of main concern pertain to the mechanism and rate of conversion, the fraction of sulfur dioxide transformed, and the chemical and physical properties of the particulate sulfur compounds.

It is currently held that the oxidation of sulfur dioxide in the absence of interfering compounds is slow compared with the observed or inferred atmospheric conversion. Hence, one challenge of atmospheric chemistry is to determine which substances and which environmental or emission characteristics promote or inhibit sulfur dioxide oxidation in the atmosphere.

Four mechanisms are believed to be important in atmospheric sulfur dioxide conversion. The first, indirect photooxidation, is homogeneous, i.e., the key step in the sulfur dioxide oxidation occurs in the gas phase. The other three are heterogeneous, the reactions occur in liquid particles or on particle surfaces. As noted earlier, direct photooxidation of sulfur dioxide in pure air or sulfur dioxide oxidation in pure water droplets is believed to be negligibly small (Beilke and Gravenhorst 1978, Calvert et al 1978, Eggleton and Cox 1978).

INDIRECT PHOTOOXIDATION

Indirect photooxidation is a major route for conversion of sulfur dioxide to sulfate in the troposphere. The sulfur dioxide is oxidized after gas-phase collision with strong oxidizing radicals, such as HO, HO_2, and CH_3O_2. One of the sources of these radicals in the polluted troposphere is hydrocarbon-NO_x mixture, which in the process of daytime photooxidation produces oxidizing radicals as intermediate products. The sulfur dioxide oxidation step is therefore indirectly linked to photochemistry. The chemical kinetics of this mechanism have been formulated in models that use measured rate constants. The modeling results were consistent with laboratory tests of sulfur dioxide conversion in the presence of photochemically reacting hydrocarbon-NO_x mixtures. An unambiguous confirmation of the

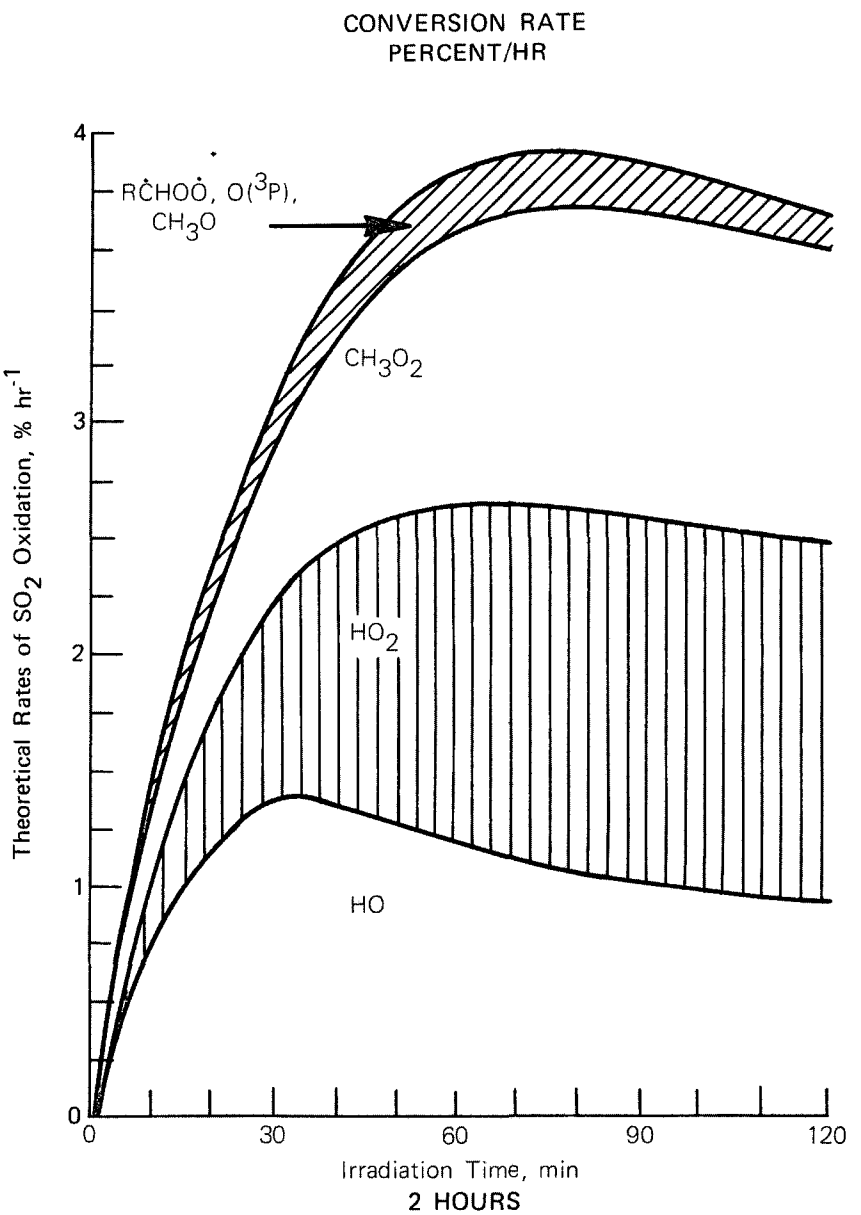


FIGURE 3—*Theoretical rate of attack of various free-radical species on sulfur dioxide (%/h) for a simulated sunlight-irradiated (solar zenith angle, 40°), polluted atmosphere. Reprinted with permission from Calvert et al.*

homogeneous conversion mechanism would require the direct observation of the reactive transients (such as HO, HO_2, and CH_3O_2 radicals) under a variety of atmospheric conditions. Such data are not available.

CHEMICAL KINETICS

Numerical simulations of chemical kinetics for typical urban mixtures (figure 3) indicate 2-4%/hour(h) for a sunny summer day (Calvert et al 1978). Eggleton and Cox 1978, in a summary of European results, concluded that, in the western European summer, sulfur dioxide oxidation rates due to gas-phase radical reactions in sunlight are expected to be between 0.5 and 5%/h, depending on the degree of pollution of the atmosphere. The lower figure refers to cleaner troposphere. In the winter, owing to the reduced sunlight intensity and duration, the conversion rates are expected to be lower by a factor of 2-5 (and perhaps an even greater factor).

SMOG-CHAMBER MEASUREMENTS

Smog-chamber measurements occasionally show higher conversion rates (Miller 1978). It is likely that the homogeneous conversion rate will depend on the absolute concentration, as well as on the initial ratio of hydrocarbons to NO_x.

The specific roles of temperature, dewpoint, and solar radiation intensity on the indirect photooxidation require systematic study. The current understanding is sufficient, however, to incorporate gas-phase chemistry into large-scale reactive plume models.

CATALYTIC SO_2 OXIDATION

Catalytic sulfur dioxide oxidation in droplets has been studied extensively, but the results regarding its role in the atmosphere are less conclusive. The consensus reached at ISSA Workshop 1 is as follows:

> The catalyzed oxidation of SO_2 in solution by transition metals (e.g., Fe, Mn) is believed to be important in situations in which relatively high ($>10^{-5}$ M) molar concentrations of catalyst are present in the droplet and in which the total atmospheric concentrations of catalytic elements are also high. Such conditions can exist in urban areas and in stack plumes and perhaps in urban fogs. In cleaner rural air, this reaction would occur only in clouds. However, unless the pH and metal concentrations are substantially different from those in rain water, this process is unlikely to be of significance. Both laboratory and field results of such reactions are necessary.

Oxidation in the liquid phase by strong oxidants has recently been receiving increasing attention (Beilke and Gravenhorst 1978, Eggleton and Cox 1978). Ozone and hydrogen peroxide absorbed in liquid droplets can promote the rate of oxidation to be comparable with or exceed the rate of indirect photooxidation. However, the current oxidation rate data vary by a factor of around 100; this prohibits an assessment of its importance in the atmosphere. The ozone and hydrogen peroxide in polluted atmospheres originate from the gas-phase photooxidation of hydrocarbon-NO_x mixtures. In clouds or fogs, such gases are absorbed into the water droplets within seconds. Measurements of hydrogen peroxide in polluted and clean atmospheres are necessary, as well as chamber studies, to resolve the discrepancy of existing laboratory data.

SURFACE CATALYZED OXIDATION

Surface-catalyzed oxidation of sulfur dioxide on collision with solid particles has been demonstrated in the laboratory. Elemental carbon (soot) appears to be particularly effective in this regard (Novakov et al 1974). However, because the existing data refer to sulfur dioxide oxidation on filters containing soot, the importance of this mechanism for suspended catalytic aerosols cannot be assessed.

A common feature of these major sulfur dioxide conversion mechanisms is that the rate-controlling species can be identified; they may in principle be controlled independently of sulfur dioxide, and their source is not necessarily that of the sulfur dioxide. It is regrettable that only the indirect-photooxidation mechanism can now be expressed in terms of oxidation rates and therefore the relative importance of these mechanisms cannot be evaluated. A major difficulty in the interpretation of laboratory liquid-phase reactions is that in the atmosphere that reaction occurs *sporadically (in clouds), rather than continuously.*

The burden of establishing the actual conversion mechanisms and rates in the atmosphere rests with the field experiment. In recent years, a variety of approaches have been used for this purpose.

LARGE-SCALE MONITORING AND MODELING

In large-scale monitoring and modeling, an emission inventory over a region and meteorological (transport) conditions are used as the input data for regional-scale (about 1,000-km) transport models. The models also incorporate the rates of sulfur dioxide conversion and removal. The actual rate constants are unknowns, but they can be extracted from a best-fit comparison between calculated and observed values. In the Organisation for Economic Co-operation and Development (OECD) 1977 study, the trajectory models were tuned to monitoring data obtained daily at about 70 stations. The measured daily concentration data for sulfur dioxide, $\overline{SO_4^{--}}$, and $\overline{SO_4^{--}}$ in precipitation were compared with calculations, and the rate constants for transformations and dry and wet removal were adjusted until a best fit was obtained. The key model values for the OECD study are listed in table 1.

TABLE 1
Values applied in the calculations with the Lagrangian Dispersion Model in the OECD Project*

Characteristic	Value
Fraction of Emitted Sulfur Deposited Locally	0.15
Fraction of Emitted Sulfur Transformed Directly to Sulfate	0.05
Decay Rate of Sulfur Dioxide Rain	4.10^{-5}/s (14.4%/h)
Decay Rate of Sulfur Dioxide Dry	1.10^{-5}/s (3.6%/h)
Transformation Rate SO_2 SO_4^{--}	$3.5 \cdot 10^{-6}$/s (1.26%/h)
Loss Rate of SO_4^{--}	$4 \cdot 10^{-6}$/s (1.44%/h)
Mixing Height	1,000 m

*Data from OECD.

MAJOR STUDY PROJECTS

The year-round average conversion rate of 1-2%/h and the overall average dry removal rate of about 3-4%/h were key new results of the OECD study. Studies similar in scope and objective to the OECD study are being conducted in the United States. The Sulfate Regional Experiment (SURE) (Perhac 1978) of the Electric Power Research Institute, the Multistate Atmospheric Power Production Pollutant Study (MAP3S) (MacCracken 1978) of the Department of Energy, and the Sulfur Transport and Transformations in the Environment (STATE) study of EPA are examples. The close coordination of these major projects appears to be highly desirable and is being pursued by the various project directors.

The main utility of the regional approach is that the obtained rate constants are inherently averages over all sources and spatial-temporal scales of interest. It is recognized, however, that the rate constants for removal and transformations are actually variables that may depend on source configuration, meteorologic conditions, and the presence of external (nonsulfur) species.

PLUME STUDIES

The average rate constants can be obtained from the regional monitoring and modeling efforts, but the specific dependence of the rates on the underlying chemical and physical processes has to be studied on a smaller scale. The gap between regional (1,000-km) scale and laboratory simulation can be bridged by mesoscale studies of sulfur transport, transformations, and removal (transmission). These are generally referred to as plume studies. Inherently, quantitative single-plume studies are limited to a spatial scale of less than 500 km and a plume age of less than 12 h.

CONVERSION RATES

The average oxidation rate over the lifetime of sulfur dioxide is about 1-2%/h, as determined by fitting the rate constants in regional-scale models to European monitoring data. In plumes of a midwestern power plant, as part of the Midwest Interstate Sulfur Transformation and Transport Study, (MISTT), the conversion rate was measured to be 1-4%/h during the daytime and <0.5%/h at night, yielding a daily average conversion of 1-2%/h during the summer (Husar et al 1978), (figure 4). Laboratory simulations and chemical kinetic model calculations of gas-phase controlled sulfur dioxide conversion in the presence of oxidizing radicals also indicated a 1-2%/h daily average conversion rate for summer conditions. The contribution of liquid-phase oxidation is not well established, but it is thought to be important.

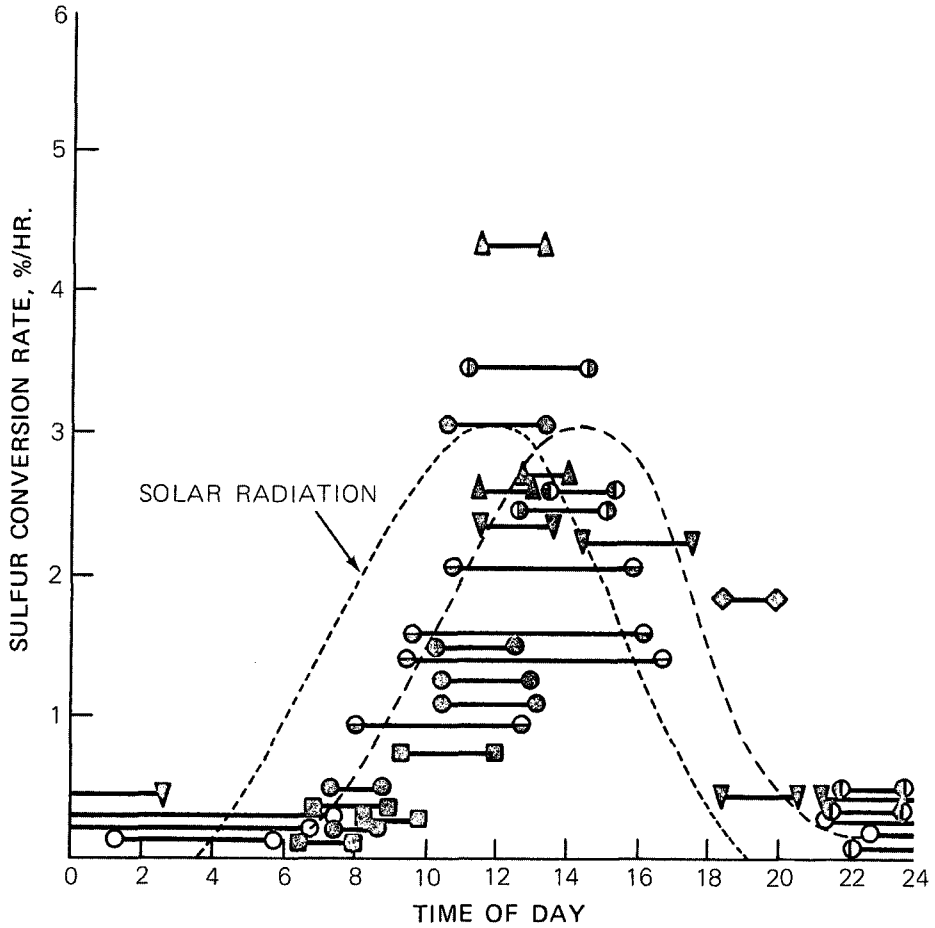


FIGURE 4—*Sulfur conversion rate for the Labadie power plant plume for nine sampling missions. The points to the left of each bar are the release times and to the right the sampling times.*

REMOVAL OF SULFUR COMPOUNDS

The residence time and the transport distance of atmospheric sulfur are determined by the overall removal rate of sulfur compounds from the atmosphere. Overall removal has four major components: dry removal of sulfur dioxide, wet removal of sulfur dioxide, dry removal of SO_4, and wet removal of SO_4. Dry removal of sulfur dioxide and wet removal of SO_4 appear to be the two major components.

DRY DEPOSITION

Dry removal of sulfur dioxide is a mass-transfer process whereby sulfur dioxide is first transported to a surface by turbulent and molecular diffusion and then removed by adsorption or absorption at the surface. The overall mass-transfer rate can be characterized by a mass-transfer coefficient (v_d) and the difference between the bulk and surface concentrations. Because the unit of v_d is length per time, it is called deposition velocity. Conceptually, it is also convenient to use the overall resistance to mass transfer ($r = 1/v_d$), which is the sum of several, largely independent resistances.

The surface resistance (r_s) incorporates adsorption and absorption. In the case of vegetation, r_s is believed to be dominated by the size of the stomatal openings. The aerodynamic resistance (r_a) is due to turbulent diffusion in the atmospheric surface layer and controls the rate of dry deposition during stable conditions (inversions) (Garland 1978).

The range of deposition velocities was summarized at ISSA Workshop 2 and is shown in tables 2 and 3.

WET DISPOSITION

Wet deposition of sulfur compounds proceeds through a combination of in-cloud and below-cloud scavenging by precipitation (rain and snow). The rate of wet deposition can be calculated from the sulfur concentration of precipitation and precipitation rate. Sulfur deposition rates are compiled here for a number of different areas that vary in climate and industrial activity (table 4).

TABLE 2
Sulfur dioxide deposition velocities over vegetation*†

Vegetation			Deposition Velocity (V_d), cm/s.	
Height	Example	Height, m	Range	Typical
Short	Grass	0.1	0.1–0.8	0.5
Medium	Crops	1.0	0.2–1.5	0.7
Tall	Forest	10.0	0.2–2.0	Uncertain

*ISSA Workshop 2.

†Values were obtained in a humid climate, much smaller values are likely in arid climates.

TABLE 3
Sulfur dioxide deposition velocities over soil*

		Deposition Velocity (V_d), cm/s	
Acidity (pH)	State	Range	Typical
Calcareous (≥7)	Dry	0.3–1.0	0.8
Calcareous (≥7)	Wet	0.3–1.0	0.8
Acid (~4)	Dry	0.1–0.5	0.4
Acid (~4)	Wet	0.1–0.8	0.6

*ISSA Workshop 2. No information is available to assess V_d on desert sand or lateritic soils.

TABLE 4
Representative annual average rates of wet and dry deposition of sulfur*

Location		Excess† Precipitation Sulfate Concentration (as sulfur, mg/l)	Wet Deposition Rate of Sulfur, $g/m^2 \cdot yr$	Dry Deposition Rate of Sulfur, $g/m^2 \cdot yr$
Heavily Industrialized Areas	North America	3–?	0.1‡–3	?
	Europe	3–20	2–4	3–15
Rural	North America	0.5–2	0.1–2	0.2–2.6
	Europe	0.5–3	0.2–2	0.5–5.0
Remote	North Atlantic	0.2–0.6	1–3	0.04–0.4
	Other Oceans	0.04	0.01‡–0.2	<0.1
	Continents	0.1	0.01‡–0.5	0.4

* ISSA Workshop 2.

† Excess over concentration due to sea salt.

‡ Low deposition rates result from low precipitation.

DRY AND WET DEPOSITION

To understand sulfur deposition, rates of both wet and dry deposition must be measured. On a regional scale, this has been done only by the OECD study in northern Europe, although a similar study, the Multi-State Atmospheric Power Production Pollution Study (MAP3S), is currently underway in the United States.

In the OECD study, overall dry and wet removal rates were estimated by comparing monitoring data with appropriately tuned model calculations. The rate constants that were extracted from these comparisons are given in table 1. The study concluded that, of the total emission of 20 Tg of sulfur oxides per year, dry deposition accounts for 11 Tg, or about 55%, wet deposition accounts for about 6 Tg, or 30%, and the balance is exported out of the study area.

WET VERSUS DRY

Although regional information is lacking for the United States, there have been intensive investigations on the relative magnitude of wet versus dry deposition for plumes (Granat and Rodhe 1973), urban areas (Husar et al 1976a), and rural areas (Likens et al 1978). The results of these, coupled with the results of the OECD study, indicate that, near sources (stack and urban areas), dry deposition is more important as a removal mechanism than wet deposition. In areas removed from local sources, wet deposition is more important. For the purposes of constructing sulfur budgets for a large area (such as the eastern United States), the rates of wet and dry deposition of sulfur can be assumed to be roughly comparable.

RESIDENCE TIME

The residence time of sulfur dioxide is determined by the competing rates of transformations to sulfate and by removal of sulfur dioxide and SO_4. Using a conversion rate of 1-2%/h and an overall removal rate of 2-4%/h leads to a characteristic residence time of 14-33 h or about 1 day for sulfur dioxide. The residence time of sulfur dioxide in single plumes was estimated from aircraft sampling data and combined with simple models (figure 5). The residence time of sulfate is the sum of the formation and removal times. According to the current estimates (ISSA Workshop 3) the sulfate residence time is 3 to 5 days.

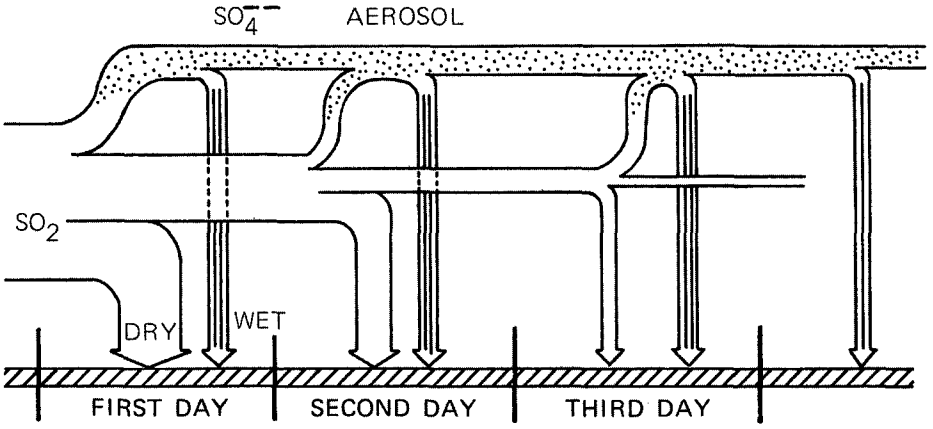


FIGURE 5—*Flow diagram of sulfur transmission through the atmosphere. Over half of the SO_2 is removed or transformed to sulfate during the first day of its atmospheric residence.*

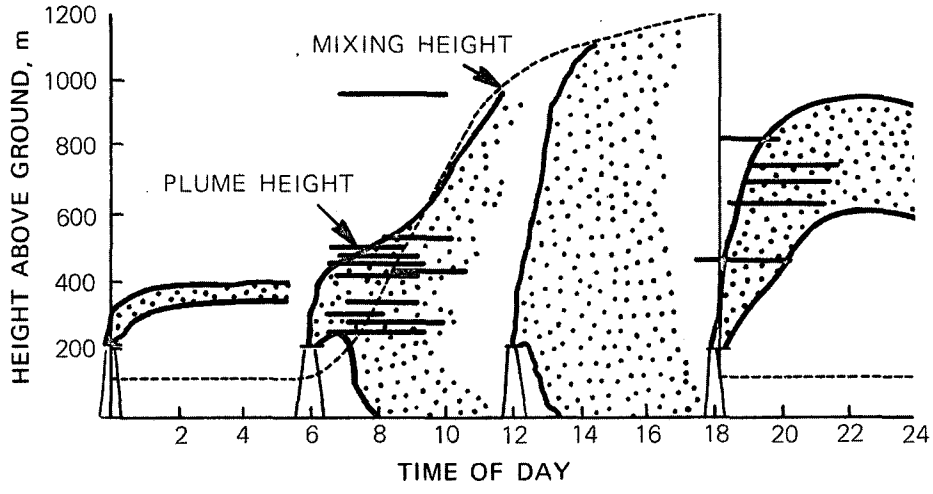


FIGURE 6—*Schematics of plume geometry at four different parts of the diurnal cycle*

TRANSPORT

Once the residence times are set, the transport distance and the region of impact are determined by the mean horizontal wind speed at the height of the sulfur layer. Wind speeds of 500 km/day are typical for the midwestern United States. In the MISTT study, for instance, power plant plumes have been identified and mapped up to the age of 12 hours or transport distance of 300 km (Gillani et al 1978).

VERTICAL TRANSPORT

The plume dispersion within the planetary boundary layer is facilitated by vertical transport. Due to the increased atmospheric stability at night, narrow ribbon-like plumes develop isolated from the surface. During the day, these plumes flood the rising mixing layer and are subject to dry deposition. During the unstable afternoon hours, plumes frequently mix up to 1-2 km heights, creating pollutant layers aloft (figure 6).

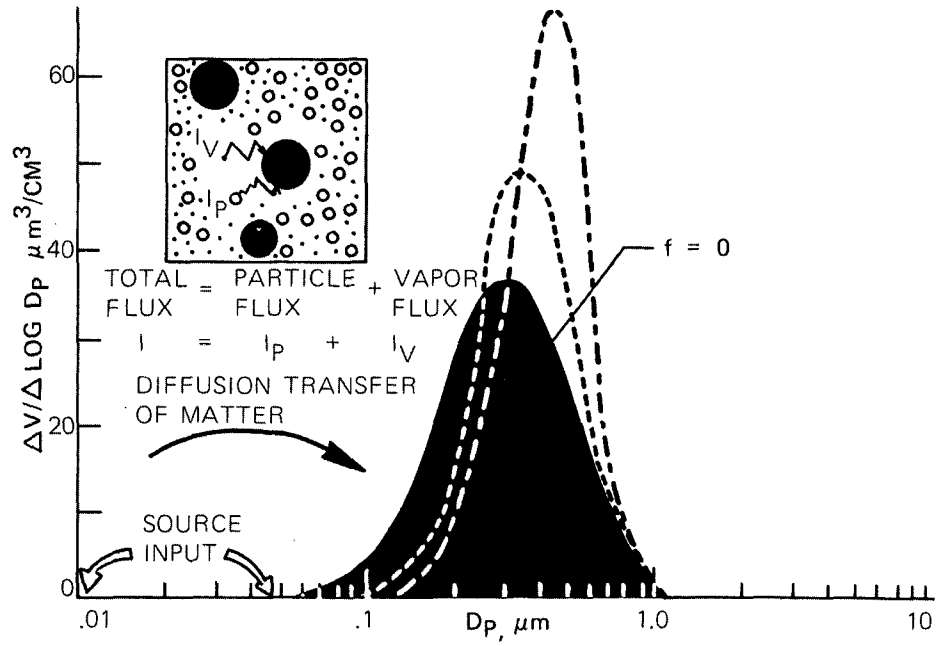


FIGURE 7—*Aerosol volume distribution*

After a hard day of convection, reaction, and removal, the lower atmosphere relaxes at dusk, while the midwestern plume takes off overnight on a low-level (nocturnal) jet and starts the next day's work 300-400 km from the stack.

During synoptically stagnating periods (Lyons et al 1978), or when sources are aligned in the wind direction (Gage et al 1977), the superposition of plumes can result in the development of large scale hazy air masses (Husar et al 1976b).

PARTICULATE SULFUR

The result of SO_2 oxidation is the formation of particulate sulfur, which has been positively identified to be the sulfate ion (Stevens and Dzubay 1978).

In the case of homogenous or gas phase controlled SO_2 oxidation, the reaction product, sulfuric acid, either self nucleates or gets deposited onto the existing aerosol population. The diffusional transfer of gaseous or ultrafine H_2SO_4 results in a preferential growth of sulfate aerosol in the size range between 0.1 and 1.0 μm (figure 7). This size window has been referred to as the accumulation mode (Whitby 1978).

From the symposium deliberations (ISSA Workshop 3), it was concluded that, at temperate climates in mid-latitudes, about 20-50% of the SO_2 converts to sulfate before removal.

Over the eastern United States, sulfates constitute about 30-50% of the aerosol mass below 2 μm (Stevens and Dzubay 1978). The sulfate aerosol occurs either as H_2SO_4 or as its partially or fully neutralized salts (Charlson et al 1978, Brosset 1978). Regrettably, the relative abundance of these sulfur compounds is not known.

The emission rate of SO_2 for the states in the Ohio River Valley Region is between 20 and 30 g/m^2/year (figure 8).

MAXIMUM SULFATE CONCENTRATIONS

Contours of yearly average sulfate concentration reveal that the maximum concentrations occur in the region of high emission density. In the Ohio River Valley, for instance, the yearly average sulfate concentration exceeds 15 μg/m^3 and

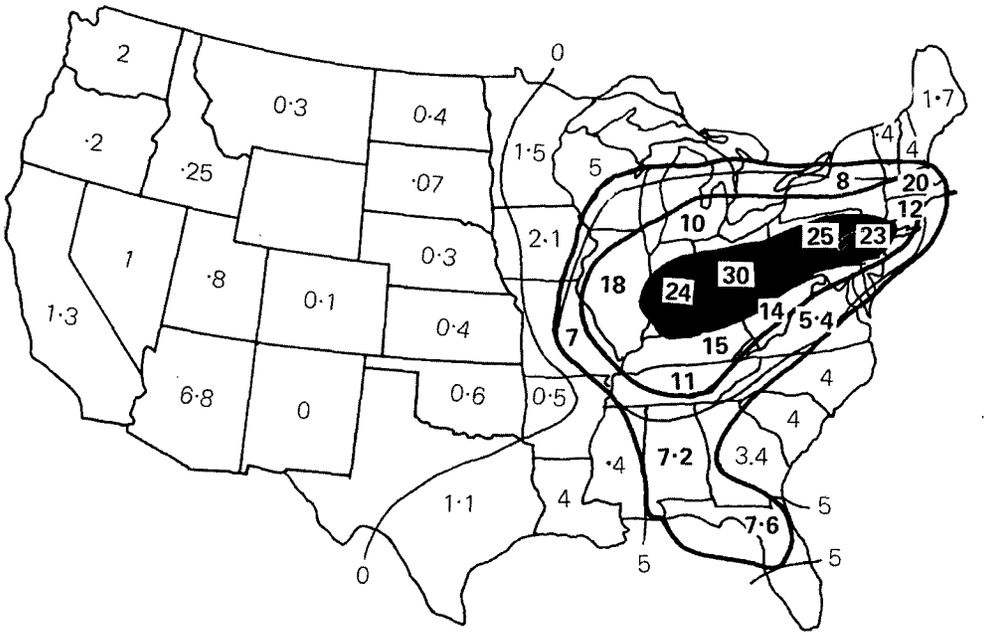


FIGURE 8–*SO_2 emission contours*

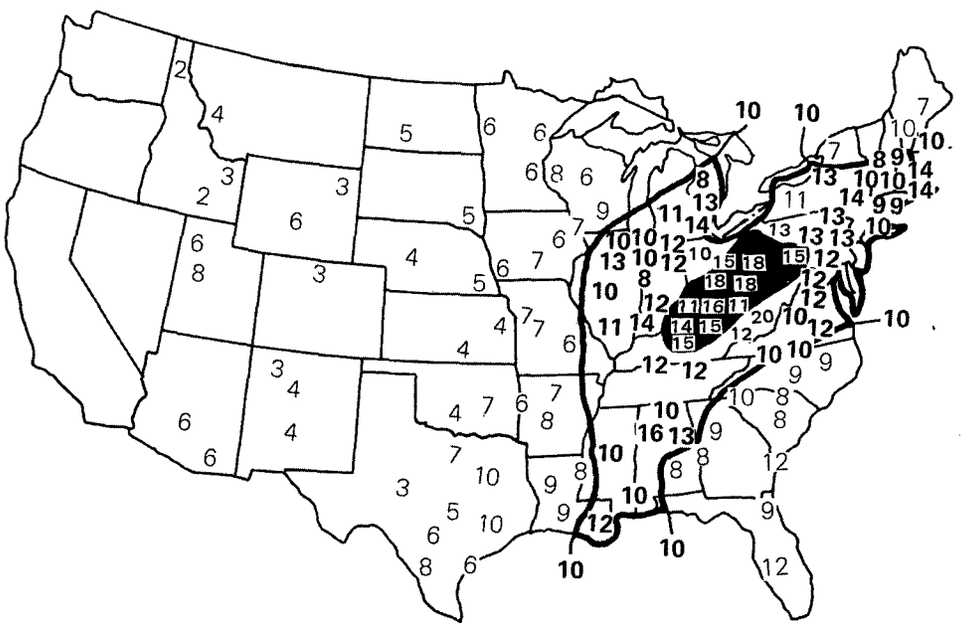


FIGURE 9–*Yearly average sulfate concentrations*

is between 10 and 15 $\mu g/m^3$ over a large part of the eastern United States (figure 9). The seasonal pattern displays a greater geographical extent of the high sulfate concentration in the summer than in the winter months (figure 10).

DEFINITE SUMMER PEAK

The monthly average sulfate concentration at non-urban sites of the eastern United States shows a definite summer peak (figure 11), while the seasonal emissions are almost the same. The seasonal pattern of sulfate in precipitation, obtained by the MAP3S study, also shows a pronounced summer peak (figure 12).

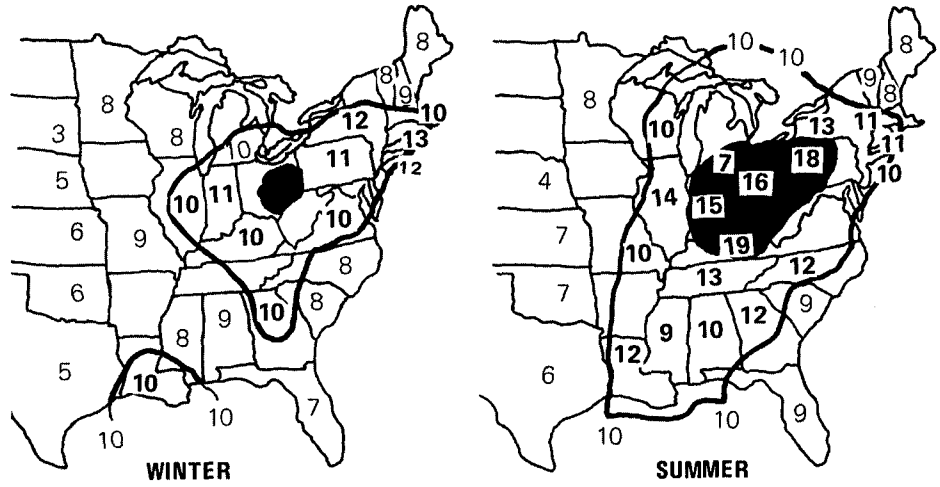


FIGURE 10—*Seasonal sulfate concentration patterns*

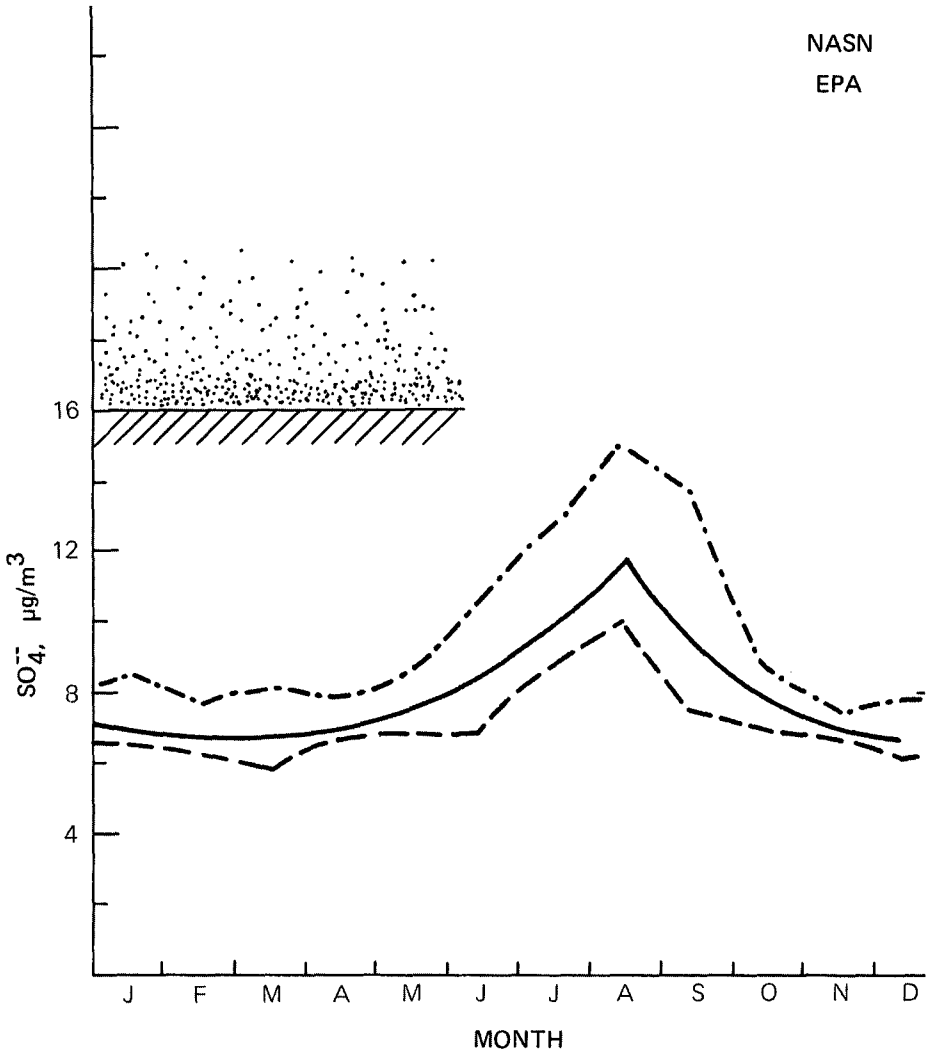


FIGURE 11—*Monthly average sulfate concentration [µg/m^3] 1970-1974 for 18 eastern nonurban sites (——). The seasonal pattern at 6 stations in the industrialized northeast (—·—) is more pronounced than the seasonal pattern of 12 peripheral stations in the midwest and southeast (– – –).*

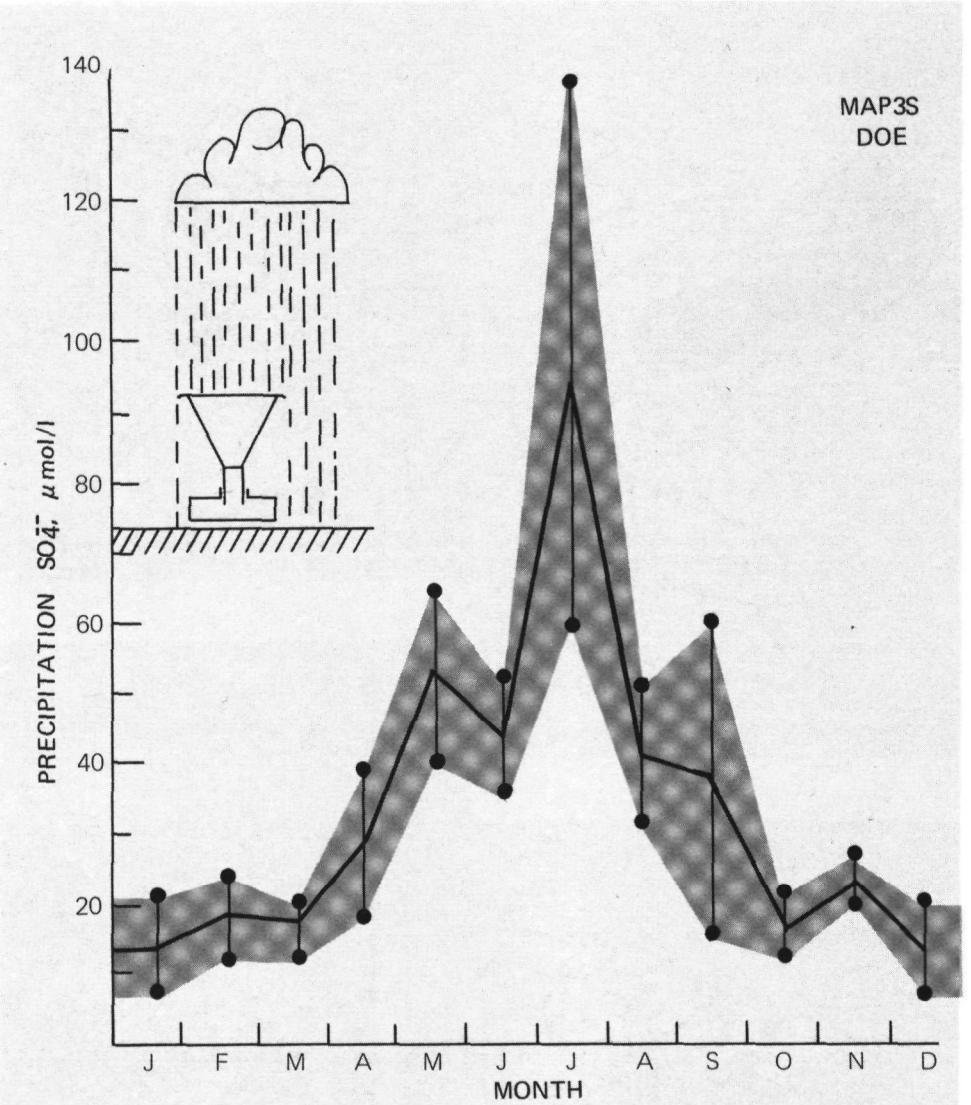


FIGURE 12—*The seasonal pattern of sulfate in precipitation, from MAP3S study*

ATMOSPHERIC SULFATE

The atmospheric turbidity obtained by the National Oceanic and Atmospheric Administration (NOAA) at 26 eastern United States sites is consistent with the seasonal sulfate pattern (figure 13). The consistency is to be expected, since at least half of the aerosol light scattering is associated with sulfur compounds (Charlson et al 1978). It is therefore evident that the amount of sulfate contained in the atmosphere is by a factor of two or three higher in the summer than in the winter months. Therefore any SO_2 reduction scheme during the summer (e.g., solar augmented energy supply) would yield more than its share in the reduction of sulfate.

Visibility degradation, which is primarily due to the light scattering by aerosols, also exhibits a summer peak over the eastern United States (figure 14). The spatial-temporal dynamics of aerosol-containing air masses during the summer period can be illustrated by contours of visibility data gathered at the National Weather Service sites. In figure 15, successive visibility contours illustrate the transport of hazy air masses.

REGIONAL SCALE DISTRIBUTION

The regional scale distribution resulting from a variety of sources is being monitored by large scale programs, such as the Organization for Economic Co-operation and Development (OECD) (Ottar 1978), Sulfate Regional Experiment (SURE) (Perhac 1978) of the Electric Power Research Institute (EPRI), and the

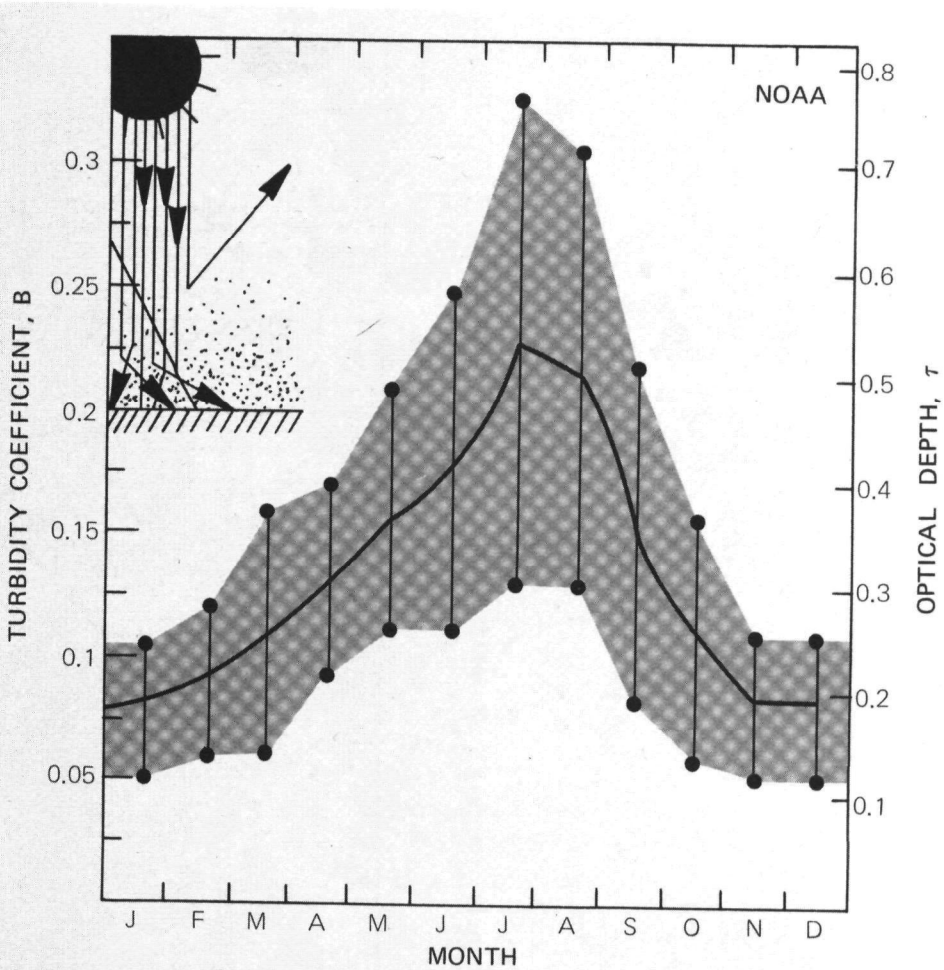
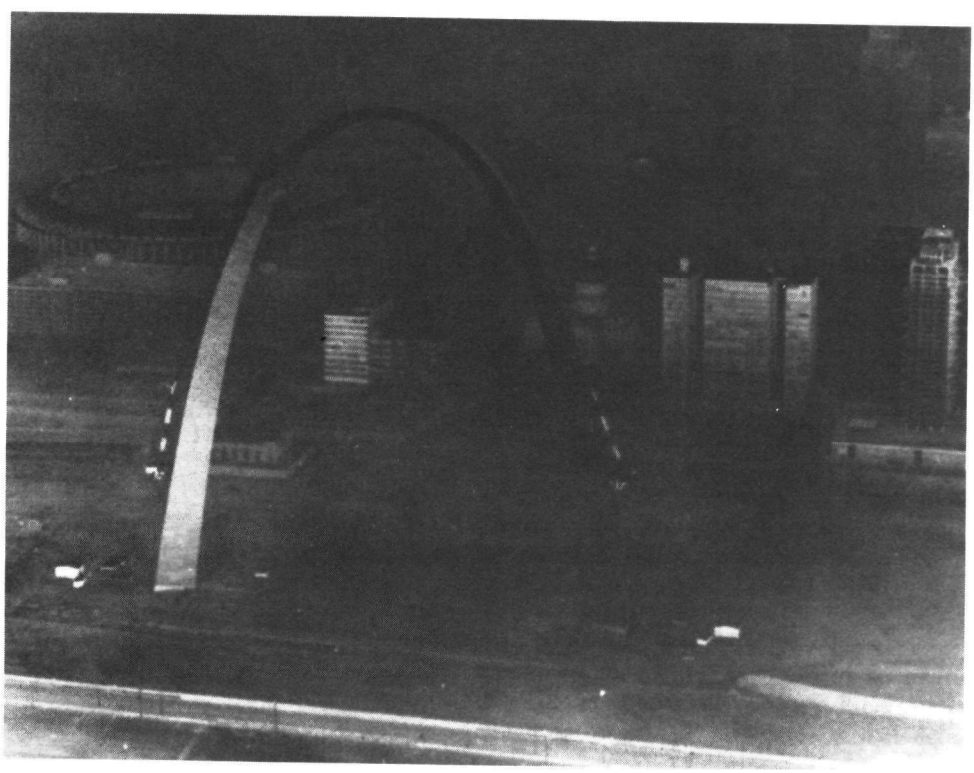


FIGURE 13—*The seasonal pattern of turbidity of 26 eastern United States sites*



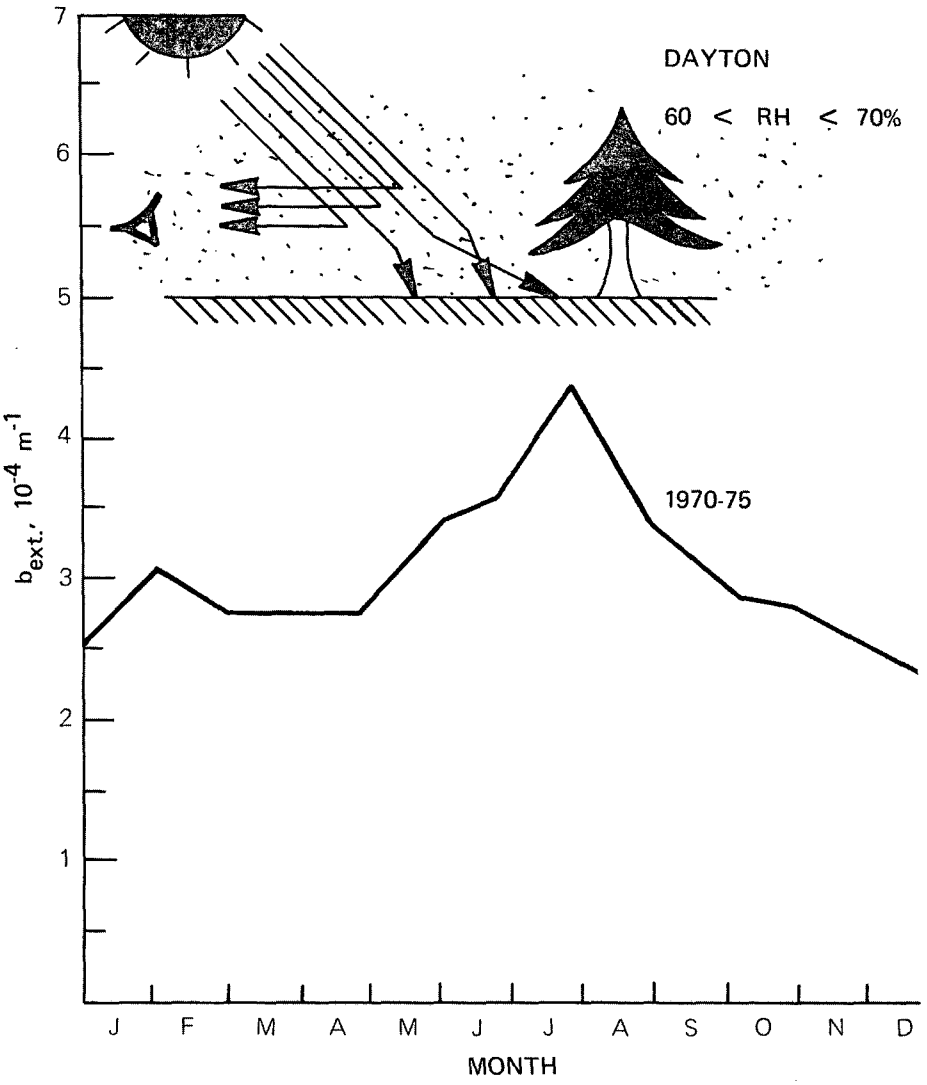


FIGURE 14—*The seasonal pattern of visibility at Dayton, Ohio, 1970-1975*

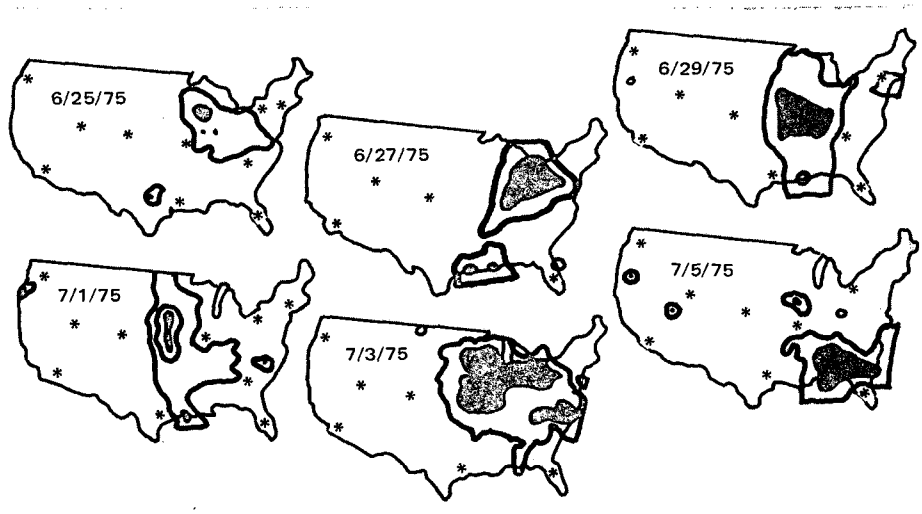


FIGURE 15—*Maps of noon visibility over the continental United States between June 25 and July 5, 1975. Contours are plotted for extinction coefficients 4, 6, and 8 (x 10^4 m^{-1}), corresponding to visual ranges 6-4 (light shade), 4 (medium), and <3 miles (black).*

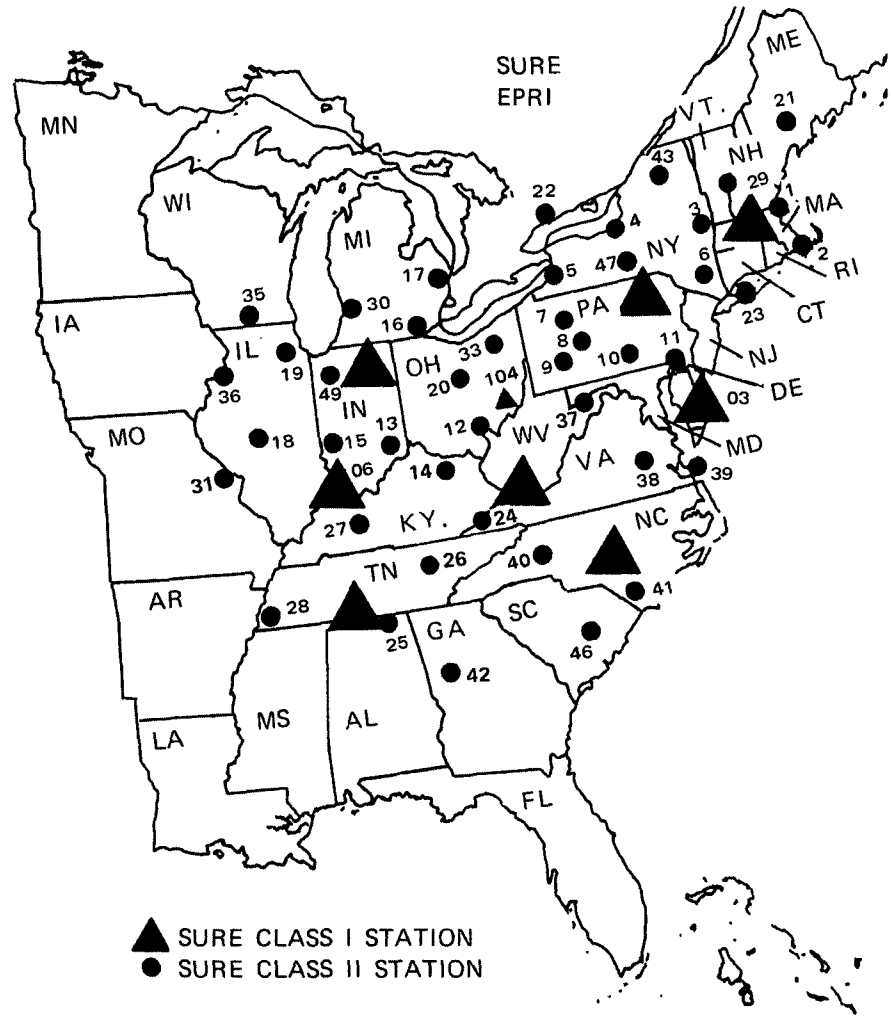


FIGURE 16—*The SURE network*

PLUME STUDIES

Multi-State Atmospheric Power Production Pollution Study (MAP3S) (MacCracken 1978). On the other hand, mesoscale or plume studies, such as MISTT and the new STATE program, elucidate the diurnal pattern and other details of transport, transformation, and removal processes.

The contribution of the electric utility industry to the total atmospheric sulfate levels over the Northeastern United States is being investigated by EPRI's SURE program, which is now operational. The high spatial density (figure 16) and temporal resolution of this network permits the study of sulfur budget over the northeast on a scale comparable to the transport distance of sulfur compounds in the atmosphere (Perhac 1978).

NUMERICAL MODELING

The MAP3S program of DOE has focused its attention on improving capabilities for numerical modeling of regional pollutant patterns. To accomplish this, a wide range of special studies focusing on precipitation scavenging and chemistry, transformation and dry removal processes, and measurement of pollutant concentrations in the boundary layer is underway (MacCracken, 1978).

In Europe the international exchange of sulfur was estimated by export-import budget models. The OECD program has confirmed that sulfur compounds do travel long distances (several hundred km or more) in the atmosphere and has shown that the air quality in any one European country is measurably affected by emissions from other European countries.

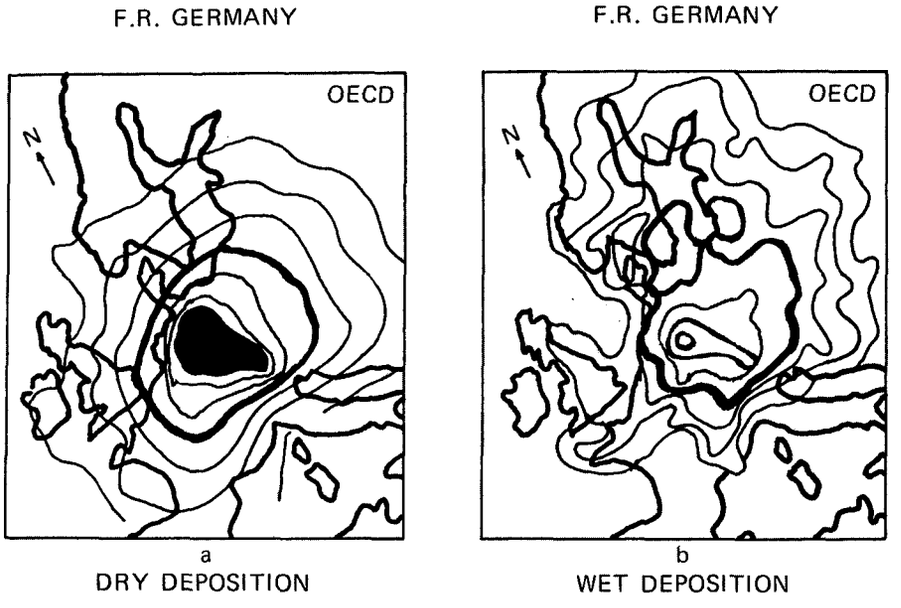


FIGURE 17—*OECD maps of dry and wet deposition of sulfur and wet deposition of sulfur emission from Federal Republic of Germany*

MOST BENEFIT—EMITTING COUNTRY

In the case of Federal Republic of Germany, for example, which is the size of a midwestern state, about 30% of its own emissions are dry deposited and 5% are wet deposited within its own boundaries (figure 17). The remaining 65% is deposited abroad (OECD 1977). The study concludes, nevertheless, that any given country impacts on itself more than on any other country. Therefore, the emission reductions will most benefit the emitting country (or state) itself.

In conclusion, it was the general feeling among the participants that the symposium has contributed to the clarification of the atmospheric portion of the sulfur budget. There was a general acceptance of the transport across national boundaries, about the residence times, about the size of sulfate particles and the homogeneous or gas phase SO_2 conversion processes.

TWO LINES OF THOUGHT

The participants also stressed that there is no reason to believe that the atmospheric part of the sulfur budget differs significantly from North America and Europe. However, in Europe and Canada scientists have been concerned more with ecological problems resulting from acid precipitation, whereas in the United States the driving force has been the health effects. Thus the United States has emphasized atmospheric concentrations while the Europeans and Canadians have stressed the sulfur deposition. One of the most valuable aspects of the symposium was the interaction and merging of the two lines of thought. This enhanced understanding is due to the international OECD project in Europe and the Interagency Energy/Environment R&D Program in the United States. A continuing interagency and international program, including government and industry, is needed to develop the most appropriate control strategies. In doing so, rules of reason should be utilized as an alternative to the adversary attitudes between the environmental groups, the government and industry.

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MONITORING OF AIR AND WATER QUALITY IN THE WESTERN REGION

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AIR QUALITY

Concern over the environmental impacts of the energy development activities in the western United States is apparent in both the executive and legislative branches of our Government. Policy statements, legislative proposals, and research mandates are appearing with increased frequency and most relate either directly or indirectly to the resources existing in the Western Energy Resource Development Area (WERDA). Historically, the West has been an area with a relatively low population density and correspondingly low industrial development. Because of these factors, it contains several so-called pristine areas generally not impacted by anthropogenic activities. However, general deterioration in the air quality over the whole region, particularly with respect to visibility over the past several years, is widely acknowledged. Concern over any additional degradation is reflected in the enactment of the Clean Air Act Amendments of 1977, particularly in Part C, Title I (Prevention of Significant Deterioration of Air Quality), and Section 169A, Part C (Visibility Protection for Federal Class I Areas).

WATER QUALITY

Also of concern in the West is the potential impact on water quality and supply. Water is already in short supply in the semiarid West. The accelerated energy developments in these areas are in direct competition with other users for the limited available water resources. The extraction of raw materials, fuel refinement, transport and utilization, and the accompanying demographic changes will place additional demands on available water. The water quality stands to be degraded as both the consumptive and nonconsumptive use increases and as major hydrographic changes are made as a result of diversion of water to use sites.

This paper describes the status and initial results of a major interagency program directed at integrating air and water quality research and monitoring data in

the WERDA. Cooperating with the U.S. Environmental Protection Agency, the U.S. Geological Survey*, and the National Oceanic and Atmospheric Administration in this program are several other agencies of the federal and state governments.

The status of environmental quality assessment in the WERDA can be described in precise terms; the results, currently, are far less specific.

DATA SITES

When national attention turned to the West as a source of energy in the early 1970's, there was relatively little information available on the water resources of the major energy area. Deposits of low sulfur, strippable coal, oil shale, and uranium generally occur in semiarid areas of sparse population, little development, and hence little prior need for information describing the local water picture, and even less for data on the quality of the water. In 1973, for example, there were only 78 sites (figure 1) in the Northern Great Plains coal region where water quality data were systematically obtained on streams. The sites where groundwater quality was measured were even fewer in number. Today, the quality of water in streams is determined at 170 sites in this region (figure 2), and the number of wells where water quality is periodically measured has also greatly increased. The pattern has been repeated elsewhere. In 1973, there was water-quality information available at three sites in or near Colorado's Piceance Basin where several billion barrels of oil

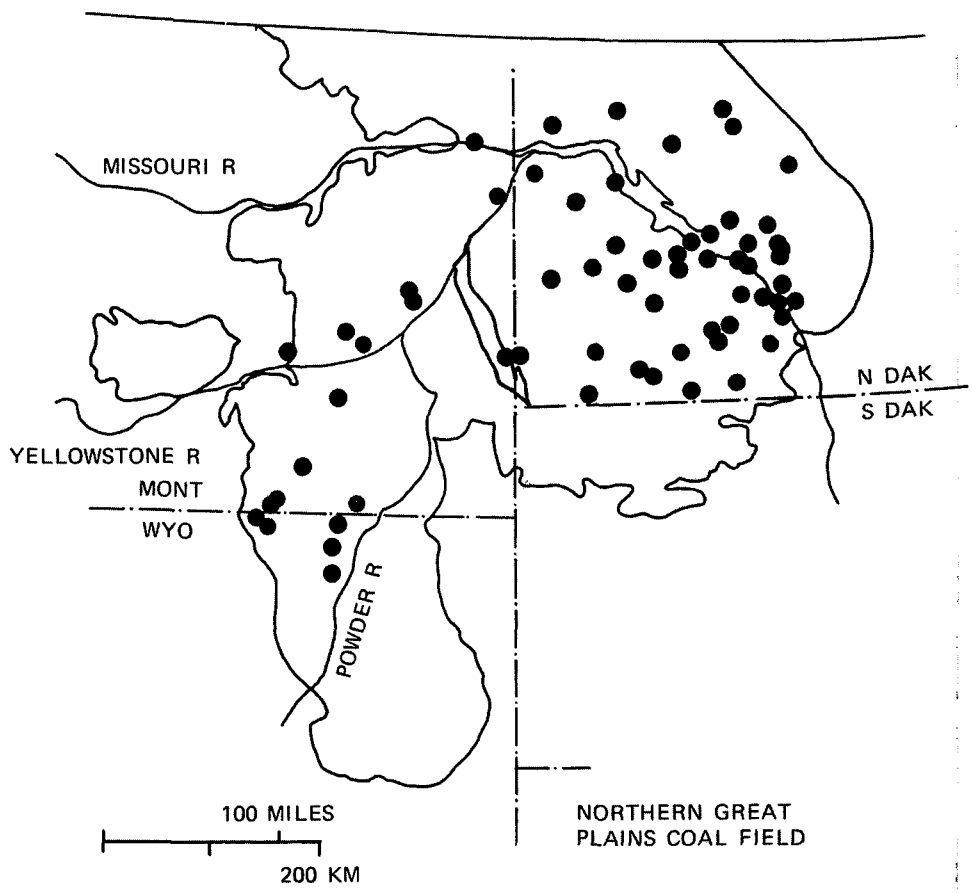

FIGURE 1—*Water quality stations, 1974*

*The input of Hugh H. Hudson, Water Resources Division, to this report is particularly acknowledged.

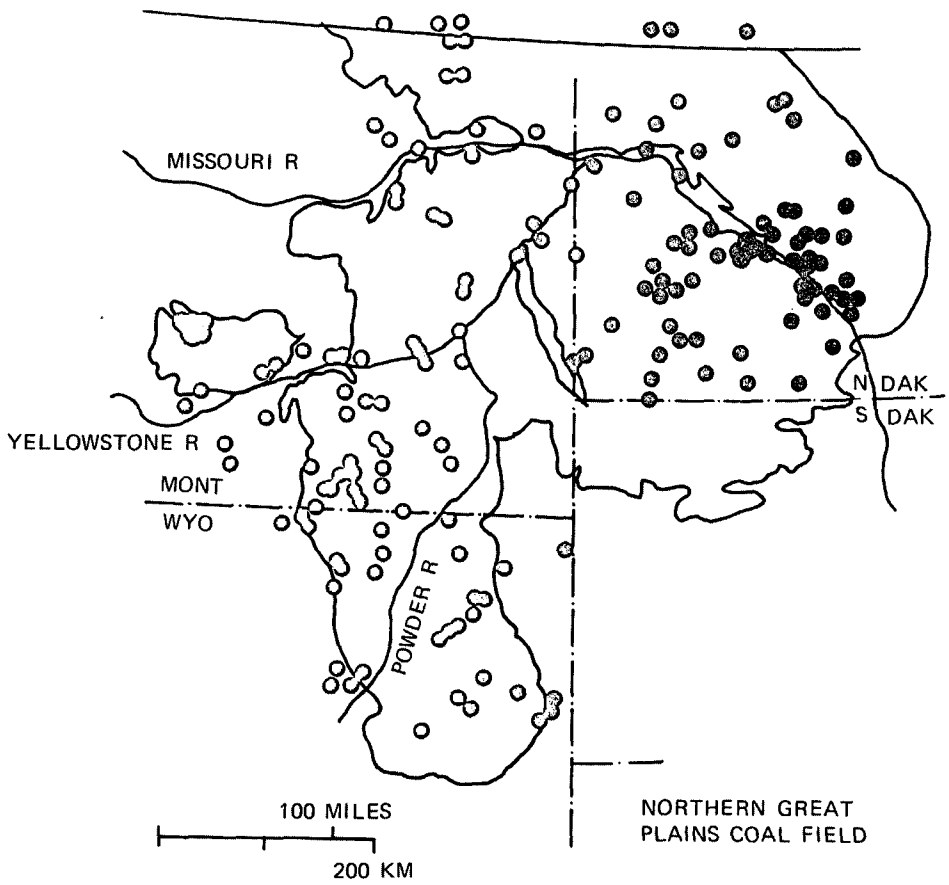

FIGURE 2—*Water quality stations, 1978*

are contained in deposits of shale. Now, 30 sites are operated to determine the water quality of streams. Streamflow quality was measured at five sites in the coal and uranium areas of northwestern New Mexico 5 years ago; today, there are 40 sites throughout these energy areas. Observation wells for determining groundwater quality in the energy areas of New Mexico have increased from near zero to about 35. Fortunately, nearly all of this increased water-quality measuring activity was achieved prior to large-scale mining and processing of energy resources.

BASELINE CONDITIONS

Before we go further into water-quality determination, let us offer some objectives and definitions of this activity. The objectives are several. Even in its natural state, water in different areas contains an extremely wide range of chemical constituents such as major ions and trace elements, as well as numerous organic and inorganic chemical compounds. In addition, natural waters contain variable concentrations of suspended sediment and have wide ranging temperature extremes, degrees of hardness, and often an aquatic biota characteristic to the area. If departures from its natural state are to be determined, these departures must be referenced to natural or predevelopment conditions; that is, baseline conditions against which water-quality changes may be measured. The first order of business is, therefore, to document the physical, chemical, and biological qualities of streamflow and groundwater systems prior to energy development.

PARAMETERS CONSIDERED

The parameters considered in measuring water quality encompass the total effects of mining and conversion. Uppermost in many minds is erosion from surface-mining activities as a measure of the success of reclamation or restoration of mined lands. Consequently, the sediment concentrations and total sediment loads in streams affected by mining operations are often measured. The chemical quality of streamflow, including its concentrations of various salts, is the next most significant parameter. The compositions of the salts and the concentration of other elements that affect the utility of the water as a fish or riparian wildlife habitat, or its compatibility with soils when applied as irrigation water, are therefore measured. Obviously, those elements as compounds that make drinking water safe have to be measured. Trace elements that may be introduced into streamflows by mining or disposal of waste materials from plants that convert coal, oil shale, or other resource raw material into energy have to be taken into account in comprehensive water-resource evaluations. Then, there is the additional possibility of water-quality degradation by the simple impact of the population whose wastes so often find their way into the natural water systems. Comprehensive monitoring of the quality of streamflows must include observing and counting the simple to complex organisms that live in the streams. Several coliform bacteria types provide direct evidence of human waste contamination. A periodic evaluation of the taxonomic composition of the benthic invertebrates in a stream reach is a means of determining the biological health of the stream, as these organisms act as integrators of water quality changes. Of course, not all of the parameters mentioned above are measured at all sites.

HIGH QUALITY FLOW

In addition to the introduction into water courses of materials that degrade water quality, the matter of withdrawing, for various energy-associated uses, the water of highest quality also affects the overall water resource. In the energy areas of the West, water quality generally deteriorates as flows progress downriver from their mountain snowmelt sources. If energy demands call for a removal of the high-quality headwater flows, then consideration must be given to what happens to the residual water and its utility for other purposes in the downstream reaches. These are among the factors that are considered in designing and operating a system of streamflow-quality measuring sites.

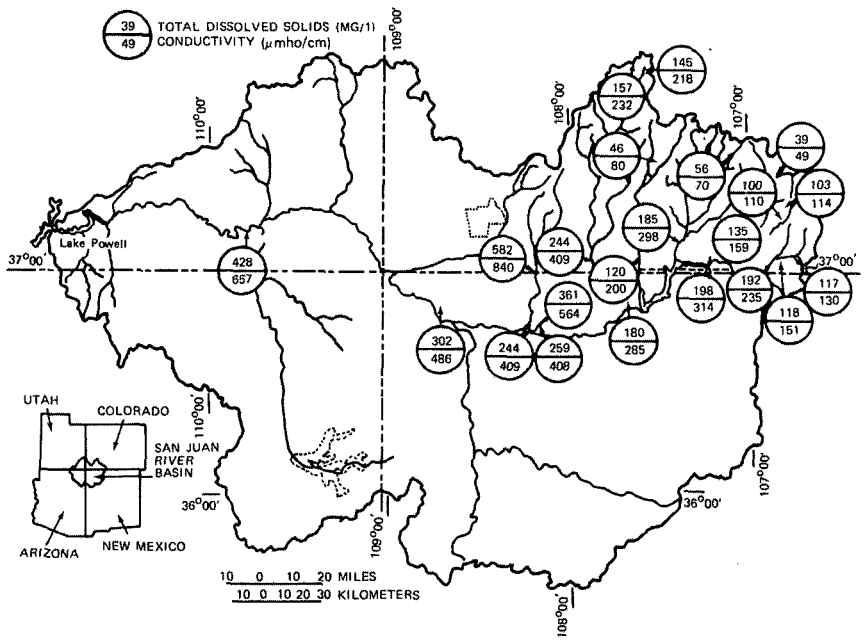

FIGURE 3—*Mean total dissolved solids (mg/liter) and conductivity (μm ho/cm) U.S. Geological Survey sampling stations in the San Juan River Basin*

DETERIORATING WATER

One example of deteriorating water quality can be observed in the San Juan River Basin in the Four Corners Region of Colorado, Utah, Arizona, and New Mexico (figure 3). Total dissolved solids and conductivity values significantly increase as the San Juan and its tributary waters proceed toward Lake Powell. The specific composition of the dissolved solids varies with local geology as well as the flow, although the same general trend is apparent. A detailed discussion of the energy-related source contributors as well as a treatment of the implications of the consumptive and nonconsumptive water use are contained in the Energy Impact Assessment Report on the San Juan Basin which will be distributed in July 1978. Based on the materials presented in the report, the following were concluded:

- Surface water availability in the Basin will limit future growth and development patterns and may impact the development of energy resources.

- Although present water quality is generally good, as availability is reduced water quality in downstream reaches will become a problem. The water quality parameters most likely affected by increased development in the Basin are salinity, toxic substances, suspended sediments, nutrients, temperature, pH, alkalinity, and flow. Organic pollutants from coal gasification plants are of special concern due to the lack of available data regarding both their nature and quantity.

- Secondary development pollution impacts are likely to become the major contributing problem.

- Mercury levels in fish in the Navajo Reservoir are among the highest in the Southwest and probably are due to the mercury-bearing sedimentary rock.

A significant contribution of the Assessment Report is a priority classification of parameters considered effective in monitoring the impact of energy development in the San Juan Basin. Three priority levels were thus established: (1) those which must be monitored, (2) those of major interest, and (3) those of minor interest.

The second in this series of Basin reports, also to be published this year, covers the Tongue and the Powder Rivers in the Northern Great Plains. The Belle Fourche and the Little Missouri River Basins will be covered in the third report.

GROUNDWATER QUALITY

Measuring groundwater quality is quite different. In a sense, this job is easier because sediment is no problem, temperatures remain about the same, biological problems are generally nonexistent, and changes in chemical quality occur very slowly. Moreover, the frequency of sampling groundwater can usually be much less than for streamflows; once or twice a year is usually adequate to detect water-quality changes. On the other hand, the groundwater monitoring job is more difficult because new approaches that have no precedent are being considered for the development and mining of coal and oil shale in the West. Therefore, no experience is available as to the impacts of these new development approaches on groundwater quality. Large-scale, oil-shale development, for example, has never been carried out, making the in situ extraction of oil from shale within the zone of water saturation an event without precedent. Work continues on the engineering aspects of in situ gasification of coal, but little is known about the actual quality of water that reenters the burned-out coal seams and resides there with the elements and compounds that do not escape with the gas.

URANIUM EFFECTS

Little is being done to determine the effects of uranium mining on water-resources systems except on a broad, regional basis. Whether the uranium is extracted by open-pit, shaft, or solution techniques, the primary initial effects, if any, will likely be on groundwater. There is some evaluation underway to detect groundwater quality changes in the vicinity of uranium mines, but the results are not widely disseminated, and the measuring techniques may be inadequate. In the case of solution mining, for example, quantities of fluid injected and withdrawn may be accounted for, and the perimeter of the mine may be measured by sampling from observation wells; but if the groundwater flow system is not well understood, its flux may mask losses of injection fluid to groundwater moving through the mine

area. There is also the potential impact from surface water runoff over spent tailing piles.

ASSESSMENT RESULTS

Results of water-resources assessments of Western energy areas have, thus far, not been particularly revealing. The reason, in the case of oil shale, is simple: there has been no commercial or even prototype development.

With coal, development has not progressed rapidly. Mining has increased, but no gasification or liquefaction plants have been built. Several thermalelectric plants have been or are being built, and their wastes are being measured and evaluated. One such plant, now under construction near Gillette, Wyoming, will utilize both wet and dry cooling to conserve water. Its cooling water will be treated sewage effluent from a nearby town, a progressive and perhaps ultimate goal in water conservation.

A CASE HISTORY

One of the few case histories of water-quality degradation associated with Western coal mining is in North Dakota. Sulfate-laden water is observed migrating downward and laterally from an abandoned water-filled mine pit. The sulfate presumably originated in gypsum that was exposed in the process of mining leonardite. The plume of sulfate now extends more than a mile from the mine and contains up to 6,500 milligrams per liter of sulfate. This mine began operating in 1960, and thus it is unlikely that present-day mining and reclamation practices would permit the recurrence of conditions that led to this problem. Nevertheless, the water-related aspects of other coal-mining operations are being observed and studied. Typically, water produced by mine dewatering is minimal, and its quality

presents no particular problem. A mine in Montana produced about 0.03 cubic meters per second and is allowed to flow into the Tongue River. Overall, its quality is better than that of the river.

WATER-QUALITY MONITORING

Water-quality monitoring in energy regions of the West is being performed largely by federal and state agencies with some local monitoring by coal companies or their consultants. The monitoring activities by industry are, as would be expected, around their developments. There is little doubt that the intensity of water-quality measuring sites will increase as new mines open, the requirements of the Surface Mining and Reclamation Act of 1977 go into effect, and new conversion plants are constructed.

The intensification in monitoring activities has also occurred with respect to air quality in the West. Table 1 shows the number of sulfate-nitrate monitoring stations in Western Energy Resource Development Area (WERDA) by state that were active in 1975 and those either on or expected to be on line this year. The real

TABLE 1
Number of stations (WERDA)

	Sulfate		Nitrate	
	1975	1978 *	1975	1978 *
AZ	56	47	19	17
CO	3	34	2	34
MT	4	15	4	15
NM	1	7	1	7
ND	30	37	30	37
SD	2	7	2	7
UT	5	19	5	19
WY	3	18	3	18
TOTALS:	104	184	66	154

* PROJECTED

MONITORING STATIONS

significance in the increase can be seen in the States of Colorado, Montana, Utah, and Wyoming where only a few stations were operating. Figure 4 shows the total suspended particulate stations. The solid dots show the sulfate-nitrate stations operational during 1976. Again the lack of coverage in the four states is apparent. Figure 5 shows how the newly activated stations are distributed and how the gaps are filled in the areas where energy activities are expected to be at the highest level. Areas with intensified coverage include Mercer County, North Dakota, where by 1986 an approximate 3 gigawatts of electric power will be added; Campbell County, Wyoming, where approximately 25% of western coal will be mined; and the oil shale areas of the Green River Formation and the areas around the Navajo, San Juan and Four Corners Facilities where by 1986 over 5.5 gigawatts of electric power will be generated.

TYPICAL VALUES

Figure 6 shows some typical values encountered, in this case, in the State of Arizona for the first quarter of FY 77. The concentration values for the uninhabited regions in the North are generally low (1-3 $\mu g/m^3$) while in the South—in the vicinity of Phoenix and Tucson where several smelters are in operation—the values are much higher.

AIR QUALITY BASELINE

Another approach to establishing an air quality baseline for this whole area and to studying trends is through the use of airborne monitoring platforms. This becomes increasingly important when the objective is assessing other than local impacts. The long-range transport and transformation studies need data on the 3-dimensional distribution of pollutants. Figure 7 shows a typical plume flight over the Navajo power plant in Northern Arizona. Spirals are performed to determine the vertical plume centerline and then downwind and crosswind passes are made to determine the concentrations of the various pollutant components in the plume. The same types of measurements are made over the large areas as shown in figure 8. This is a typical mission up through the Central Utah power corridor.

AIRCRAFT DATA

Aircraft participating in these types of missions generally carry a broad spectrum of monitoring instrumentation (table 2). In addition to the criteria pollutants (with the exception of carbon monoxide), visibility, condensation nuclei, particle-size distribution, and meteorological data are collected. Wind speed and direction can be calculated from the aircraft position and vectoring data.

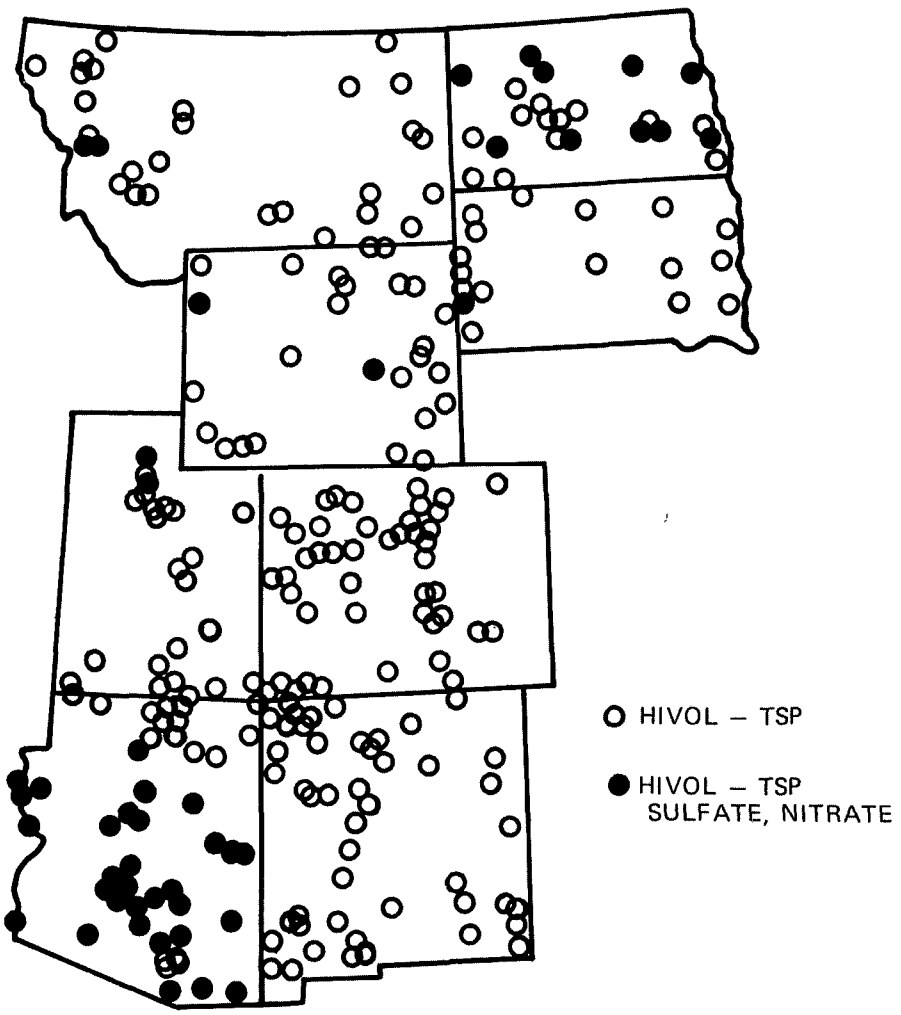

FIGURE 4—*Particulate sampling in WERDA, 1976*

TABLE 2
Instruments installed in the wide area monitoring aircraft

Parameter	Instrument/Method	Typical Operating Range	Minimum Detectable Concentration
Visibility (Scattering)	Integrating Nephelometer	B_{Scat} 0-10 x $10^{-4}m^{-1}$	.2 x $10^{-4}m^{-1}$
Nitric Oxide	Chemiluminescent	0-50 PPB	1 PPB
Ozone	Chemiluminescent	0-500 PPB 0-1000 PPB	5 PPB 8 PPB
Sulfur Dioxide	Pulsed Fluorescence	0-500 PPB	2 PPB
Temperature		———	———
Dewpoint		-50°C to +50°C	———
Altitude (Pressure)		———	———
Position	DME/VOR	———	Accurate To Within .1 NM
Hydrocarbons		———	———
Condensation Nuclei	Automatic Cloud Chamber	300 10^7 particle/cm^3	———
Particulate Size Distribution	Two Stage Impactor And Final Filter	Stage 1 Greater Than 3.6 μm Stage 2 Greater Than 0.65 μm After Filter Greater Than 0.1 μm	———

TRACE ELEMENT ANALYSIS

A modified Sierra cascade/impactor is used to collect the aerosol data in three size fractions as shown at the bottom of the table. These fractions are subsequently subjected to trace element analyses which yield results as shown on table 3 for the wide area monitoring flights through Arizona and Utah. Note that for these missions the observed concentrations are very low and, assuming the accuracy of the cutoffs, that most of the activity for sulfur is associated with particles between 0.65 and 3.6 μm, while for silica most of the activity is associated with particles between 0.1 and 0.65 μm in diameter.

Other characterizations of aerosol particulates over several different geographical and geologic regions are also being conducted to provide clues as to the origin and the formation mechanism of the particles. Scanning electron microscopy and X-ray energy dispersive analyses are applied to materials collected on Nucleopore filters for these studies.

AEROSOL PARAMETERS

In particular, aerosol parameters that are being observed and their potential effects investigated are as follows:

- *Particle size* which helps to determine the effectiveness of an aerosol to scatter light and to nucleate cloud drops.
- *Particle shape* which indicates the mechanism by which the aerosol has been formed. Sphere are almost exclusively formed by a mechanism that includes a phase transition.

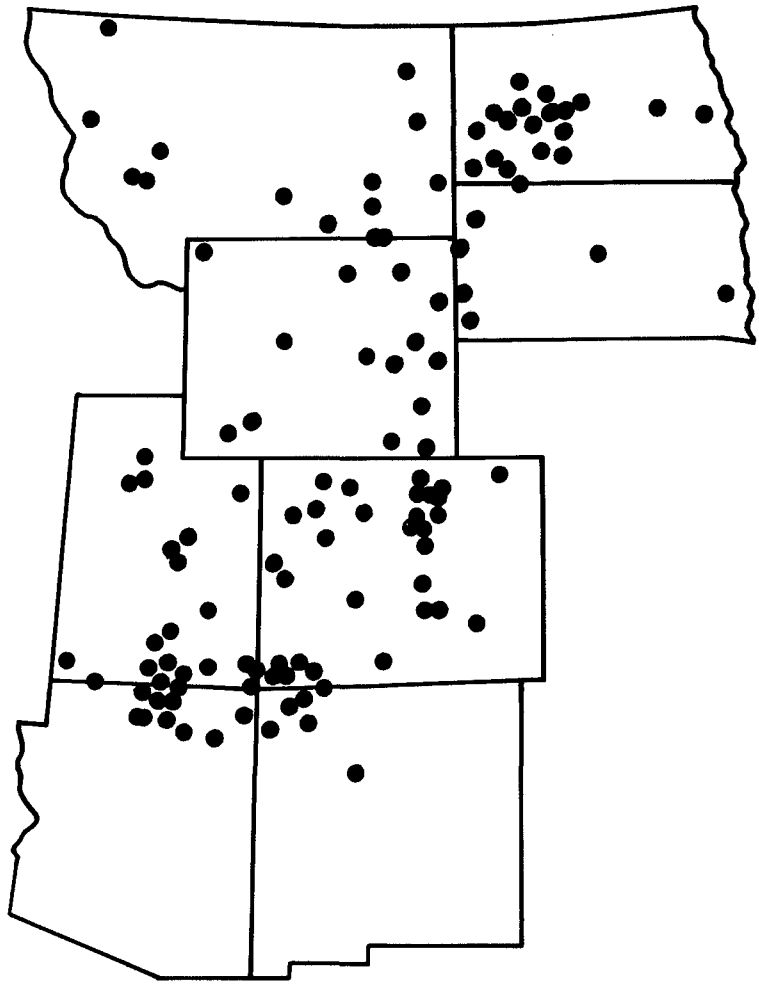

FIGURE 5—*New sulfate-nitrate monitoring sites*

TABLE 3
Trace element analysis

Element	Concentration ($\mu g/m^3$)	Stage (Most Mass)
AL	0.2 0.4	1
SI	0.2 10	3
S	0.05 0.2	2
CL	1.5 3	3
K	0.1 1	3
CA	0.02 0.2	1 & 2
TI	0.02 0.08	1 & 2
FE	0.04 0.2	1 & 2
P	0.06 0.2	1 & 2 ONLY

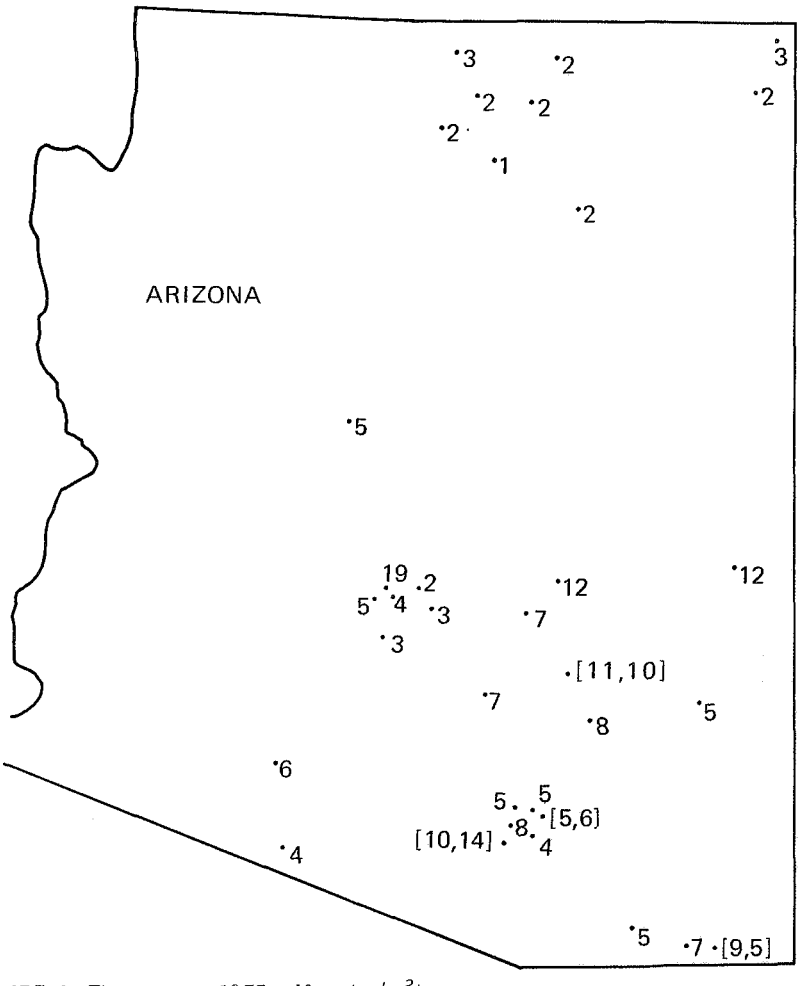

FIGURE 6–*First quarter 1977 sulfate ($\mu g/m^3$)*

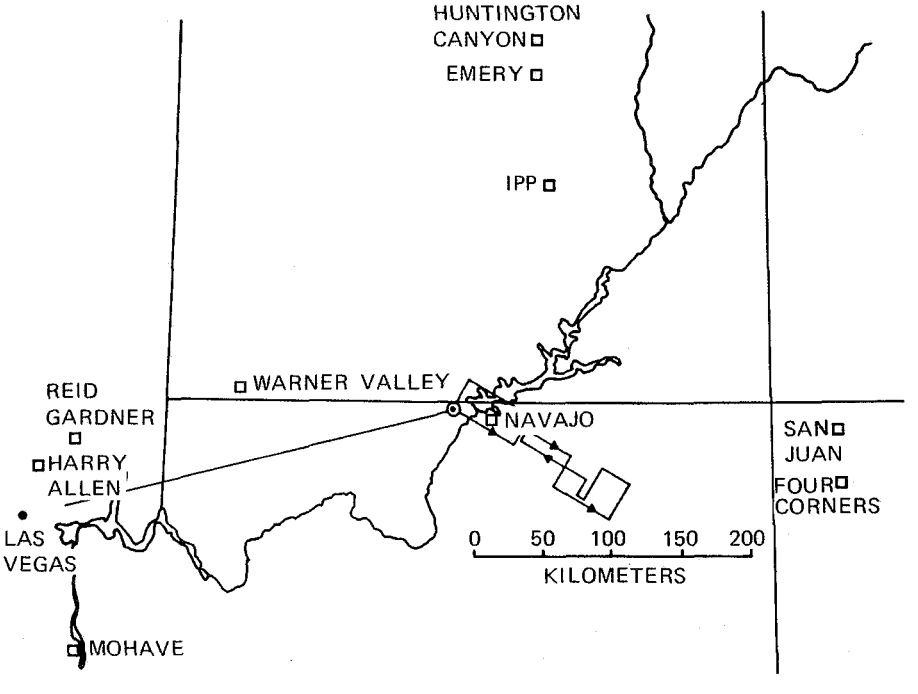

FIGURE 7–*Typical plume flight*

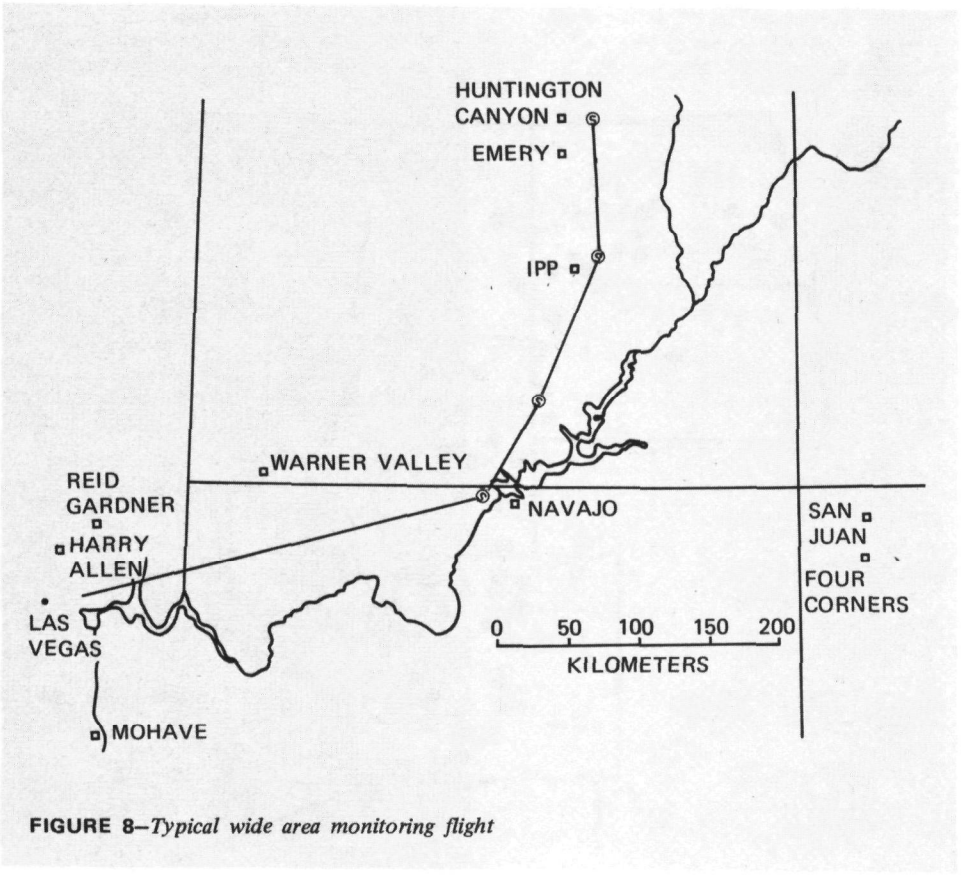

FIGURE 8—*Typical wide area monitoring flight*

FIGURE 9—*Four Corners power plant plume*

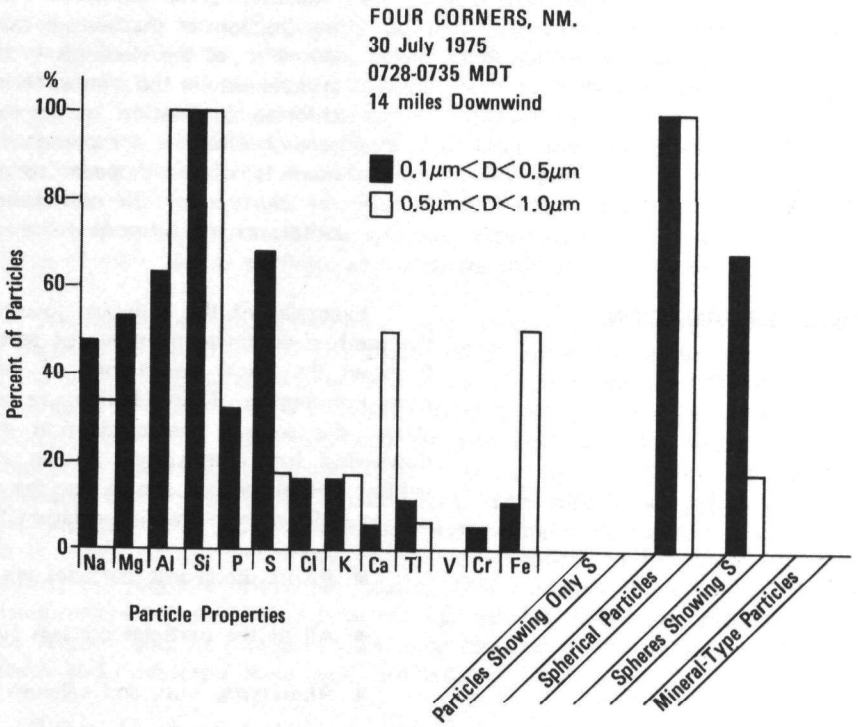

FIGURE 10—*Aerosol characteristics of the Four Corners power plant plume*

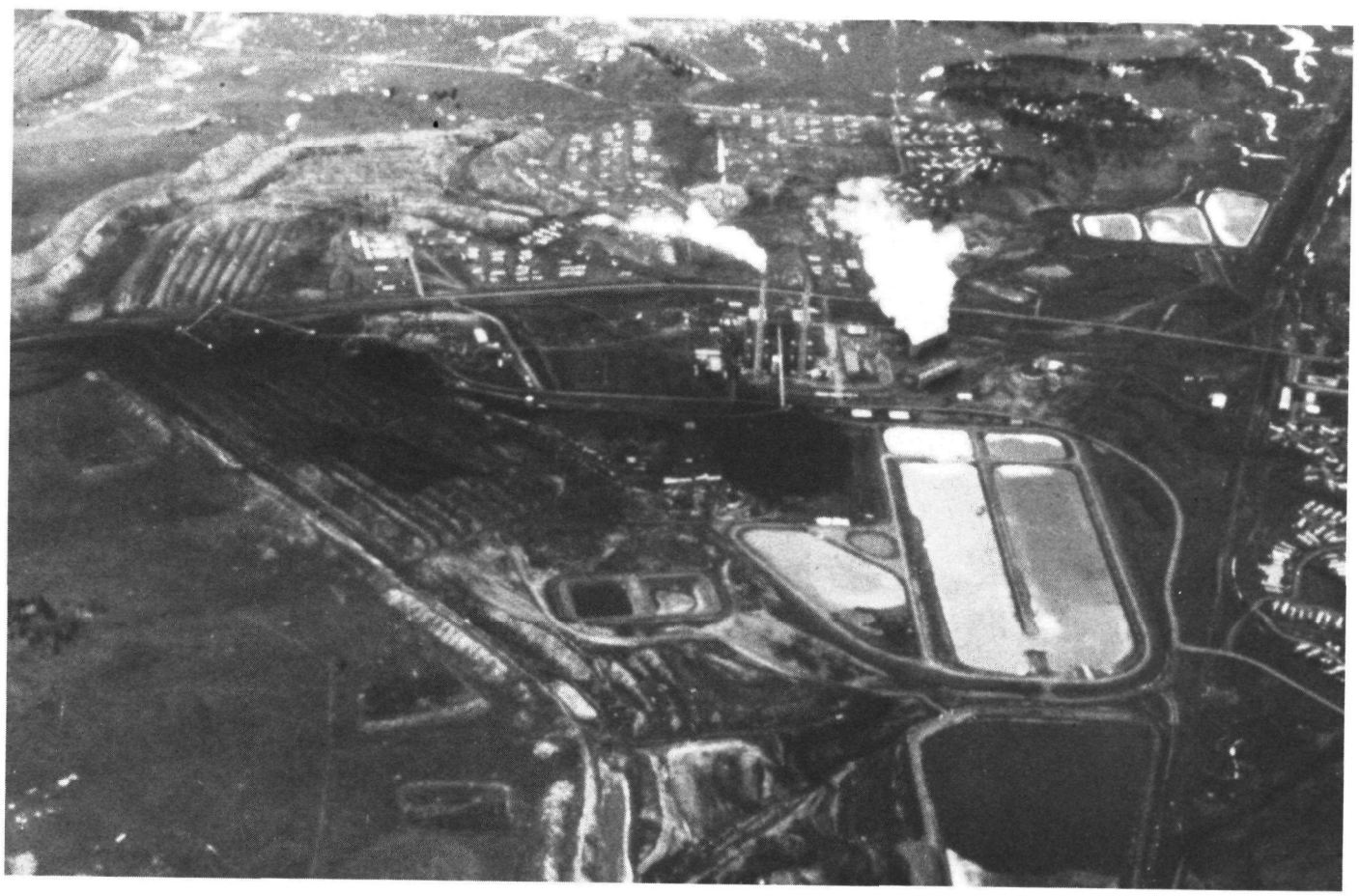

FIGURE 11—*Colstrip power plant plume*

- *Elemental composition of the particles* which provides information on (1) the portion of the aerosol that is mineral-derived, based on a comparison of the ratio of the elements in the particle to that in the earth's curst; (2) the enrichment in the atmospheric aerosol of certain elements, e.g., lead sulfur, chlorine, in relation to the earth's crust; (3) the portion of the atmospheric aerosol that is composed of elements lighter than sodium due to the inability of the detector to measure the X-rays of these elements, and (4) the portion of the atmospheric aerosol that is made up of ammonium sulfate as the ammonium ion is not detectable.

AEROSOL INFORMATION

Examples of the types of information that can be gained from application of the method to different types of aerosols are shown in the next few figures. Figure 9 shows the visual appearance of the plume from the Four Corners Power Plant near Farmington, New Mexico, to a distance of about 13 kilometers. Figure 10 shows the aerosol characterization of a sample that was collected 22 kilometers downwind from the stacks. Shown are the percentage of particles by number that exhibit the properties shown for the diameter ranges 0.1 to 0.5 μm and 0.5 to 1.0 μm. It follows from this information that:

- All of the plume particles are spheres.
- All of the particles contain silicon.
- Aluminum, iron, and calcium dominate in the larger aerosol range size.
- Sulfur dominates in the smaller aerosol size range and all of the sulfur is associated with siliceous types of materials.

SULFUR CONCENTRATION

This suggests that ammonium sulfates are virtually not detectable in this plume at this particular distance from the stacks. A more thorough analysis of the sulfur concentration as a function of particle diameter shows that sulfur is deposited on the surface of the siliceous flyash aerosol.

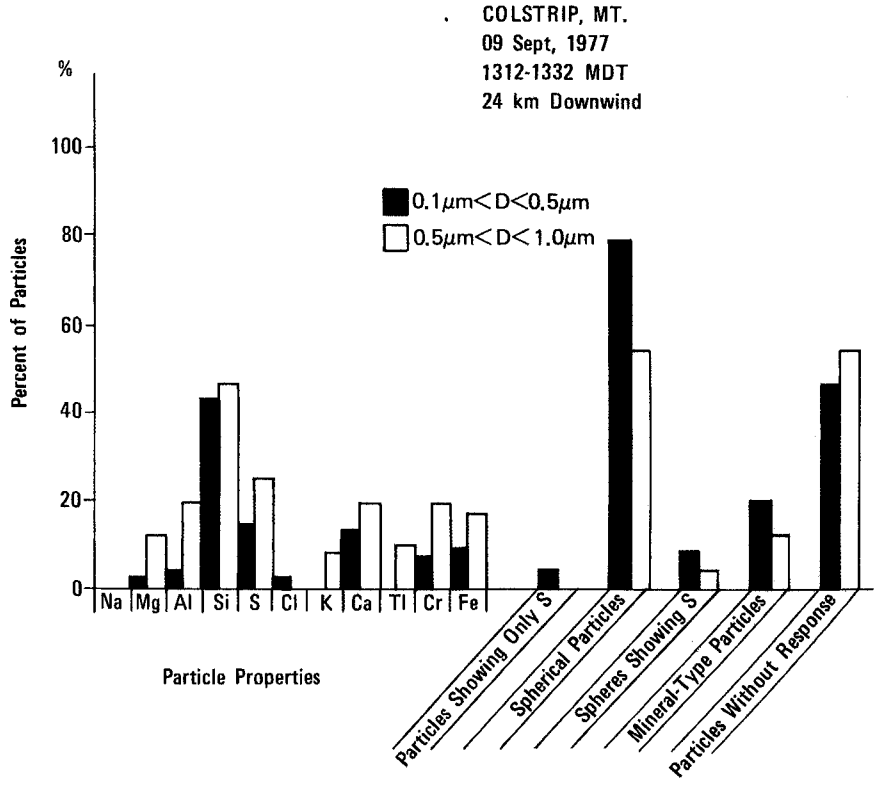

FIGURE 12—*Aerosol characteristics of Colstrip power plant plume*

COLSTRIP PLUME

More recently constructed power plants with more efficient particulate (flyash) emission controls have significantly different characteristics of the plume aerosol. A portion of the Colstrip, Montana, power plant plume is shown in figure 11. It can be seen that the plume appears invisible even at a short distance from the stacks. The aerosol characteristics of a sample collected at 22 km downwind from the Colstrip stacks are shown on figure 12. While the aerosol is still dominated by spheres, their number concentration is smaller than for the Four Corners Power Plant plume. Chemically, they consist of about equal parts of siliceous materials and non-emitting species, or particles without response. A small portion of the aerosol consists of mineral-type particles and particles that emit only sulfur.

A NATIONAL GOAL

The particulate characterization data which I have been discussing were only for particles in the 0.1 to 1 μm decade of diameter. These are the particles which are the most efficient at causing visibility degradation. Section 128 of the Clean Air Act Amendments of 1977, PL 95-95, declared as a national goal the prevention of visibility impairment from manmade air pollution and the restoration of natural visibility in federally designated Class I areas. In the section on Prevention of Significant Deterioration, the Amendments also specify allowable increments for Total Suspended Particulates (TSP) and sulfur dioxide increases. It appears, however, that it may not be technically possible or practical to use these increments for achieving the required optical air quality. It is necessary, therefore, to describe both a measurement scheme and a standard for visibility based on objective criteria. For these reasons and to establish a visibility baseline for the western region, visibility research and monitoring have been initiated.

AEROSOL CHARACTERISTICS CEDAR MOUNTAIN

Figure 13 shows one of the vistas from Cedar Mountain in east-central Utah which eventually will be affected by local energy development activities. Figure 14 shows the aerosol characteristics that were found for that site in December 1976, on a day when the average visibility was 193 km. It can be seen that the aerosol is again dominated by spherical particles, particularly in the size range from 0.1 μm to 0.5 μm. Between 30% and 50% of the particles contain sulfur, depending on the size range. Approximately 30% of the particles show sulfur only, which is typical of ammonium sulfate particles. The mineral-type particles amount to about 20%. Approximately 60% of the smaller particles don't show X-ray emissions and are made up of ammonium nitrates and/or organic matter.

FIGURE 13—*Vista to the south from Cedar Mountain, Utah*

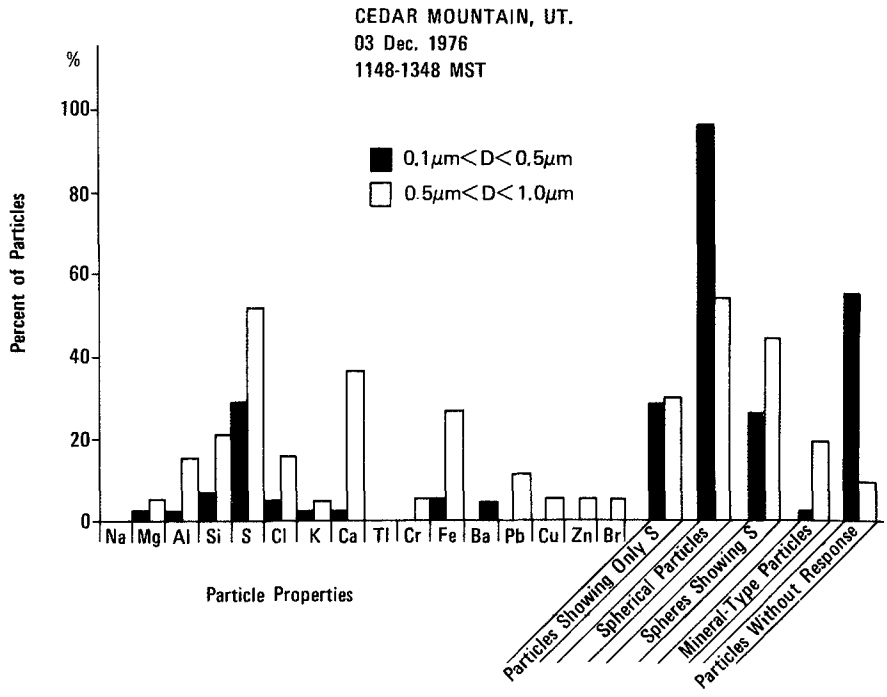

FIGURE 14—*Aerosol characteristics (193 km visibility)*

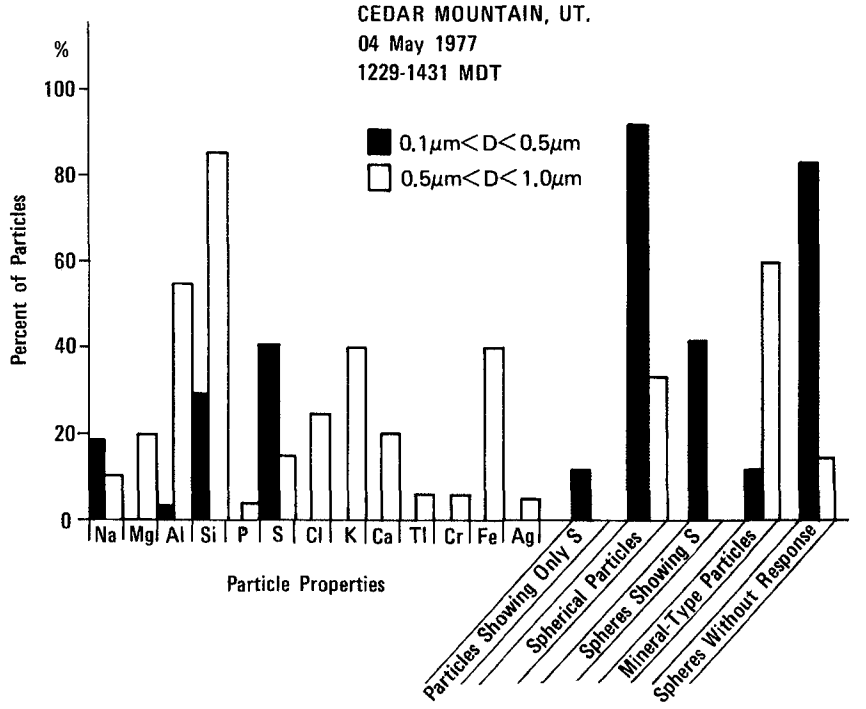

FIGURE 15—*Aerosol characteristics (95 km visibility)*

SILICEOUS AEROSOL INCREASE

May 3, 1977, was a day on which the average daily visibility was only 95 km. The aerosol characteristics that were found on a sample collected on this day are shown on figure 15. Compared to the information on figure 14, it is noted that the portion of the sulfur aerosol, which almost unequivocally, based on Eastern data, is held responsible for environmental degradation, has not increased within the optically important size range from 0.1 to 1.0 μm diameter. Increased, however, is the siliceous portion of the aerosol, which is also reflected in the increase of the mineral-type particles. There is also a noticeable increase in the non-emitting portion of the aerosol.

VISIBILITY MEASUREMENTS

The visibility measurements made at Cedar Mountain were based on a photographic technique, i.e., photographing a distant mountain range against the horizon sky. A measurement of the contrast ratio of the film densities of the target and the sky is then used to calculate visual range. Figure 16 shows the results of visibility measurements made at a research station located at Canyonlands National Park which is to the south and east of Cedar Mountain. These data are from an integrating nephelometer and are based on light scattered from the particulates. It is a point rather than a long path measurement, but again shows the consistent long visual ranges typical in this area of the West, which over this period of measurements, were generally over 170 km.

Correlations between these types of light scattering measurements and several other classes of visibility monitoring techniques will be conducted at the Canyonlands Station. Transmissometers, telephotometers, and cameras will also be used, and measurements of wind speed and direction, particle size distributions and trace element analyses will also be performed.

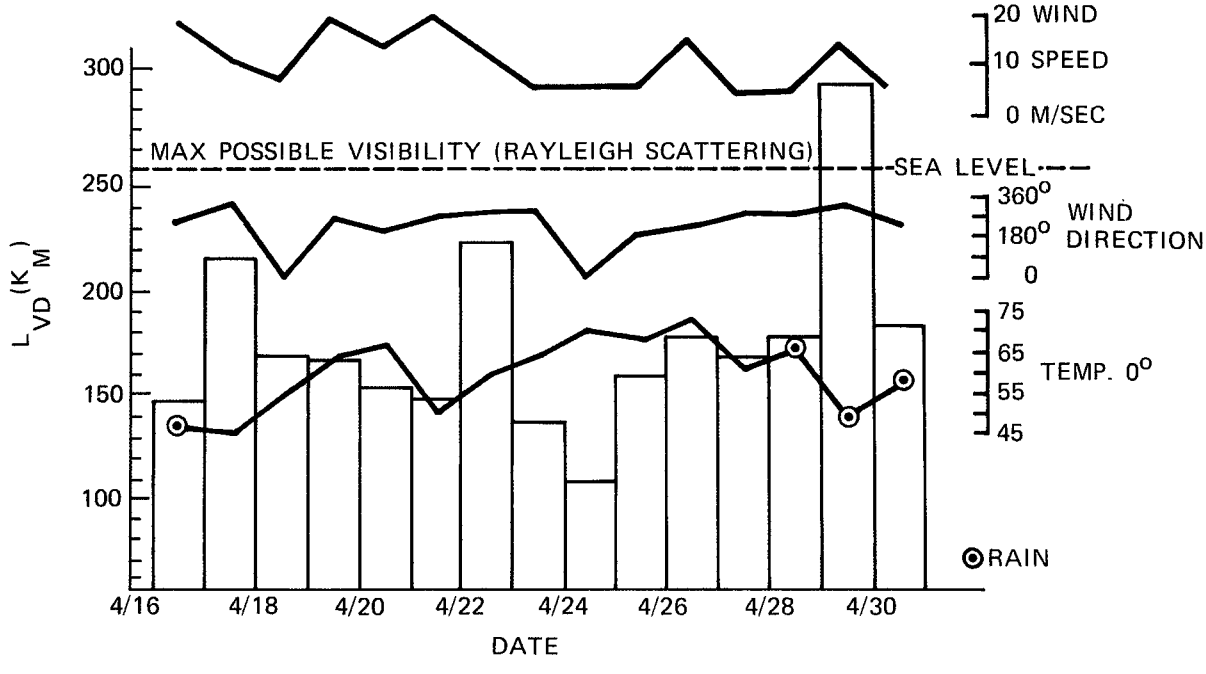

FIGURE 16—*Visibility—Canyonlands National Park, Utah*

INITIAL SYSTEM ESTABLISHED

Finally, an initial system of seven visibility monitoring stations is currently being established in the Four Corners Region of Utah, Arizona, New Mexico and Colorado. This area was chosen because of its unusually good visibility, its grand vistas and its expected rapid growth in energy resource development activities. Multiwavelength contrast telephotometers, which measure the brightness of distant objects and their background sky, will be sited at National Parks as shown as circles on figure 17. The second group of seven stations noted as squares will result from an agreement between the EPA and the National Park Service currently being finalized.

SUMMATION

In summation, only the status of environmental quality assessment in the Western Energy Resource Development Area can be described in precise terms. The objectives of the research and monitoring programs, however, are highly specific, and the results are beginning to provide significant baseline data and clues as to the mechanisms and cause-effect relationships associated with energy-related pollution.

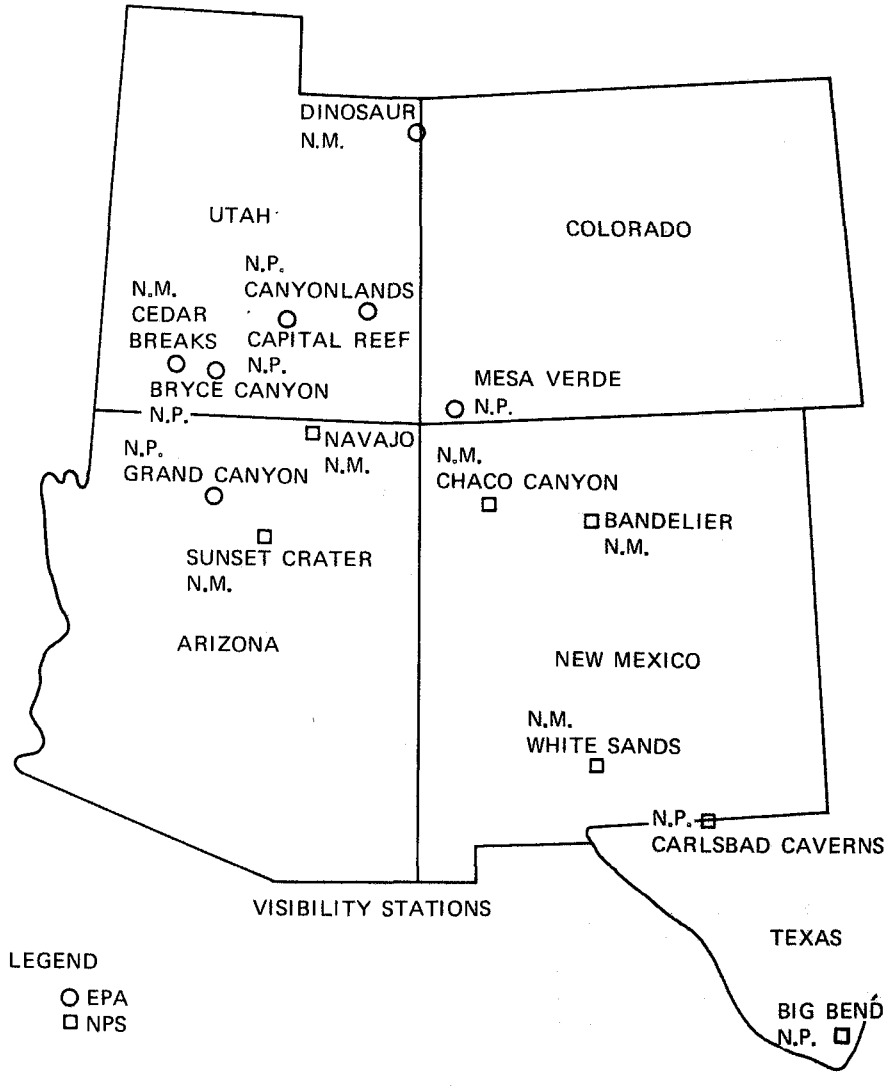

FIGURE 17—*Visibility monitoring network*

THE ECOLOGICAL EFFECTS OF ATMOSPHERIC DEPOSITION

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U.S. Department of Agriculture

ECOLOGICAL EFFECTS OF ATMOSPHERIC DEPOSITION

The United States National Energy Plan calls for an increased use of combustion of fossil fuels for the indefinite future. This will cause an increase in atmospheric emissions of some or all of the precursors of acid precipitation even if best available control technology (BACT) is implemented on new sources and old sources are retrofit with BACT. This is due to the conversion of natural gas and, perhaps, fuel oil installations to coal. Because of the long distance transport phenomena and associated atmospheric chemical transformations of acid deposition precursors, the use of very tall stacks will probably not ameliorate the deposition of acidic substances at great distances (on the order of 100 km or more downwind) from major sources.

Although the problem of acidic atmospheric deposition is largely an eastern United States problem, there is increasing evidence that parts of the west and southwest may also be impacted.

EAST AND WEST U.S. AFFECTED

Precipitation in much of the west is lower in acidity than in the east. Local deposition of acid substance may neutralize excess alkalinity in some western soils. Long-distance transport and deposition, however, will increase deposition of acid substances in both the eastern and western states.

In the western United States there is increasing evidence that acidic precipitation exists both in the vicinity of major point sources and in and near large urban areas. In Pasadena, California, measured values of pH in rainfall during portions of 1976 and 1977 show a range of 2.7 to 5.4 with a weighted mean value of 3.9 (Morgan pers. comm.). This is a pattern of acidity that is commonplace in

the eastern United States. In the San Francisco region, pH of rainfall has frequently been measured (McColl, Likens, pers. comm.), and the indication is that it is below the CO_2 *equilibrium value of* 5.7. *McColl's data show that* 80 percent of the samples taken have a measured pH of less than 5.2 with a range of 4.8 to 5.6 and a mean pH of 4.9. Acidic precipitation likewise has been measured in the Seattle-Tacoma area at distances from the major SO_2 sources at the Tacoma Smelter and nearby refineries.

SULFUR AND NITROGEN REMOVAL

Sulfur and nitrogen compounds are removed from the atmosphere by two processes: a) dry deposition including the absorption of gases on exposed surfaces and the sedimentation and impaction of particulates and b) wet deposition in which sulfur and nitrogen compounds are frequently deposited as acids. Acidity of precipitation should be understood as a reflection not only of the amounts of sulfuric, nitric, hydrochloric, and organic acids in the atmosphere, but also of the balance between all the cations and anions dissolved in precipitation. Some of these ions are beneficial mineral nutrients; others are injurious to plants and animals.

DRY AND WET DEPOSITION

Dry deposition is a continuous process depending mainly on the concentration of sulfur oxides near the ground, the yearly amounts deposited generally decreasing with increasing distance from the source. Wet deposition is much more variable and is dependent both on the pattern of precipitation and on the burden of sulfur and nitrogen compounds within the mixing layer. Deposition can be substantial in areas exposed to precipitation from air which has passed large emission sources. In cold climates, air pollutants deposited during the winter may accumulate in the snow pack. When snow melts, much of the pollutant load is released in concentrated form with the first melt water. This release may lead to sudden increases of acidity in watercourses and also to some extent in the soil.

Recent reviews of available data (1, 2, 3, 6) indicate that precipitation in a large region of the United States is highly acidic when compared with the expected pH value of 5.7 for pure rainwater (5,9). Figure 1 shows that the average pH of precipitation in the northwestern United States was routinely less than 4.7 in the mid-1960's. It has been further shown, by the change in the position of pH isopleths between 1955-56 and 1972-73 (figure 2), that acid precipitation has spread southward and westward in the United States (1,6). More recent information indicates that in this area, pH values between 3.0 and 4.0 are observed during individual storms (3).

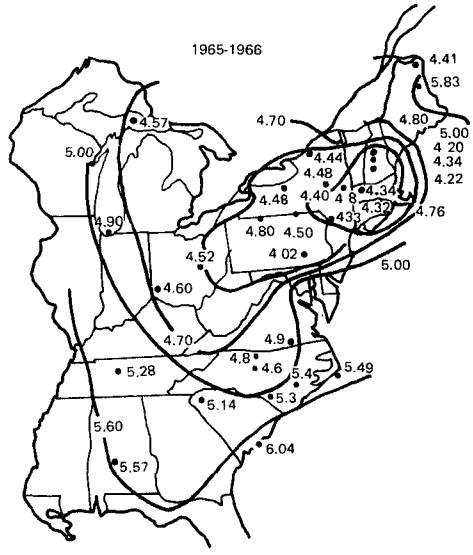

FIGURE 1—*Predicted pH of precipitation, 1965-1966, Cogbill and Likens (1974)*

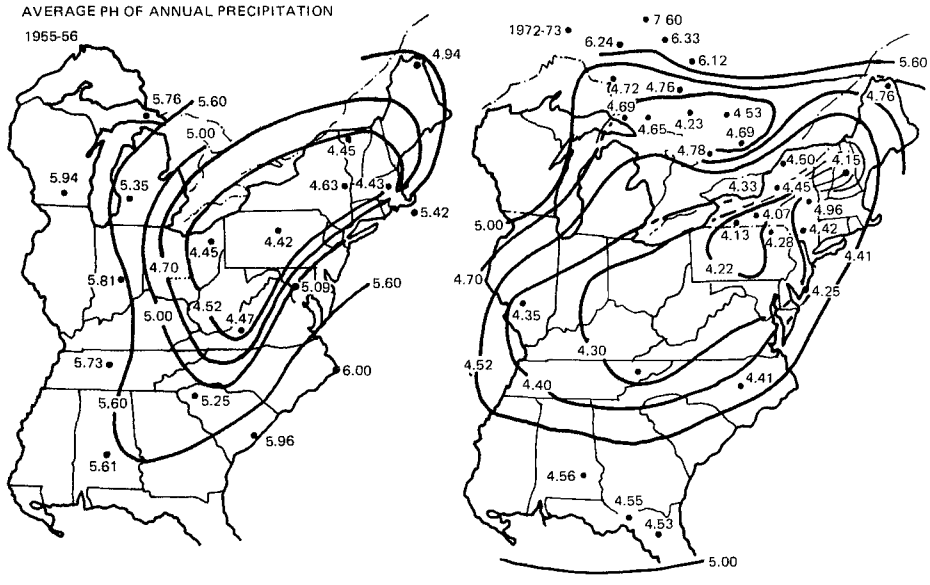

FIGURE 2—*Time source of change in pH of precipitation from 1955-1956 to 1972-1973 in the northeastern United States, Likens (1976)*

Although the historical record on changes in acidity of precipitation is sparse, there are definite indications that precipitation in the eastern United States was already acid by 1955 and that the acidity of rain and snow there increased significantly sometime between 1930 and 1950 (6).

DAMAGE FROM ACID RAIN

A growing body of evidence suggests that acid rain is responsible for substantial adverse effects on the public welfare. Such effects include acidification of lakes, rivers, and groundwaters, with resultant damage to fish and other components of aquatic ecosystems; acidification and demineralization of soils; reduction of forest productivity; damage to crops; and deterioration of manmade materials (7,12,27). These effects may be cumulative or result from peak acidity episodes (8).

NORTHWEST EUROPE AFFECTED

A similar drop in the pH of precipitation has been observed in Scandinavia (9,27,28). A network showed that since the mid-1950's, precipitation in northwestern Europe had increased in acidity and that this acidity was currently more widespread geographically. The hydrogen-ion concentration of precipitation in some parts of Scandinavia has increased more than 200-fold during the past two decades (10). Data from New York State and New England indicate that about 60 to 70 percent of the acidity is due to sulfuric acid, 30 percent to 40 percent is due to nitric acid, and that the relative importance of nitric acid has increased during the last 10 years. These strong acids are thought to stem primarily from gaseous, manmade pollutants such as sulfur dioxide and nitrogen oxides produced primarily by the combustion of fossil fuels. Hydrochloric acid predominates in local acid rain events in Florida which originate from exhaust byproducts from space launches (11,12).

EMISSION SOURCES

Emission sources for sulfur dioxide and nitrogen oxides are widely distributed within and outside of urban centers. Contributions can come from both lower and

higher height stacks and from near ground level sources. Sulfates including acid sulfates are present in the stack gases associated with coal-fired and oil-fired sources. The amounts of sulfuric acid and other sulfates found in plumes can be sufficient to effect plume opacity and fallout of acid particles near the source. In plumes from elevated sources, lack of contact with the ground tends to preserve precursors for some distance downwind. Especially at night and in the early morning hours, ground-based inversions can isolate the plume aloft so near-source deposition is minimized (13).

URBAN PLUME CONTENT

The urban plume already contains the organics sulfur dioxide and nitrogen oxide, precursors to sulfates and nitrates (14). Photochemical atmospheric reactions can form sulfates and nitrates relatively rapidly as the urban plume progresses downwind. However, during periods of effective photochemical activity urban plumes will tend to be well mixed to the ground. Therefore, dry deposition processes are competing with atmospheric reactions as sinks for the sulfur dioxide and nitrogen dioxide (13). At the present time, it is generally considered that in this country, acid precipitation is most severe in the northeast. However, there is some evidence for impact in the western United States, at least in major urban areas such as Los Angeles, San Francisco, and Seattle. Further, recent data show the geographic extent of the problem to be increasing in the southeast, with all states east of the Mississippi affected to some degree (6).

Freshwater bodies in many areas of eastern North America and northern Europe, which today lie in and adjacent to the areas where precipitation is most acid, are threatened by the continued deposition and further expansion of acid precipitation. Many of these bodies of freshwater occur in regions underlaid by carbonate-poor granitic rock, and are poorly buffered and vulnerable to acid inputs (15). A major number of the lakes in Scandinavia fall within this category. The acidification of thousands of lakes and rivers in southern Norway and Sweden during the past two decades has resulted in the decline of various species of fish, particularly trout and salmon (16,27). The fish populations in rivers and lakes in 20 percent of the area of southern Norway have been affected by increasing acidity (11,27).

FISH DECLINE

Similar effects have been observed in the Adirondack Mountains in New York. A recent survey found that 51 percent of mountain lakes have pH values below 5.0; 90 percent of these lakes contain no fish. In contrast, during the period 1927-37, only 4 percent of these lakes had a pH under 5.0 or were devoid of fish (11).

Other evidence indicates that not only are fish affected by acidification, but that a variety of other aquatic organisms in the food web are adversely altered (16,17,18,27). In general, algal communities in lakes with pH under 6.0 contain fewer species, with a shift toward more acid-tolerant forms. In particular, the Chlorophyceae (green algae) are reduced in acid lakes (10,27). Some acid lakes and streams contain greater amounts of benthic moss *(Sphagnum)* and attached algae, and the growth of rooted plants is reduced (12,18,19). There is a tendency toward fewer species of aquatic invertebrates both in the water column and in sediments in acid lakes and streams (10). The rate of decomposition of organic matter is reduced, with bacteria becoming less dominant relative to fungi. Swedish workers have observed thick fungal felts over large areas of sediments in some acidified lakes. They concluded that decreased decomposition of organic matter on the bottom of lakes, coupled with greater abundance of submerged mosses and fungal mats, reduces nutrient cycling from the sediments. This in turn leads to depletion of nutrients and reduced productivity in acid lakes (11,20).

LAKE-WATER CHEMISTRY

Acid precipitation also causes other changes in lake-water chemistry as well (21,27). Elevated concentration of aluminum, manganese, zinc, cadmium, lead, copper, and nickel have frequently been observed in acidified lakes (22). The abnormally high concentrations are apparently due in part to direct deposition with precipitation as well as increased release (solubility) from the sediments in acidified lakes (23). These metals may represent a major phvsiological stress for various aquatic organisms (11,22,24).

In recent years, concern has been expressed that forest growth appears to have been affected far away from emission sources. The rate of forest growth declined in southern Scandinavia and in the northeastern United States between 1950 and 1970, but it is not possible to state unequivocally that this decline is caused by acid precipitation (25).

ACID PRECIPITATION DAMAGE

Terrestrial ecosystems are very complex, with numerous living and non-living components. Since acid precipitation is only one of many environmental stresses, its impact may enhance, be enhanced by, or be overwhelmed by other factors. Recent experiments indicate that acid precipitation can damage foliage; accelerate cuticular erosion; alter responses to associated pathogens, symbionts, and saprophytes; affect the germination of conifer and hardwood seeds and the establishment of seedlings; affect the availability of nitrogen in the soil; decrease soil respiration; and increase leaching of nutrient ions from the soil (25).

Although many of these factors might be expected to adversely affect tree growth, it has not yet been possible to demonstrate unambiguously decreased tree growth in the field. However, it is possible that acid damage might have been partly offset by the nutrient input gained from nitrogen or sulfur compounds commonly occurring in acid precipitation. Changes already detected in soil processes and soil nutrient status may as yet be too small to affect plant growth.

Forests are complex. It has been shown that the nature of throughfall (rainfall reaching the forest floor after passing through the crown canopy) and stemflow (rainfall reaching the forest floor by draining down the trunks of trees) is affected differently by different tree species. Thus the composition of precipitation reaching soil, possibly affecting soil processes and transfers to freshwater systems, could be influenced by the nature of the tree cover (11,12,25,26).

MATERIALS

The deposition of acidic species may cause effects not only to natural ecosystems, but to manmade materials as well. Such damage to metals, paints, statuary, and other objects can affect the quality of life as well as result in substantial replacement costs. Sulfur oxides, nitrogen oxides, and particulate matter emitted by coal-burning facilities are known to damage materials (7,11,13).

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ECOLOGICAL EFFECTS OF COAL-FIRED STEAM-ELECTRIC GENERATING STATIONS

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UNDERSTANDING EFFECTS

President Carter's National Energy Plan, presented to Congress in the fall of 1977, recommended an 80-percent increase in the use of coal for electricity generation. If implemented, such an increase will lead to the construction of many more coal-fired generating facilities to meet forecasted higher demands for electricity. Thus, a complete understanding of the effects of such facilities on their surroundings is critical to the agencies responsible for planning these facilities. The research program developed by EPA to meet this need in determining the ecological impacts of increased fossil-fuel utilization is in the third year of a 5-year plan. A holistic approach was taken in the design of the program and projects were funded in three major areas: mining, transportation and storage, and combustion of coal. Work in each of these areas has progressed to the point where there is a need to integrate and generalize the findings and to translate the information into a form that can be used by the appropriate agencies.

COLUMBIA STUDY

In the area of coal combustion, a multidisciplinary research project based at the University of Wisconsin has contributed significantly to meeting these needs. The research, at the Columbia Coal-Fired Generating Station near Portage, Wisconsin, has been funded by the Wisconsin Power & Light Co., Madison Gas & Electric, the Wisconsin Public Service Corporation, Wisconsin Public Service Commission, and the U.S. Environmental Protection Agency. Since 1970 this study has been monitoring the effects a particular generating station in one location has on the environment before construction, during construction, and after operation has begun. Equally important, this integrated research program has tested methods of impact assessment that can serve as models for research at other sites. Thirty-one technical reports will summarize results of all the research, and will include as a part of the final product a definitive evaluation of siting problems for facilities in other locations. A list of these reports is given in the bibliography, items 1-31, with their expected completion date.

In 1969, several Wisconsin electric power companies applied to the Wisconsin Public Service Commission for permission to construct a 527-megawatt coal burning power plant in east central Wisconsin. At the time, information on the environmental impacts of generating stations was practically non-existent.

NEED FOR INFORMATION

The need for such information led Professor Dan Willard and associates at the Institute for Environmental Studies of the University of Wisconsin, Madison, to propose a study to measure the impact of the proposed power plant. Their goal was to assess the effect of the plant on all aspects of the environment—water, wildlife, plants, air, and aesthetics. With support from three utility companies—Wisconsin Power and Light Company, Madison Gas and Electric Company, and the Wisconsin Public Service Corporation—they began studies of the site characteristics before construction was started. These studies were continued during the construction and early operation of the plant from January 1971 until July 1975.

In July 1975, the Environmental Research Laboratory, Duluth, recognized the unique research opportunity that existed at the site and the national importance of the findings and awarded the investigators a 3-year grant (R803971) to continue and expand the research. The project is now at the close of its third year and currently involves over 100 persons in 24 research areas.

IMPACTS—EXTRAORDINARILY COMPLEX

Evidence so far is that the impacts are extraordinarily complex. They range from an increase in waterfowl in the degraded sedge meadow (15) and small increases in air pollutants (3,5) to significant shifts in land use patterns—agricultural to residential (31).

TABLE 1
Organization of the Columbia coal-fired generating station study

I. Studies of Chemical Constituents and Their Fates
  1. Chemical Related Studies
    (a) Aquatic Chemistry
    (b) Trace Elements
    (c) Plume Chemistry and Isotope Tracers
    (d) Hazardous Chemicals in Fish
  2. Chemical Transport Mechanisms
    (a) Air Pollution Modeling
    (b) Meteorology
    (c) Hydrogeology
    (d) Water Use Analysis
  3. Synthesis
    (a) Mass Flow and Balance of Water, Air, and Chemicals

II. Assessment of Biological Effects of Project Integration
  1. Aquatic Systems
    (a) Aquatic Invertebrates
    (b) Fish
    (c) Assessment of a Cooling Lake Ecosystem
    (d) Wetland Ecology
    (e) Remote Sensing
  2. Terrestrial Systems
    (a) Plant Damage
    (b) Visual Changes

III. Integration of All Components
  1. Data Center
  2. Assessment and Synthesis of Impact
  3. Administration

IV. Siting Criteria

TWO AREAS OF STUDY

To bring coherence to a study made up of so many subprojects, often overlapping in subject areas, required careful organization and reorganization by university researchers and close attention by the EPA Project Officer, G. E. Glass. The research design that evolved in 1977 consisted of two major areas of study (table 1): 1) studies of chemical constituents and their fates and 2) assessment of biological effects. An additional area, siting criteria, addressed broader implications of the results.

Within the area of chemical studies, one group of investigators has worked on identifying and measuring the chemicals that result from the combustion of coal, whereas others investigated the means by which these chemicals are transported after combustion. In addition, a synthesis group has used systems modeling to describe the major flows and balances of water, air, and chemicals through the system.

The studies assessing biological effects were further subdivided into aquatic and terrestrial systems (table 1). The study group, Assessment and Synthesis, has used special techniques to integrate the data from all biological studies.

SEPARATE SUBPROGRAM ON SITING

A separate subprogram on siting criteria was designed to incorporate results from all of the site studies into a generalized step-by-step method for assessing available energy options and procedures on how to select the best site that would be applicable in any location.

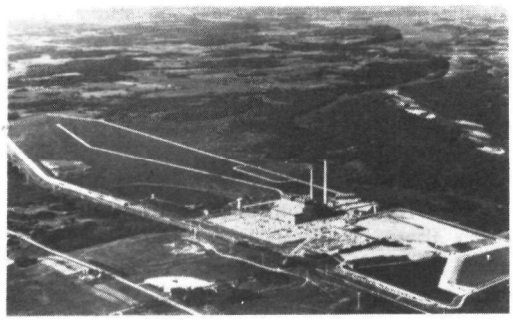
This report is a cursory review of some of the findings to date with examples of the methods being used and the implications of the answers for future construction of coal-fired generating stations.

Burning coal to produce electricity releases chemicals into the air, soil, and water around a generating station. Thus the studies of chemical components included a multitude of organic and inorganic compounds; their constituents and fates cover a broad range of air, land, and water environments. The Columbia plant unit one (527 MW) burns about 5,000 tons per day of low-sulfur, pulverized coal from Colstrip, Montana, with a typical ash content of 7 to 8 percent. The high energy electrostatic precipitators installed to reduce particulate emissions collect approximately 98 percent of this flyash residue and discharge it into an ash pond adjacent to the plant. Smaller particulate matter is released into the air. The gaseous combustion compounds are discharged into the atmosphere through a 500 foot stack. Figure 1 shows a photograph and diagram of the plant, ash basin, cooling lake, and proximity of the Wisconsin River.

Construction of the first unit began in 1971 utilizing an artificial lake for cooling water. The cooling lake was filled in 1974 and the first power generation began in late 1975. Before the first plant was complete, however, the utilities announced plans for a second unit on the same site, doubling the size of the facility. The Wisconsin DNR required that the stack for the second unit be 650 feet in height. In addition, cooling towers were required to accommodate the summer discharge of waste heat from the second unit so that the cooling water intake temperature was below 40° C. The water level of the cooling lake is maintained by pumping freshwater in from the Wisconsin River.

ASH PIT DRAIN

From the coal handling and storage area east of the cooling lake (figure 1), coal enters the plant and is burned. Ash is washed and trucked from the ash hoppers (using some water from the cooling water flow) and enters the ash basin as a slurry. Water entering the ash basin flows through a series of lagoons that allow the ash to settle out; the water is then pumped down the ash pit drain and combines with the water of Rocky Run Creek. Since this creek supports desirable aquatic life including trout and other game species during the spawning season, the effects of the ash pit drain on water quality and aquatic life of the stream are being studied (10,11).



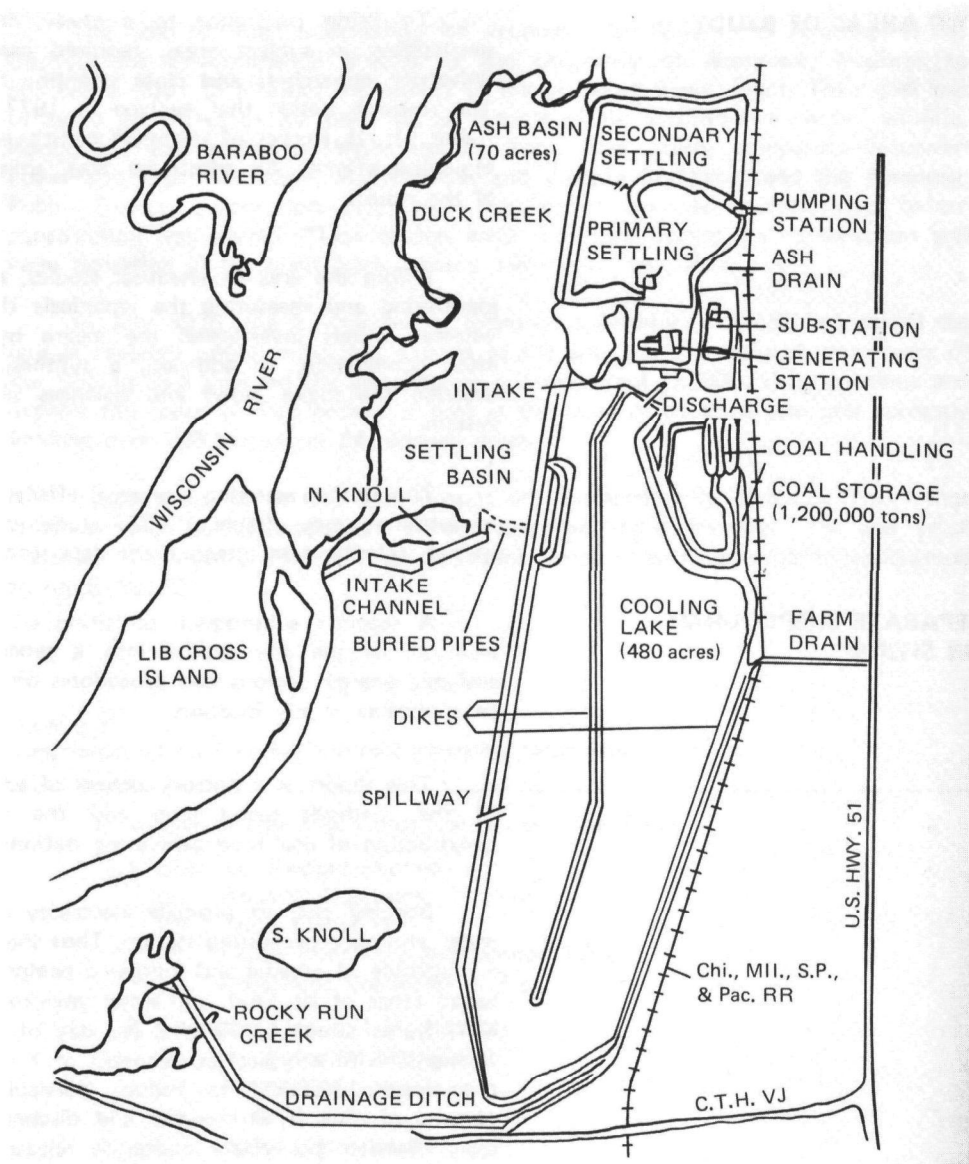


FIGURE 1—*Photograph and diagram of the Columbia Generating Station located near Portage, Wisconsin*

MOVEMENT OF CHEMICAL COMPONENTS

In order to trace the flow of potential pollutants through the facility, the movement of water must be traced through the system. As the replenishment water from the Wisconsin River moves into the cooling lake and through the power plant, some of it is taken out to transport ash into the ash basin. Also, the materials from coal combustion and plant operations which do not end up as emissions from the stack move with this water into the ash basin. In figure 2, the water concentrations of some of the principal constituents (e.g., iron, aluminum, copper, chromium, and cadmium) change as water moves through the generating station (1,3). Concentrations in the ash delta, where most of the ash settles, show that there has not been enough time for chemical equilibrium to form in the slurry. By the time the ash and water reach the first settling basin, most of the concentrations have risen markedly. Other constituents of the water also have been shown to increase from input to discharge, such as sulfate, 12 to 180; calcium, 30 to 70; chloride, 5 to 10; all in mg/liter. Peak concentrations of these materials occur in the second settling basin. It is from this basin that the ash basin drainage water is pumped into the ash basin drain.

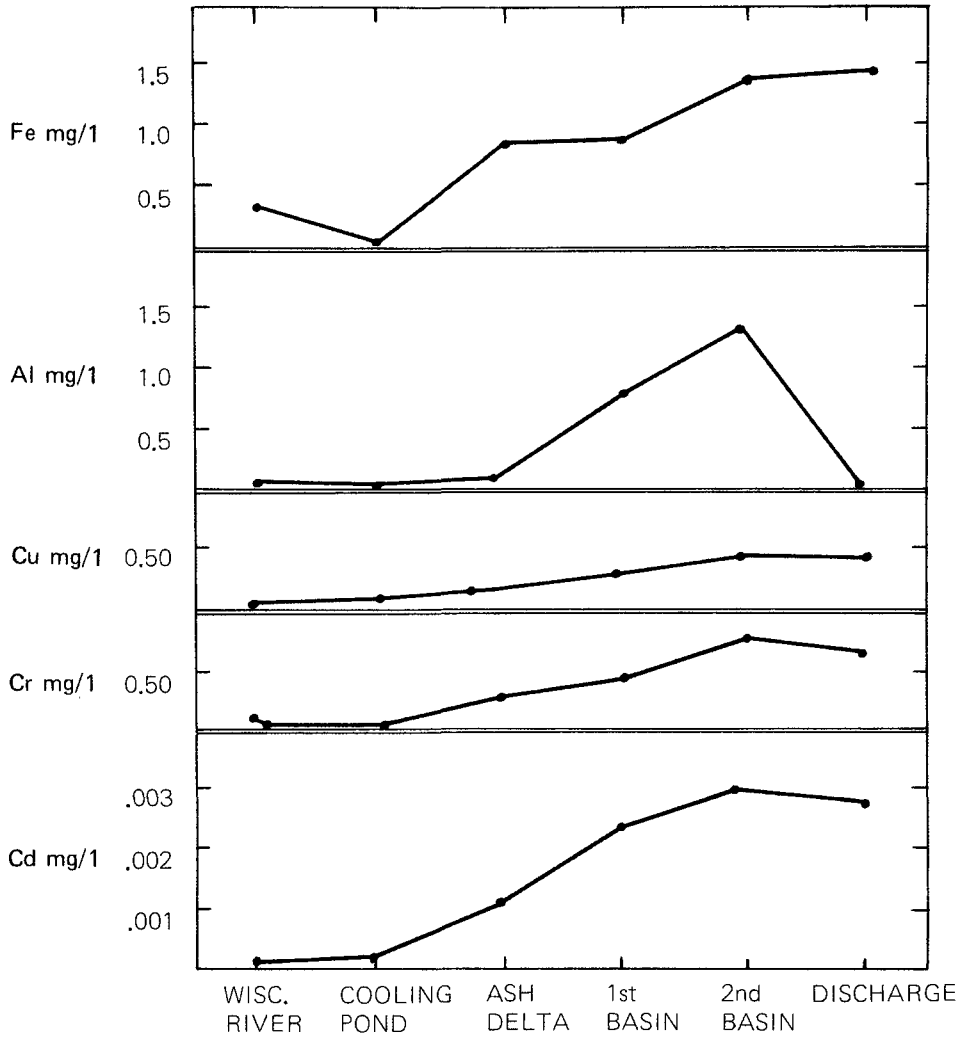


FIGURE 2—*Soluble metal concentrations at various stations on the Columbia Generating Station*

ASH BASIN CHEMISTRY

The chemistry of the ash basin is exceedingly complex and has been studied in detail (1,3). Figure 3 shows scanning electron micrographs of flyash and ash basin solids and weathering products; bars indicate size in units of micrometers. Figure 3A shows typical flyash spherical morphology and examples of hollow flyash grains. Magnification is 1,000 times. Figure 3B shows a large flyash grain coated with abundant small grains of flyash and condensed phases. The surface material is readily removed by water and is reactive. Figure 3C shows crystals of sodium sulfate, Na_2SO_4, in the form thenardite as a condensed phase inside a hollow grain of flyash. These crystals are common in fresh flyash from the Columbia Generating Station and are the source of soluble sulfate in the ash basin drain (3). Figure 3D shows a smaller flyash grain with surface coatings. In the ash basin weathering or leaching of flyash initially produces small pits, indicating selective dissolution of components; (figure 3E, magnification 4,500 times). Other grains of flyash weather by spallation of surface rinds, producing small flakes of material (3).

NEW SOLID PHASES

New solid phases are formed in the ash basin as this aqueous system approaches equilibrium. Figure 3F shows an example of cancrinite, $Na_3Ca[CO_3(OH)_2]Si_3Al_3)_{12}$, a mineral formed by the weathering of flyash in the ash basin (3).

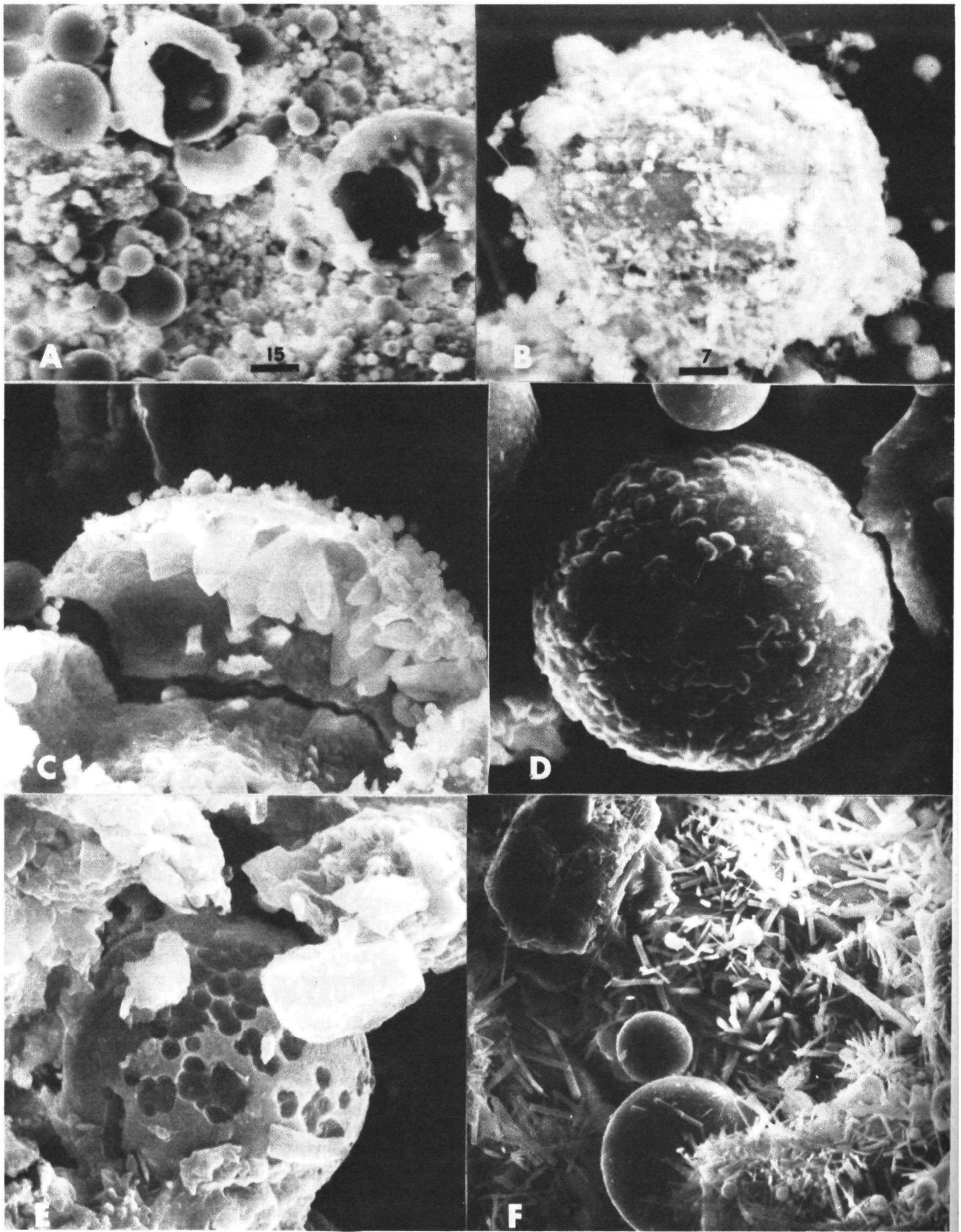


FIGURE 3—*Scanning electron micrographs of flyash and ash basin solids from the Columbia Generating Station. Bars indicate scale in units of micrometers. A, an example showing typical flyash spherical morphology and hollow flyash grains; B, a large flyash grain coated with small grains and condensed phases; C, crystals of thenardite, Na_2SO_4, condensed as a solid phase inside a hollow grain of fresh flyash; D, a small flyash grain showing surface coatings (32); E, a weathered flyash grain showing pits where selective leaching has occurred; F, an example of cancrinite, a mineral formed by weathering of flyash.*

HIGH PH LEVEL

The metal oxides which compose the major reactive portions of the ash cause the pH of the water to rise to 10-11 units. Since standards in Wisconsin prohibit the release of water at a pH above eight, sulfuric acid is added to the ash basin drain to bring the pH down. This addition of acid causes the precipitation of barium and aluminum components. The resultant flock coats the bottom of the ash basin drain and produces a suspended solids addition to Rocky Run Creek. However, by the same standards, the ash basin drainage is of better water quality than some of the surface water running off Wisconsin agricultural lands.

DEGRADATION OF BENTHIC COMMUNITY

The flock of this complex mixture of aluminum and barium has accumulated all the way down into Rocky Run Creek, and although it may not be toxic in its own right, it is not a suitable habitat for benthic organisms to feed and grow in. As a result, there has been a slow degradation of the benthic community for the fishery downstream.

Table 2 lists the concentrations of metals in the ash basin in comparison to laboratory derived water quality criteria, which if exceeded, may become toxic to aquatic life (24). The levels of these six elements are a cause for continued concern and evaluation. Chromium has been shown to bioaccumulate in the aquatic organisms of the ash basin drain but no substantial evidence has yet emerged indicating toxicity (10,11).

TABLE 2
Comparison of ash basin metal concentrations with water quality criteria

Element	Concentration in Excess Possibly Toxic to Aquatic Life	Range Observed in Ash Basin
	Milligrams per liter	Milligrams per Liter
Al	0.1	0.02–52.6
As	0.5	0.006–0.216
B	0.22	0.1–6.4
Cd	0.0001	0.0001–0.004
Cr	0.1	0.066–0.142
Cu	0.01	0.01–0.028

MASS FLOW OF METALS

The mass flow of these elements through the ash basin is obtained by multiplying the flow of water by the concentrations in the water. Unfortunately, this is not a trivial calculation because of the complex pathways, volumes, and uncertainties inherent in the actual operation of a 527-MW steam-electric power plant. There is some loss into the groundwater under the ash pit, and therefore further flow of some soluble portions out of the ash basin. Table 3 shows the annual quantities of the various elements which come into the Columbia Generating Station in the coal and flow into the ash basin and out the stack. For example, of the 678 kg of arsenic, 554 kg go into the ash basin; and of the 145 kg of cadmium, 54 kg enter the ash basin; whereas of the 28 kg of mercury only a trace enters the ash basin because it is volatized and leaves via the stack. About two-thirds of the zinc is left in the ash basin.

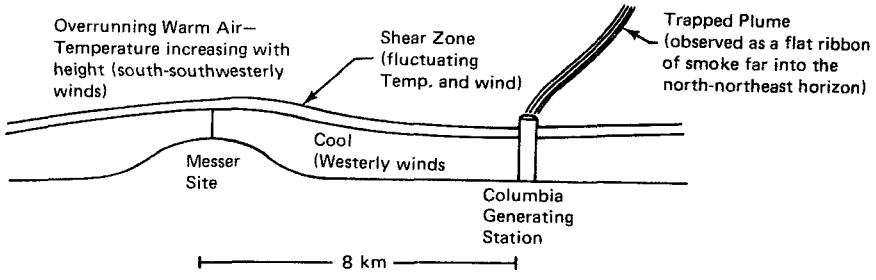
CONTINUOUS MONITORING REQUIRED

At the present time, such information exists for 40 elements and work is being completed on an additional 25. One of the most difficult aspects to this approach is caused by the variation over the year in coal composition. Although the coal comes from one source, the variability of the minor and trace components is not uniform enough for computations of total mass balance over periods of an entire year. Continuous monitoring is required for accurate computations.

TABLE 3
Partitioning of selected annual elemental flows at the Columbia Generating Station during 1975*

Element	Flow Into CGS (kg)	Total Flow Into Ashpit (kg)	Flow-Out Stack (kg)
As	678 ± 39	554 ± 43	120 ± 60
Cd	145 ± 53	54 ± 8	91 ± 54
Cr	5,920 ± 660	2,250 ± 129	3,670 ± 670
Cu	5,460 ± 200	3,460 ± 43	2,000 ± 200
Fe	465,000 ± 15,100	Essent. all	Trace
Hg	27.6 ± 2.6	Trace	Essentially all
Mn	57,500 ± 790	47,200 ± 431	10,300 ± 900
Na	98,700 ± 2,600	Essent. all	Trace
Se	494 ± 46	145 ± 9	349 ± 47
Th	2,170 ± 70	1,220 ± 43	950 ± 80
Zn	5,030 ± 70	2,920 ± 137	2,110 ± 150

* Partitioning rates of stack test of September 5, 1975, assumed to be valid for all of 1975. Inflow rates from a 1974 analysis of Colstrip coal.



Schematic of the frontal system, 20 January 1976 PM

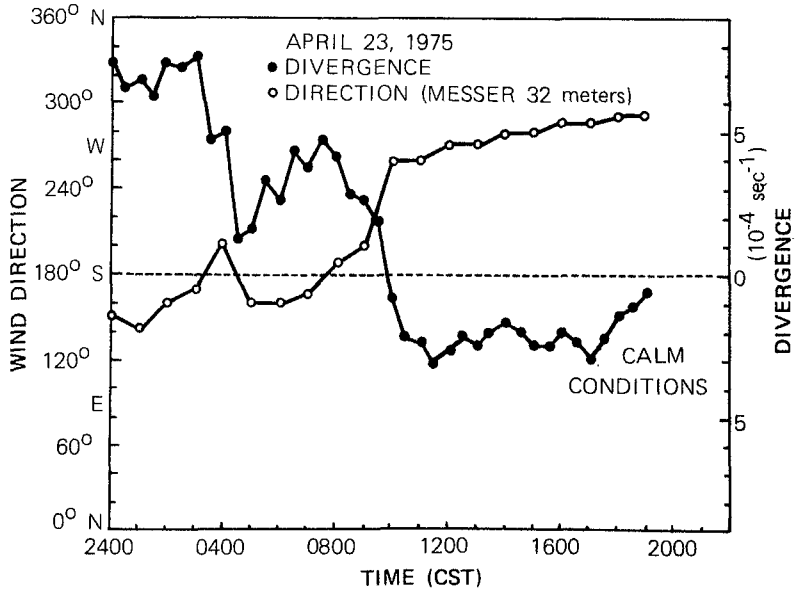


FIGURE 4—*Measured and observed plume divergence (23 April 1975) and frontal surface schematic (20 January 1976 p.m.) at the Columbia Generating Station study area 2*

STUDY OF PLUME FLOW

In examining the movement of components out of the stack, the transport medium is in a gaseous state and requires knowledge of the meteorology of the conditions around the stack to determine transport and deposition. Detailed meteorological studies have been made in a complete network around the stack (6). Analysis of this data gives fairly accurate reflections of conditions where the plume exists, rather than of ground level where a low inversion can cause a change in wind direction near the ground. A complete study of the plume flow is necessary in order to compute the mass balance and deposition of gaseous and particulate emissions.

As an example of the complexity of air dispersal in relation to monitoring, figure 4 shows a period of about 7 or 8 hours and gives the angle of divergence between wind speeds in the vicinity of the plant, and wind speeds at the top of the adjacent hill. The dots are the angle of divergence and the squares show wind direction at the top of the hill. If measurements were made at a ground station, there could be as much as 100 degrees of difference in wind direction compared to a station at the stack height.

SULFUR DIOXIDE MONITORING

One of the major gaseous components of interest is sulfur dioxide. Sulfur dioxide monitoring data has been collected for a series of locations, in all directions from the stack. These results, in a before and after form, are summarized in table 4. A complicating aspect in the monitoring of sulfur dioxide concentrations is that it takes place against a variable background. The background, even in this area, was not uniform because communities in the region generated plumes that were just as recognizable as the power plant plume itself. A community of 200 people in the wintertime generates a reasonably well-defined sulfur plume that moves across the landscape. The city of Madison, which if 40 miles away, also generates a plume, and these have to be recognized and taken out of the background data before sulfur dioxide comparisons can be made (24).

TABLE 4
Distribution of hourly ambient SO_2 concentrations at all monitoring sites before and after operation of the Columbia Generating Station

Concentrations Greater Than $\mu g/m^3$	Percentage Time Exceeded	
	Before Columbia Operation (1973–1975)	After Columbia Operation (1976)
10	12.9	15.0
20	6.75	9.17
40	2.03	3.75
60	0.701	1.717
80	0.340	0.856
100	0.166	0.501
120	0.0908	0.3056
140	0.0545	0.1756
160	0.0333	0.1131
180	0.0227	0.0692
200	0.0136	0.0422
220	0.0121	0.0270
240	0.0076	0.0220
260	0.0045	0.0135
280	0.0015	0.0084
300	0.0000	0.0068

PREDICTED AND OBSERVED SO_2 COMPARED

This large data set also has been used to compare the predicted concentrations in the plume from the standard plume model with observed concentrations and their frequencies (figure 5) (5). Point by point comparisons of some of the low concentrations that are fairly frequent, compared with the predicted values, indicate that the modeled values are off by a factor of 2 part of the time. If these data are plotted in a different form, they show that for some of the stability conditions that are handled in plume models, there is really little forecasting capability for accurate plume concentrations. There are eight atmospheric stability classifications (33), or eight types of atmospheric conditions, two of which give reasonably good results when comparing observed sulfur concentrations with the predicted, and six do not. This suggests that further meteorological studies are required to determine what characteristics of atmospheric instabilities are causing the plume concentration to diverge so markedly from what is predicted.

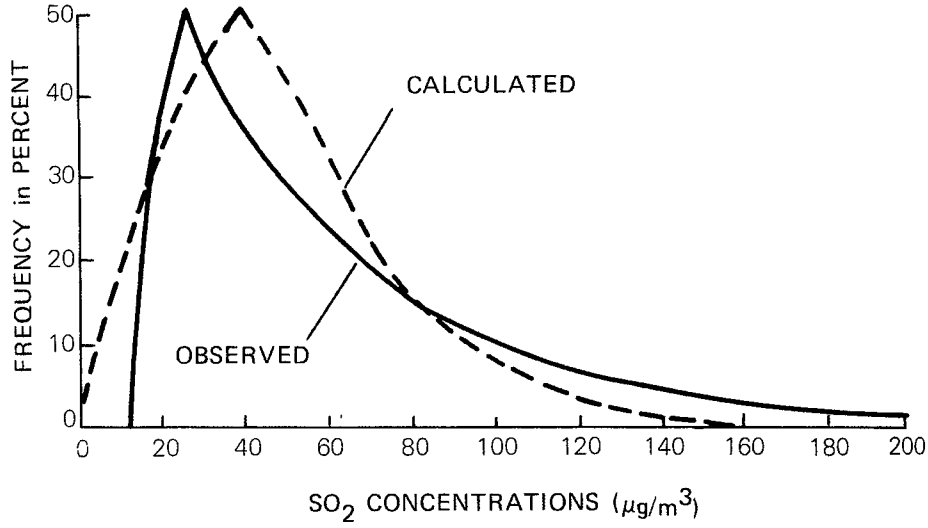


FIGURE 5—*Frequency of occurrence comparison of the calculated (standard plume model) and observed hourly concentrations of sulfur dioxide*

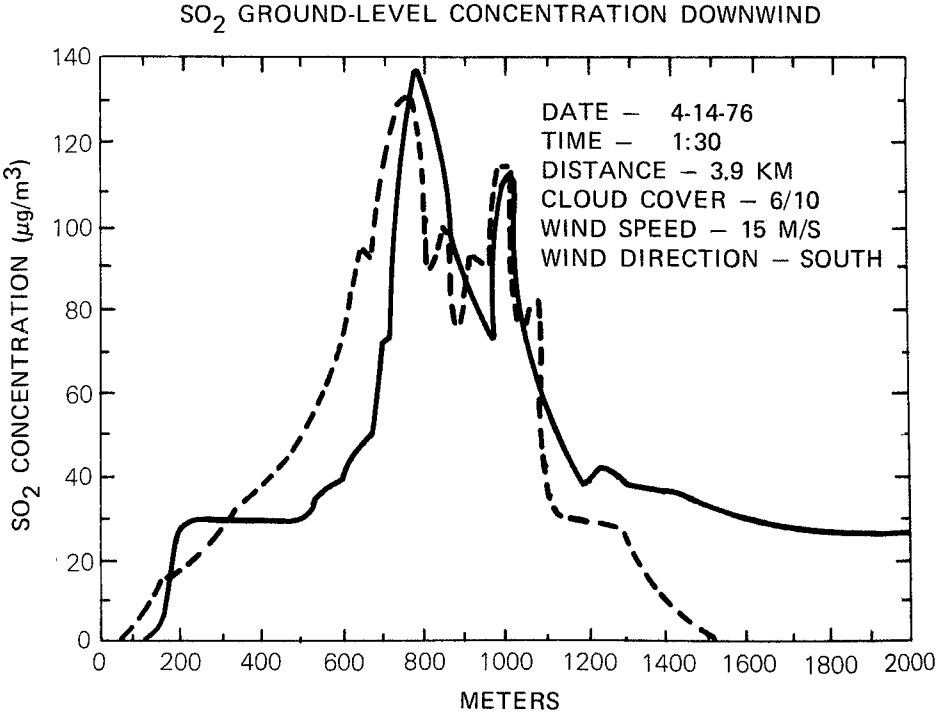


FIGURE 6—*Sulfur dioxide concentrations measured at ground level during plume touch-down; a 2,000 meter cross-section shown 3.9 km from the stack*

SULFUR DISPERSION FROM PLUME

In order to define the dispersion and deposition of pollutants from the plume, field measurements were made in the area by locating the plume on the ground, and then running cross sections through it (5). Figure 6 shows sulfur dioxide concentrations in a 2,000 meter cross section of the plume at ground level taken at 3.9 km from the stack. High concentrations, up to 140 micrograms per cubic meter ($\mu g/m3$), were measured in the center of the plume, with a tailing off on both sides. This indicates that the plume spreads out when contacting the ground, but that there is still a central core to the plume where sulfur dioxide remains at relatively high concentrations. This information is required to determine the dose received in the fumigation of crops, trees, and people living in the area.

The reaction and deposition of reactive gaseous components of the plume at the air-earth interface has been measured and the data for various plume touchdown conditions are shown in figure 7. Data of these kind are being used to develop and validate deposition models for air pollutants.

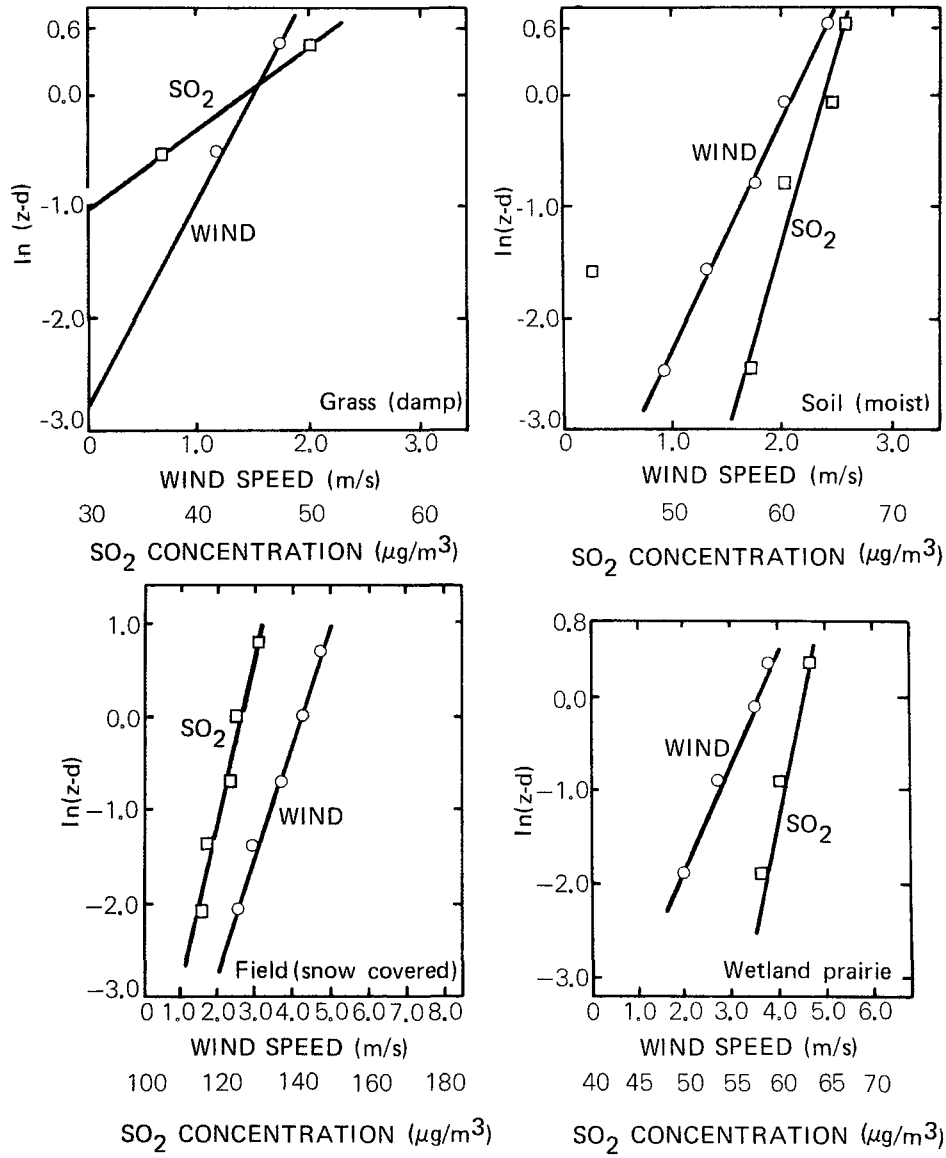


FIGURE 7—*Measured concentration profiles of sulfur dioxide in the plume of Columbia Generating Station over grass, soil, snow, and prairie. Ln(z-d) is the log of the height above the aerodynamic displacement height, d.*

TABLE 5
The flux of flyash into the environment as measured by the content of flyash in the material collected in a fallout bucket. Each collection period was about 30 days ending on the date shown for a site 3.9 km east of the Columbia Generating Station.

Collection Date	Flux of Flyash $mg/m^2/Day$	Total Number of Grains Counted	Percent Flyash	Diameter of Largest Flyash Grain Micrometers	Columbia* Flyash %
Before Operation					
11-17-74	—	1,374	18,2	7	0
12-14-74	0.62	2,671	18.2	13	0
01-13-75	—	2,955	13.4	16	0
02-11-75	0.47	3,617	8.2	9	0
03-13-75	0.32	2,894	12.5	9	0
04-14-75	0.95	1,428	14.5	22	0
After Operation					
05-12-75	0.54	7,974	4.6	19	2
07-07-75	3.16	4,815	31.7	9	83
08-05-75	0.78	3,110	9.4	7	4
09-05-75	0.57	3,447	5.9	4	8
10-06-75	0.54	2,652	6.9	7	5
10-24-75	0.97	2,321	9.0	10	12
11-21-75	0.63	2,291	7.2	9	9
12-19-75	—	2,651	7.1	12	11
01-23-76	0.74	3,392	16.0	14	8

* Differentiation criteria for Columbia flyash versus other flyash: Si $\geqslant$ Al : Si $>>$ Al; Ca $>$ K : K $>$ Ca; S not detected : S present; Na, Mg not detected: Na, Mg present.

FLYASH

In addition to sulfur dispersion, the other component of stack emissions that has been monitored is the flyash, the very small-sized particles that escape the electrostatic precipitator in this system. Initially, these precipitators were operating at 98 percent efficiency, but the addition of sodium carbonate to the coal has increased their efficiency to the required 99.5 percent. The data in table 5 are from operation when it was about 98 percent efficient. Flyash was collected on the ground in buckets at various distances from the power plant (3). In the first column of table 5 is the total flux of flyash in milligrams per square meter per day reaching the ground. By using an electron microscope, differences in shapes of the particulate material can be determined. Dust, which is angular, can be removed as nonflyash and constitutes a fairly substantial proportion. Flyash from other power plants or other sources in the region is pitted from having traveled some distance, and flyash from the local source has a smooth surface. Thus, from the number of grains counted, it is possible to get an indication of the percentage of the total amount of material that is local flyash. Figure 8A shows an example of the material collected in a dust fallout bucket. Spherical grains are flyash and others are soil dust. It appears that of the material coming down, approximately 20 percent is flyash, and of that, 5 percent to 80 percent is of local origin.

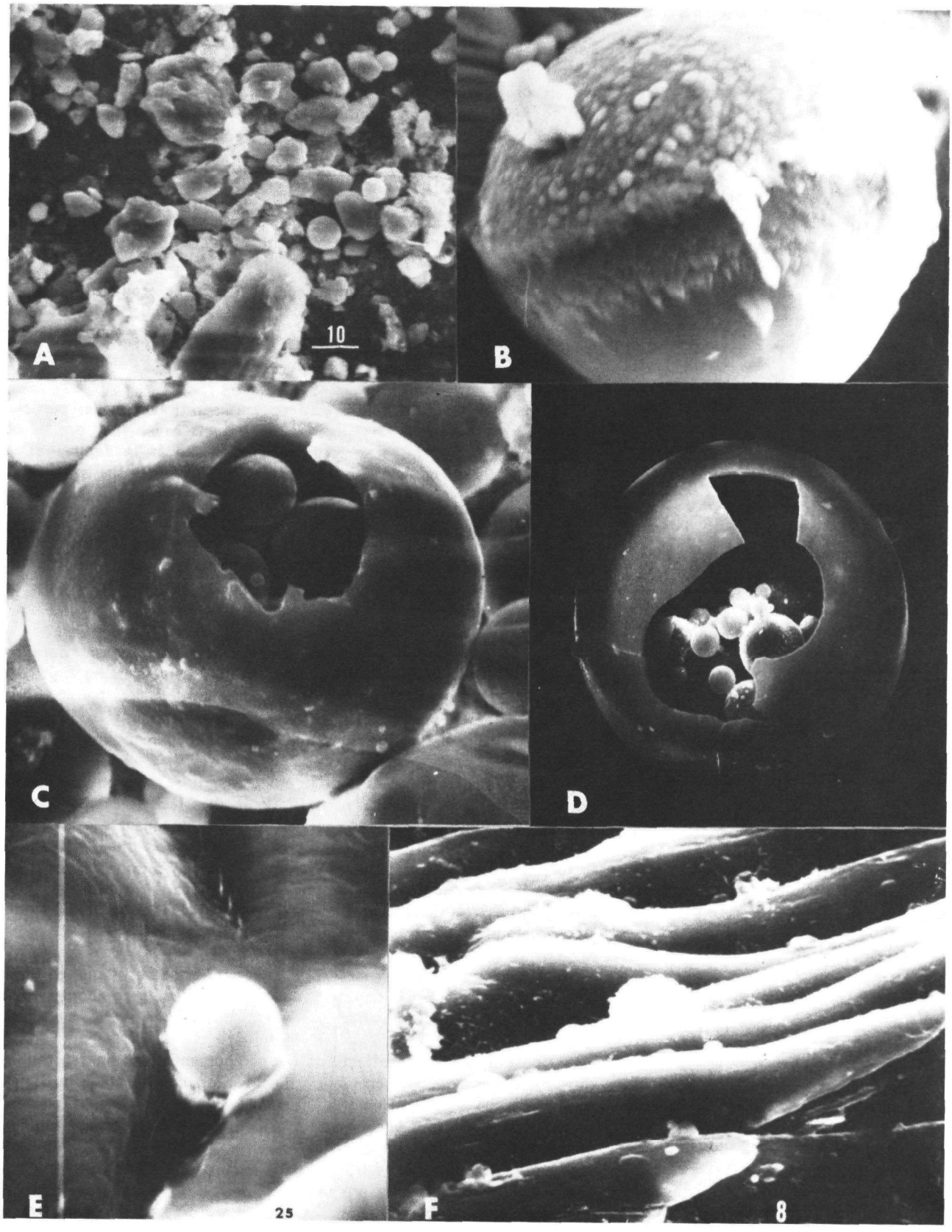


FIGURE 8—*Scanning electron micrographs flyash particles in various environments. Bars indicate scale in units of micrometers. A, an example of solid material collected in a dust fallout bucket located in the vicinity of the Columbia Generating Station; B, a flyash grain showing detailed surface deposits and morphology (32); C and D, hollow flyash particles showing inner contents—the outer shell was penetrated using the electron beam of the SEM (32); E, a large flyash particle on the surface of an oak leaf—the leaf surface is pitted by the particle; F, small flyash grains and other dust shown on veins of an oak leaf.*

DETAILED FLYASH STUDIES

Detailed studies of flyash particles indicate that their surfaces are highly reactive after being formed during the combustion process and as they cool other products of combustion in the gas phase condense, causing surface enrichment (figure 8B) (32). The surface enrichment of these particles cannot be measured by analysis of a total sample (bulk analysis) and previous assessments of the possible impacts have understated this potential by comparing the concentrations of components with the earth's crustal abundance. This type of comparison underestimates the availability of certain components which have been shown to be readily extractable (32). A comparison of surface analysis to bulk analysis shows concentrations ($\mu g/g$) of lead 2,700:620; thallium 920:28; chromium 1,400:400; zinc 14,600:1,250; and arsenic 1,500:600. Disposal or use of flyash must be carefully evaluated with these surface properties in mind.

Complex organic compounds such as polycyclic aromatic hydrocarbons that are formed during the combustion of coal are also associated with the surface of flyash particles. However, these compounds leave the stack as a vapor and condense on the particles after the plume cools (32).

HOLLOW FLYASH

Some particles are hollow and contain additional smaller particles. These have, in theory, the potential for timed release effects which may not be observable until some future date. The electron micrographs shown in figures 8C and 8D show examples of flyash particles of this type (32). The outer shells were penetrated using the electron beam of the SEM revealing the inner contents.

Some evidence for highly reactive flyash particles is shown in figure 8E where the surface of an oak leave is pitted and the leaf area around the particle shows calcium enrichment attributable to the flyash particle (3). Figure 8F shows small flyash grains and other dust or veins of an oak leaf.

During the period where the electrostatic precipitators were operating at 98 percent efficiency, about 1,051 pounds of flyash were being emitted per hour. This mass is equivalent to about 10^{19} particles emitted per day (assuming one micron diameter and a density of 1.65). Subsequent additions of sodium carbonate to the coal have increased precipitator efficiency to 99.5 percent removal.

Using the sulfur and flyash emissions, it is possible to estimate the yearly output and mass balance of materials from the stack (see table 3) which are arsenic 120 kg, cadmium over 90 kg, copper 2,000 kg, manganese over 10,000 kg, mercury 27 kg as a gas, and zinc over 2,000 kg. Based on these estimates, and through further analysis, it is estimated that only between 5 and 6 percent of the emissions from the stack come to the ground within 35 to 40 kilometers. Additional studies are underway to determine the ultimate fate of the balance of these compounds exported outside of the region currently under study.

MASS BALANCE APPROACH

A mass balance approach is in general a good technique to define areas where additional information is required to determine missing components and the fate and effects of emitted compounds.

In considering the effects of the gaseous emissions on vegetation, a wide range of studies was possible because of the location of the plant in a highly productive agricultural area (19). However, the studies are complicated because this area of southern Wisconsin is where part of the St. Louis and Chicago plume contributes to ozone levels in the summertime close to or above tolerance levels for some vegetation. Mixtures of sulfur dioxide and ozone exist over the study areas and detailed laboratory studies are being conducted to define the interactions. Figure 9 is based on experimental work in the laboratory, using controlled fumigations of various pollutants. Ozone alone has an effect on peas (2-hour exposures) at a little above 300 micrograms per cubic meter. However, in a mixture of ozone and sulfur dioxide setting SO_2 concentrations at over a thousand micrograms per cubic meter ($\mu g/m^3$), damage occurs at lower ozone levels, down to about 75 ($\mu g/m^3$) which frequently occurs. Figure 10 shows the increase of effects of sulfur dioxide concentrations on pea plant leaves with increasing ozone concentrations. Results of this type may be used to revise and improve air quality criteria.

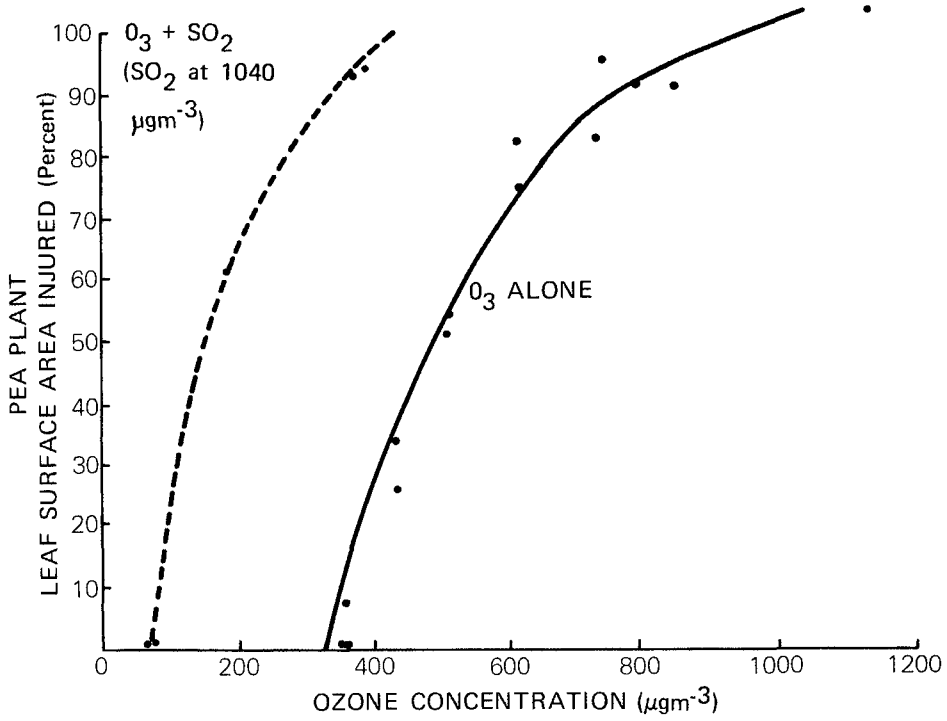


FIGURE 9—*Pea plant leaf injury versus ozone concentration at a constant sulfur dioxide concentration*

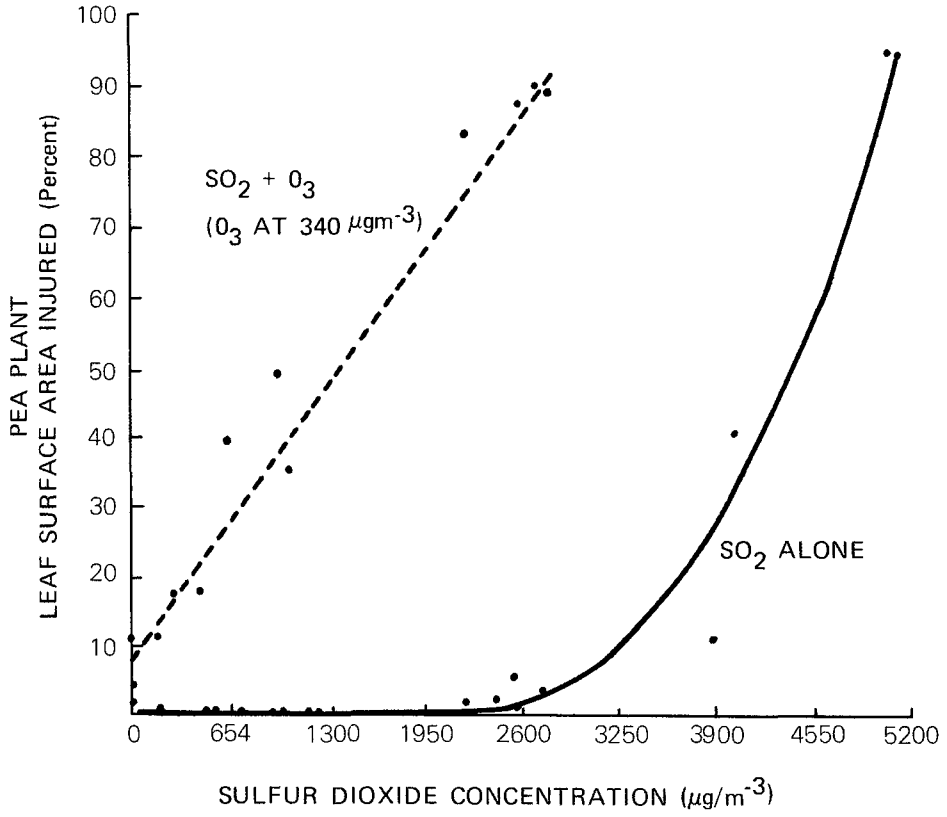


FIGURE 10—*Pea plant leaf injury versus sulfur dioxide concentration at a constant ozone concentration*

LEAF INJURY

Normal sulfur levels in this system have never been very high. Before the operation of the Columbia plant, a level of over 10 micrograms per cubic meter ($\mu g/m3$) was present 12 percent of the time (table 4). After the Columbia plant went into operation, sulfur concentrations reached this level 17 percent of the time and reached concentrations of 80 or 100 $\mu g/m^3$ a little less than 1 percent of the time. The ozone-sulfur interaction is shown in figure 10 from the other point of view. Sulfur alone does not cause damage on this pea variety until it reaches a level of over 2,000 $\mu g/m^3$. But in combination with ozone at 340 $\mu g/m^3$ a level reached occasionally under current conditions, damage is seen ranging up to 100 percent at levels where, without the ozone, damage would be less than 10 percent. Even at the low sulfur levels common in the area, e.g., 80 to 100 $\mu g/m^3$ the synergism with a high ozone level could cause 10 percent damage on this particular variety of pea. The likelihood of this combination occurring and generating noticeable effects in a single year is minimal. However, species such as white pine and lichens could accumulate significant effects from these low concentrations over several years of exposure. Current plans call for monitoring these perennials for several years.

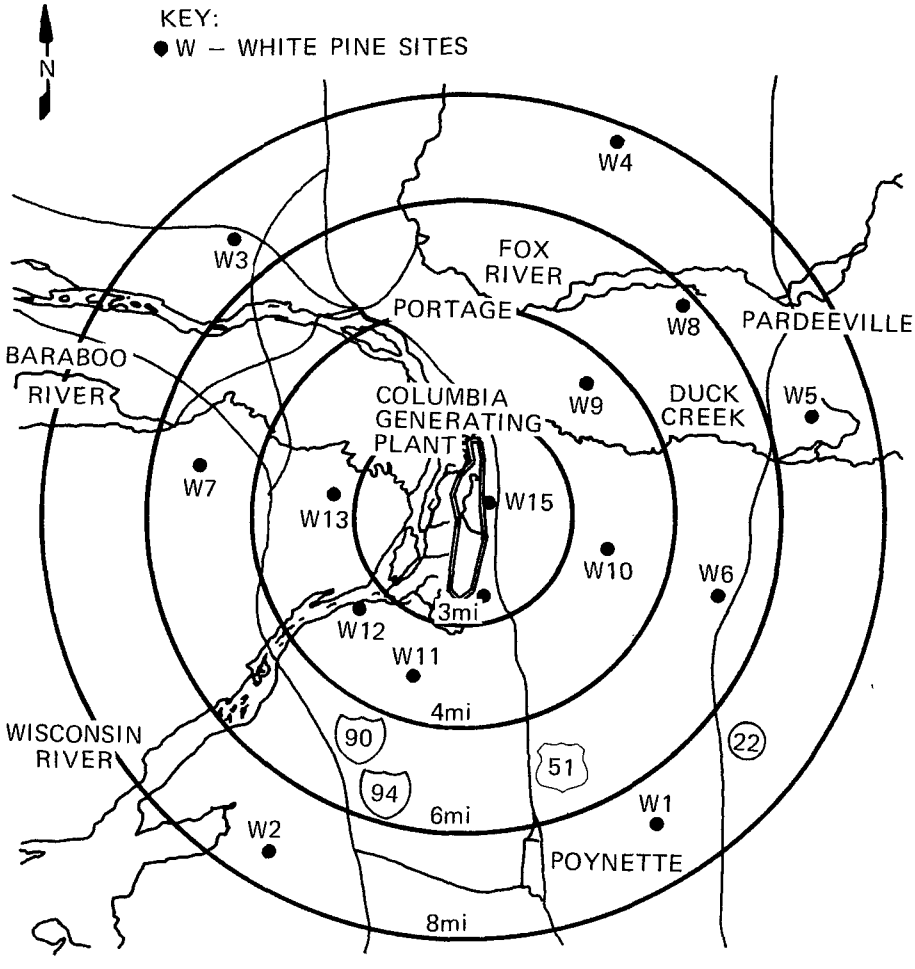


FIGURE 11—*Sampling sites for White Pine circling the Columbia Generating Station*

SAMPLING SITES

Figure 11 shows the distribution of white pine sampling stations. At these study plots, within about 15 kilometers from the power plant, white pine foliage was examined for tip-burn symptoms during the growing season for 3 years prior to the operation of the power plant and for 3 years since the operation of the plant. The overall mean of the tip-burn observed during the growing season is highly variable. However, studies of the sources of this variability are still underway. When the damage levels at individual stations are combined for the before-plant and after-plant operation, less variability results. Measurements have not yet been done

of long-term (3-year) foliage loss from exposure at a chronic level because they require observations of the pathology of the same needles each successive year. This study requires that one look at foliage during the first year, and that continuous measurements be made to determine what symptoms accumulate. The percentage of the foliage lost by the third year is indicative of the pathology. The lichens in this area show some increased plasmolysis but these observations have not yet been studied in detail.

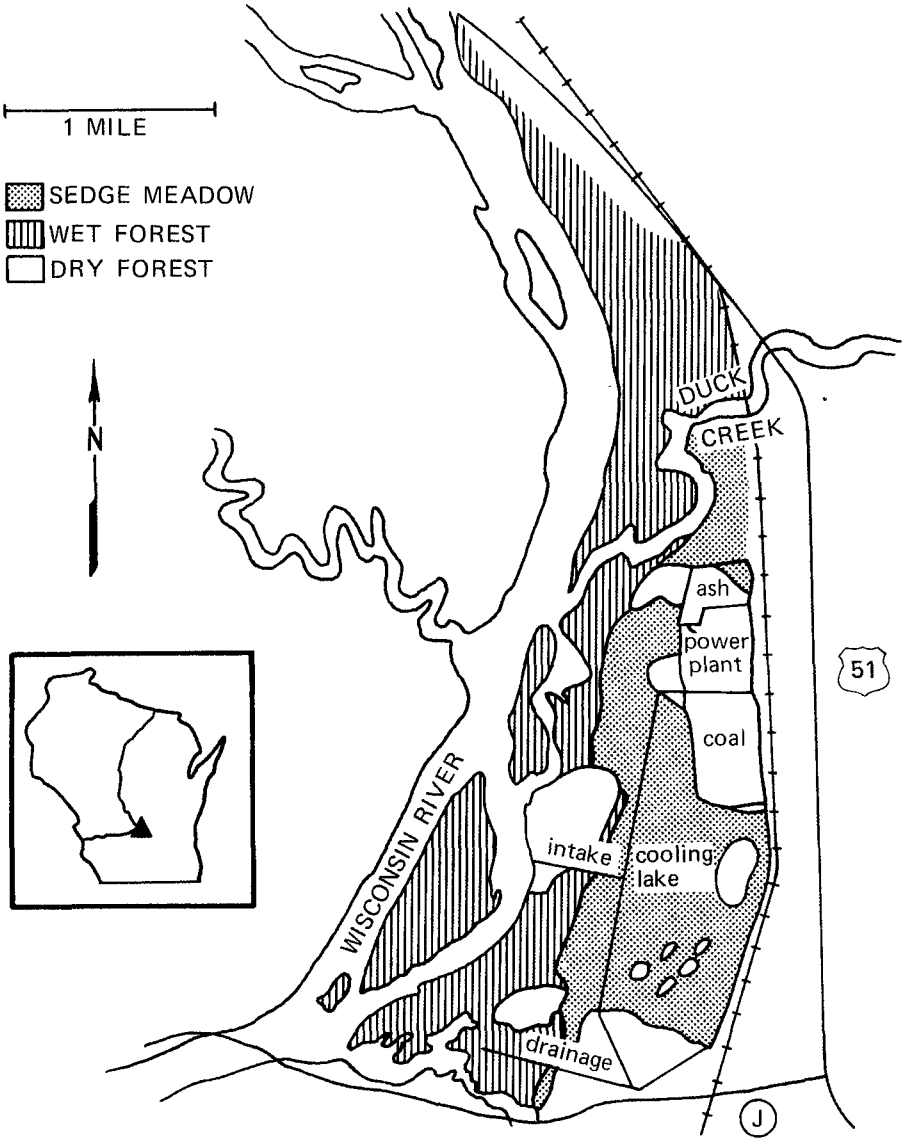


FIGURE 12—*Outline of the Columbia Generating Station and the topography of the site before construction*

HYDROLOGIC SYSTEMS AND COOLING LAKE

This study has examined impact on a coupled system, part of the generating station that is governed by water flow through the area. Figure 12 shows the before and after topography of the area (24). Before the construction of the system, the upland sloped gradually to the flood plain sedge meadow and the river. A groundwater flow from the adjacent uplands of about 1 cubic foot per second was maintaining the water level in the sedge meadow. The flow is high in the spring during snow melt, but flows would be much reduced during the summer. The 500 acre lake was constructed with a 9-foot hydrostatic head above levels in the adjacent wetlands. Its construction has drastically altered the groundwater pattern. Figure 13 shows groundwater flows before and after construction of the cooling lake (22).

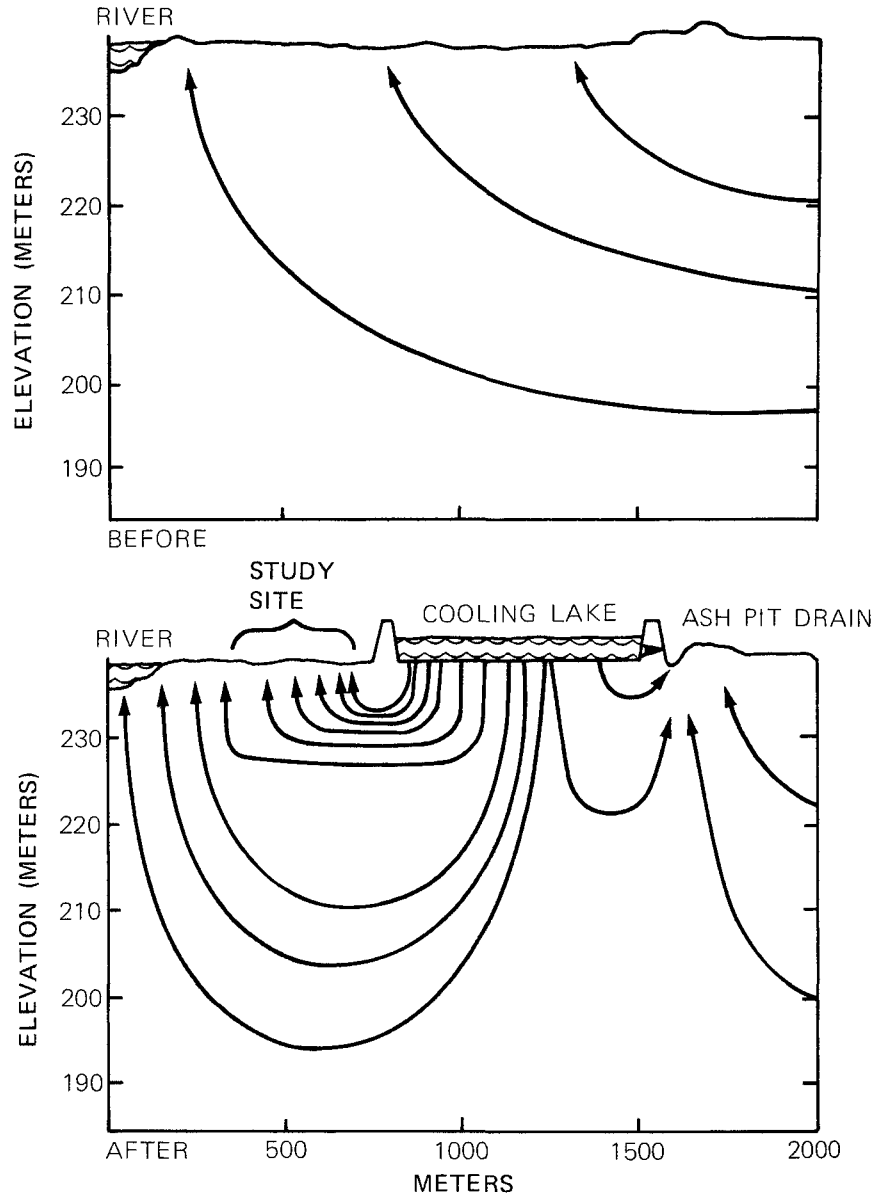


FIGURE 13—*Groundwater flows before and after construction of the cooling lake. Arrows represent integrated flows, 1 m^3/min, normal to the east-west cross section along the length of the cooling lake.*

There is now 4 cubic feet per second of seepage from the cooling lake, going out in both directions, but mostly into the sedge meadow on the west. Thus, although the lake has essentially cut off the groundwater flow from the adjacent upland, seepage at this rate is keeping the sedge meadow in a flooded condition throughout the year. Of ecological interest, not only are there now direct effects of the higher water levels in the sedge meadow, but also that there is no longer any fluctuation in water level during the growing season. Some of the species in this wetland are dependent on the annual summer drying for certain stages of their life cycle. This no longer occurs.

A MODELING APPROACH

A modeling approach has been developed to aid in predicting the changes in surface water levels in an impeded flow area, given a variety of changes in the adjacent upland (22). This is a general case approach that applies whenever construction is going to cause more runoff than occurred previously—such as along highways where creation of an impervious surface increases the water flow to the adjacent impeded flow areas. The models resulting from this approach will provide useful aids in such situations and is a sample of the kind of information that can be generated from a site specific study of this nature and generalized for many applications.

TABLE 6
Mass balance for the Columbia Generating Station lake

Element	Input (kg/yr) Dissolved	Particulates	Total	Output (kg/yr) Dissolved	Particulates	Total	Amount Remaining in Cooling Pond (kg/yr)
Particulate Matter			266,450			49,400	217,050
Al	1,200	18,600	19,800	80	1,900	1,980	17,820
As	10	6	16	2	0.9	2.9	13
Ba	40	197	237	8	28	36	201
Ca	520,000	6,200	526,000	124,000	850	124,850	401,350
Co	2	3.4	0.4	0.4	0.3	0.7	4.7
Cu	40*	5.3	45.3	40	0.5	*	*
Fe	6,000	13,570	19,570	401	1,010	1,411	18,160
K	40,000	3,325	43,325	7,620	385	8,005	35,320
Na	200,000	1,170	201,170	40,000	892	40,992	160,178
Sb	40	0.8	41	8	0.2	8.2	33
Si	42,000	87,930	130,000	2,400	16,300	18,700	111,300
Zn	100	112	212	20	25	45	167
SO_4	260,000	114	260,114	52,963	16	52,979	207,135

* A considerable amount of Cu is released to the cooling pond from the cooling system of the plant; precise values not yet determined.

BIOLOGY OF COOLING LAKE

The mass balance of materials in the cooling lake are shown in table 6 (1,3,14). Water is pumped in from the Wisconsin River with certain chemical characteristics which vary from season to season. Water going through the plant cooling condensers picks up waste heat, chlorine (defouling agent) and copper. Live aquatic plants and animals in the system grow and are transformed into detritus. Some of the water taken into the plant is used for flushing the ash to the ash basin, although most is returned to the cooling lake. The remainder of the outflow from the cooling lake occurs as seepage through the bottom of the cooling lake. A comparison of the concentrations of chemicals and particulates in the input and output water, (table 6) indicates that an accumulation is predicted in the cooling pond: 217,000 kg of particulate matter, 17,000 kg of aluminum, 400,000 kg of calcium, accumulating in the sediment at the bottom of the cooling lake as water from the cooling lake evaporates and leaks out.

Because of the warm water and a long growing season, an interesting fishery is thriving in the cooling lake. A macroinvertebrate species, a *Hyalella* sp., seems well adapted to this cooling system in a particular temperature zone. In the summertime it clusters near the plant intake. The small settling pond where the river water enters the cooling lake may actually provide a refuge for some of the biota during the few days of extreme temperatures during the hottest summer days. However, the zooplankton population moves around the lake during cooler periods to wherever the desired temperature is much closer to the warm water inflow during winter.

FISHERY IN COOLING LAKE

The fish feeding on this zooplankton are principally gizzard shad and black crappie, both of them southern species that ordinarily grow in much warmer temperatures than occur in Wisconsin. Two common Wisconsin species, bluegill sunfish and largemouth bass, were stocked in the cooling pond. Both have grown well, but the largemouth bass population is not reproducing; at the present time a 4-pound fish can be caught on the average with three casts. There has been strong

public pressure to open the fishery, and for the first time it will be opened in 1978. Preliminary analyses of fish residues for metals or organic compounds show low values. Of particular interest are mercury and chlorinated compounds. Concentrations are elevated due to paper mill wastes in the Wisconsin River water and additional chlorinated organic compounds are expected from the use of chlorine in defouling the condenser tubes (34).

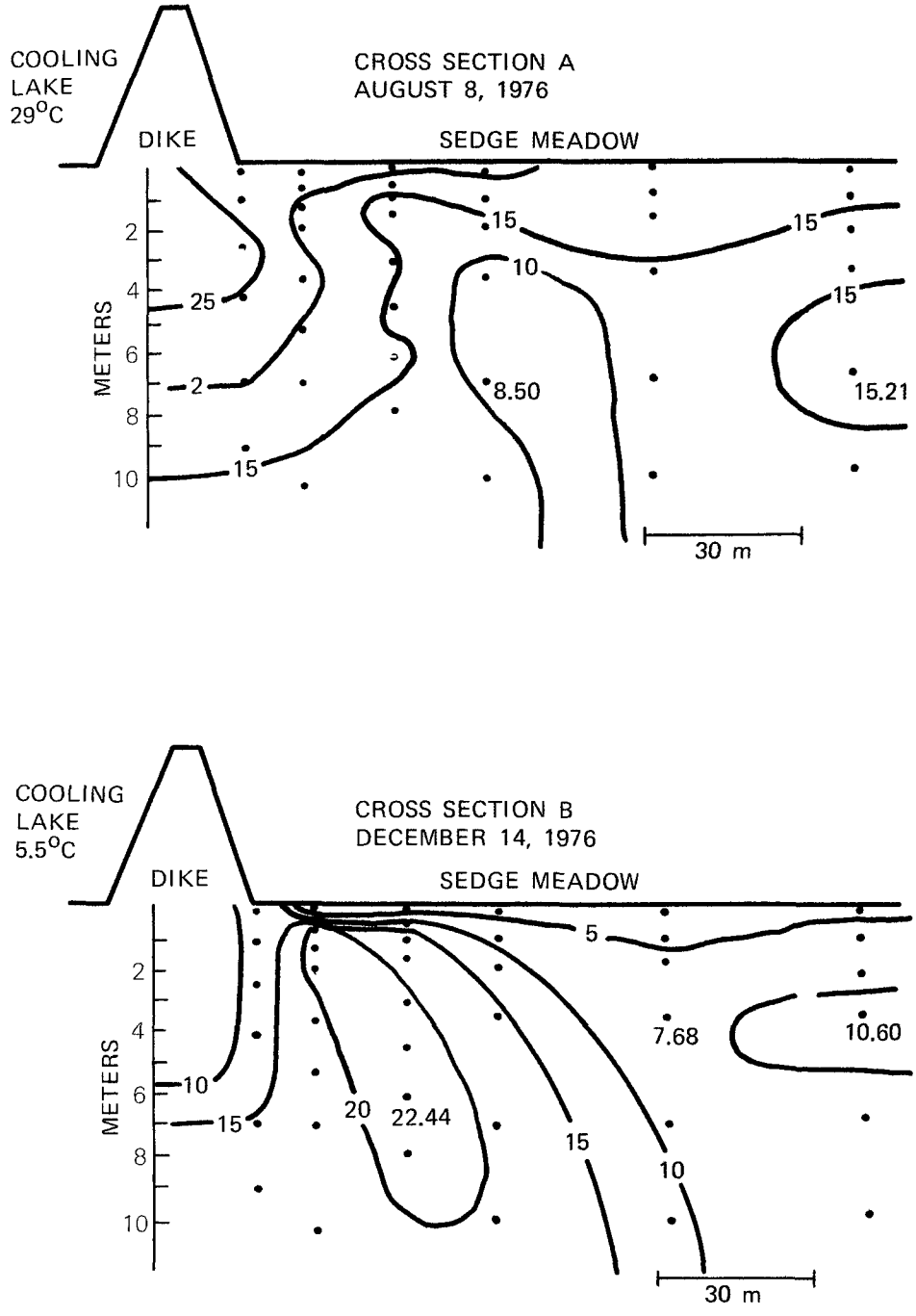


FIGURE 14—*Groundwater isotherms, °C, in vertical cross sections between the cooling lake and the Wisconsin River*

WASTE HEAT DAMAGE

One of the more interesting findings of this project concerns the conservative nature of waste heat found in the groundwater due to the seepage from the cooling lake. The movement of this waste heat into the groundwater has done the most additional identifiable damage to the aquatic system observed since the construction of the generating station (8). Figure 14, cross section A shows that in August, water of 15 °C is rising from the sediment below the sedge meadow, whereas 25-degree

water is measured under the dyke. In figure 14, cross section B shows that water at 20°C is rising in the sedge meadow but the water seeping in from the cooling lake is at 5°C (22). In June, this cold water from the lake comes up at about 5°. Although the 2° to 5° water in June doesn't bother the plants, the 20° water around the root systems in the period from December to January causes serious damage (13). The problem was unexpected since heat is not usually a considered conservative component. As long as the deep below-ground deposits are at a low enough temperature to take up some of the heat, this effect would not be noticeable. However, 6 months of plant operations saturated the sediments to the extent that any substantial body of additional heat could not be accommodated. With both 527 MW units operating, it is predicted that little or no snow cover will appear on the adjacent wetlands area after 1983 (22, 24) unless steps are taken to eliminate the seepage from the cooling lake.

CONSEQUENCES OF HEAT RELEASE

Ongoing studies in the sedge meadow revealed the biological consequences of this heat release into the wetlands (15). Photographic studies of the sedge meadow about 8 or 10 months after the initial operation of the power plant showed that in November some photosynthesis was continuing late into the fall (17). This process does not show up in other parts of the sedge meadow where there is similar plant species composition. The result over a period of 2 years is extensive mortality and decomposition and a comparatively open lake in the sedge meadow. Where there was originally a dense mass of *Carex lacustris,* which is the ideal habitat for northern pike spawning in the wetland, there is now very little cover during spring spawning time. The cattails reproduce rapidly during the growing season and then are decimated again during the following year. Thus, there is not only a loss of species, but a change in the entire substrate, a reversion of the organic accumulation and an initiation of the erosion process.

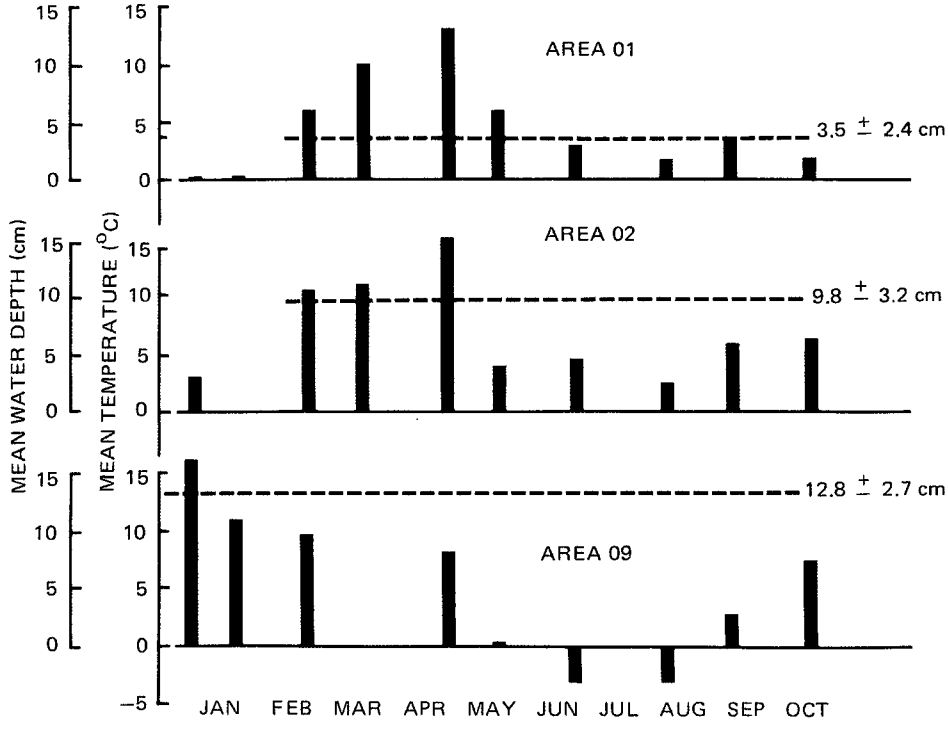


FIGURE 15—*Water depth and temperatures of impacted wetland areas. Bars represent temperatures as degrees Celsius above or below temperatures relative to control sites.*

TRANSITION IN WETLANDS

By late summer, however, annuals colonize these mudbeds and produce seed which come up again the following year, with the net result of converting this area from a perennial wetland community to a comparatively unstable wetland of annuals. There is evidence of a transition going on in the wetland, probably brought about by a combination of the changes in water level, flow rate, temperature, and perhaps dissolved components. Specific results are shown in figure 15. In some areas

of the wetland there is an enhanced water level of 12 centimeters due to the increased flow of the groundwater system. The bars show the departure from temperature of control areas at that time. Areas farther from the cooling lake receive the warm water at a later time. In area 9 there is an enhanced temperature of 18 degrees during the winter, tailing off to a depression of 2 or 3 degrees in the summertime and then back up. In this area, which is farther away, the minimum lag for the warm water of the previous summer coming up in the wetlands seems to be 4 or 5 months. For much of the area the lag is 6 months. Some areas show a time lag until May before the main temperature enhancement takes place, and then the summer depression is not as severe. There are mixed areas with combinations of magnitude of temperature enhancement and of the magnitude of delay. If the temperature enhancement is fully 12 months delayed, it is probably not out of phase with the life cycle of the plant and little damage may occur except for that induced by water flow or depth effects.

CARBOHYDRATE LOSS

A number of hypotheses exist to explain the pattern of plant responses in the wetlands. The principal one concerns the probable decline in carbohydrate storage of the plant in relation to the materials needed to grow the following spring, due to elevated fall and winter temperatures. This has been shown to be the factor inducing winter mortality of *Typha latifolia* (13).

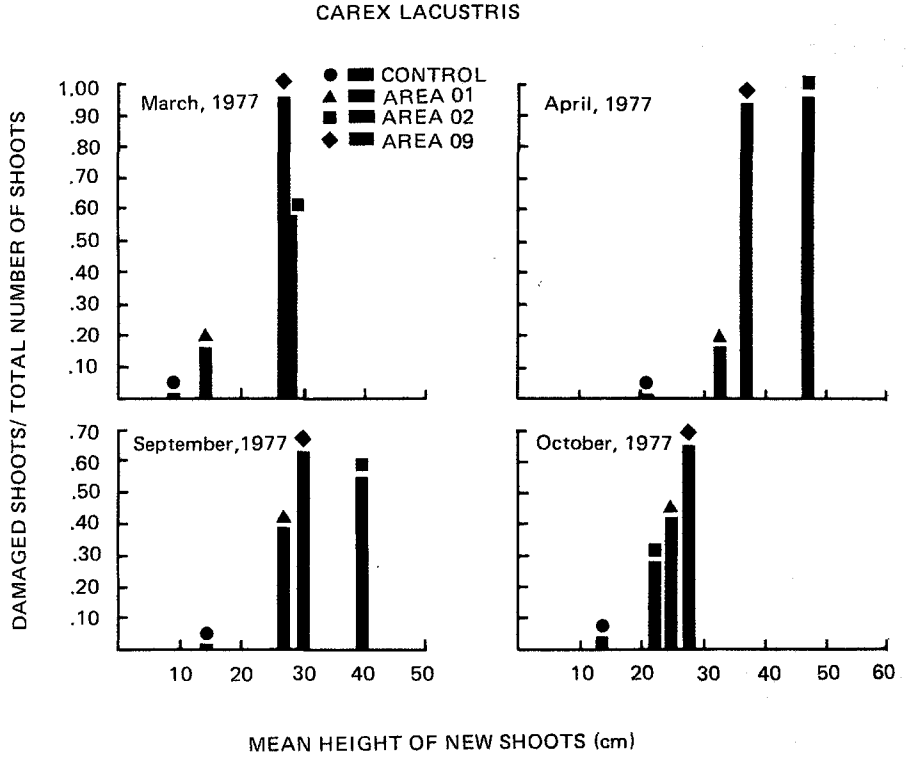


FIGURE 16—*Monitoring data for Carex lacustris in the wetlands adjacent to the cooling lake of the Columbia Generating Station*

ADDITIONAL MONITORING

Carex lacustris on the other hand, does not show a loss of carbohydrate such as in the *Typha.* The levels are reduced but the depression of carbohydrate can't be regarded as the principal reason for the mortality of these species. The data in figure 16 show that the emergence of *Carex lacustris* is adapted to the temperature in its environment. In areas most affected by warm water, high levels of total number of shoots present during March and April are seen, but in the control areas they have not emerged. Thus, of the two sedge species that were seriously hurt in this particular area, there appear to be two or more mechanisms involved in the collapse of the communities. Additional monitoring of the reestablishment of other species is needed to project whether a stable plant community can be supported.

ADDITIONAL WORK

Additional work on the fishery of the wetland over a period of years will be needed to determine whether a decline in northern pike and muskelunge reproduction due to the decline of the quality of the sedge meadow as a reproduction medium will be a major problem.

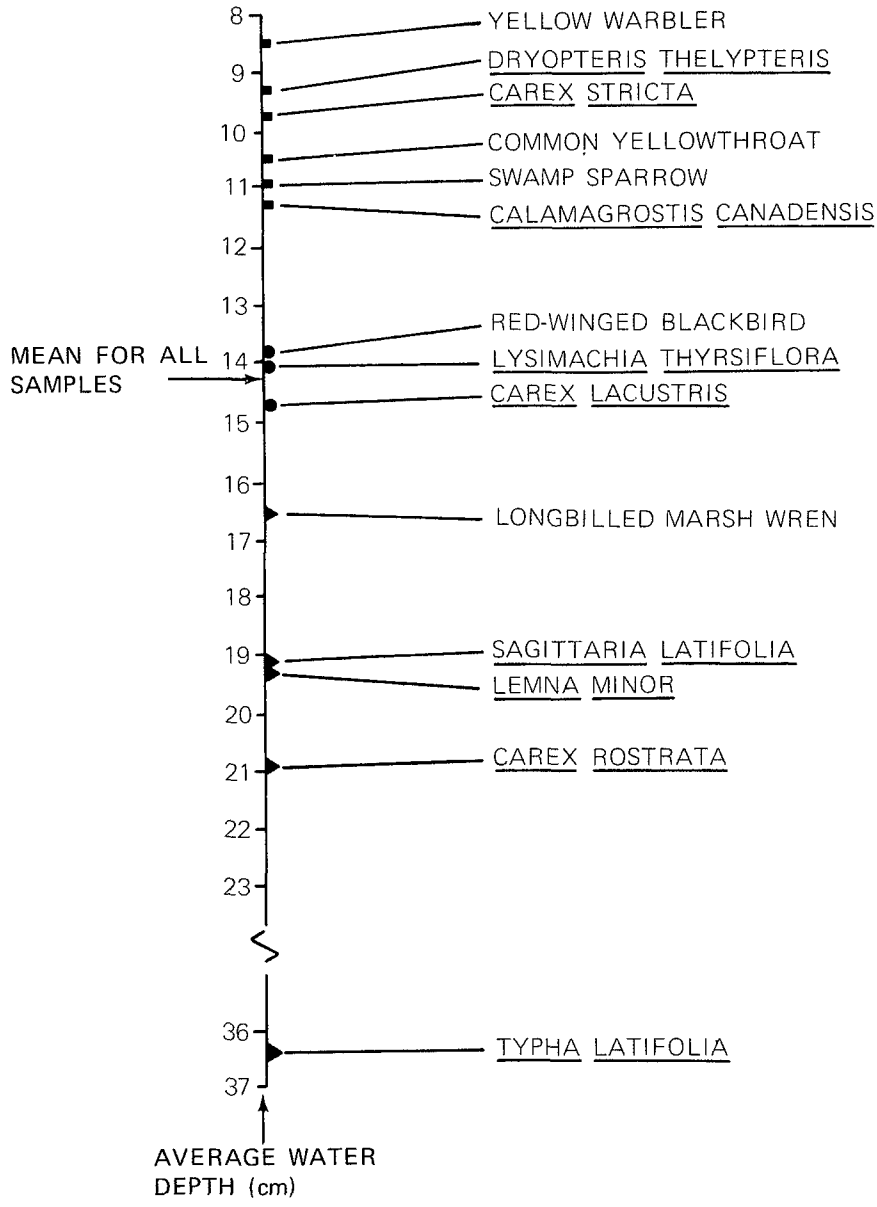


FIGURE 17—*Diagram showing correlation of bird communities with wetlands plant species and water depth*

BIRD AND PLANT SPECIES CORRELATION

Other research has been directed toward the relationship of the bird community in this system (15). This has been done principally by correlating bird species with particular plant species (figure 17). Yellow warblers and yellow throat, are associated with *Carex stricta*; in slightly deeper water the redwing blackbird and the marsh wren are usually associated with *Carex lacustris.* As the marsh is undergoing change due to the combination of water and temperature treatment, the other changes that follow must be monitored as they in turn will induce changes. Figure 18 shows the complex interconnections between the power plant and the bird communities. A gradual but small growth in waterfowl populations is occurring. Ducks did not use the area at all previously, but they are now beginning to use the emerging water patches. Some people have suggested that this should be regarded as a resource enhancement, just as the cooling lake fishery would be thought of as a resouce enhancement.

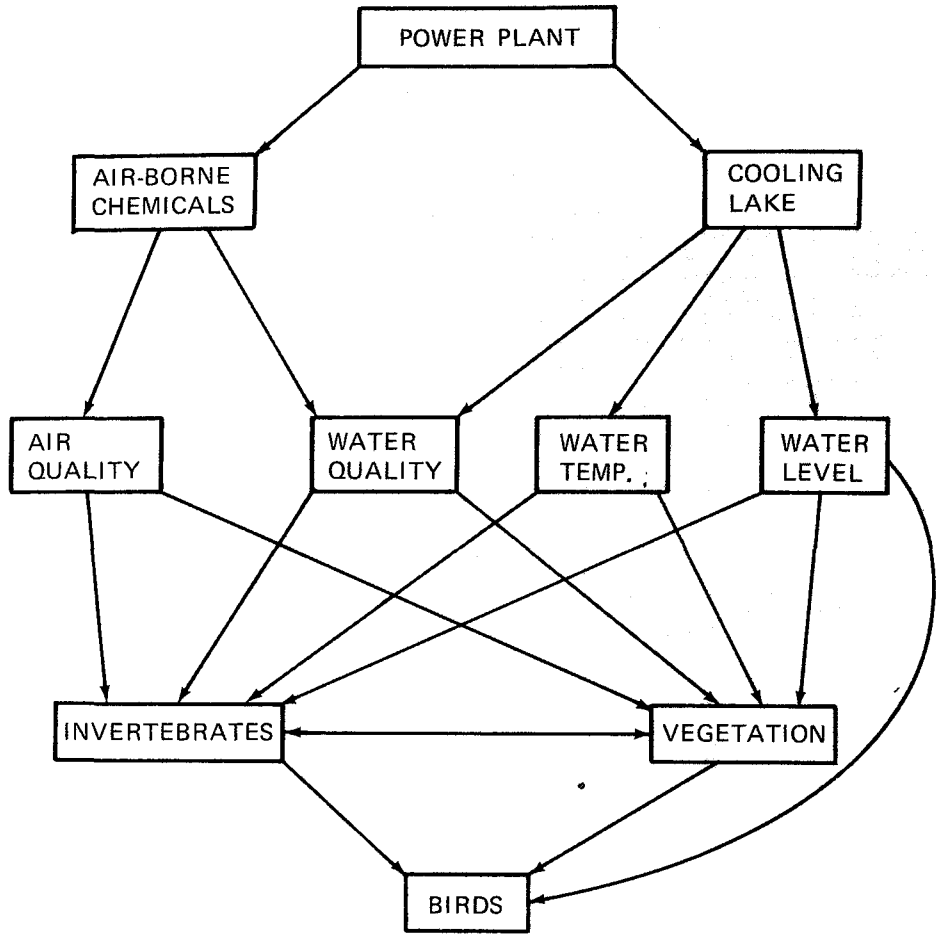


FIGURE 18—*Schematics of interconnection pathways between the Columbia Generating Station and bird communities*

PUBLIC ECONOMY AND FISCAL STATUS

Several subprojects deal with the response of adjacent human communities in some depth, including visual impacts and citizen concern with electric generating stations (20,29,31). One of the most dramatic impacts of the Columbia Generating Station is shown in table 7 concerning the public economy and the fiscal status of Pacific township where the station is located. The rapid growth in utility tax revenues paid to Pacific, following the initiation of construction in 1971, are given. Column 3 reflects the total tax levy imposed on the municipality by the state, county, and appropriate school districts. Column 4 depicts the actual amount of tax that was assessed and collected from local property owners. The final column illustrates the rapid growth of town excess funds, which have been invested in certified deposits earning between 5½ percent and 6½ percent annual interest. All data prior to 1975 were extracted from the Official Financial Reports of Pacific Township, filed with the Wisconsin Department of Revenue.

The resultant land use pattern changes are shown in figure 19 in comparison with a control township. The net result from Wisconsin tax laws show that an agricultural area is being strongly driven toward residential land use. This type of impact will depend on state law and vary greatly from state to state.

SITE IMPACTS

From the samples of research results given above, one can conclude that the electric generating station and the impacted environment are not a closely coupled system in the same sense that a watershed is a coupled system with known inputs and transfers that are linked throughout. Portions of this system are directly coupled; certainly the system from the leakage of the cooling lake, through the wetland plants, to the birds supported by the wetland operates as a coupled system. However, this is only one part of the system, and must be considered in evaluating the total ecological impact of the generating facility itself.

TABLE 7
Budget figures for pacific township

Year	Utility Tax Revenues (Including Makeup)	Total Tax Levy (State, County, School)	Total Local Tax Collection	Total Town Investment Fund (Annual Interest not Included)
1971	$ 19,935	$ 176,176	$ 154,635	$ 50,958
1972	59,937	184,903	152,720	81,922
1973	388,969	201,046	25,283	320,000
1974	1,171,344	201,735	0	1,311,902
1975	752,248	213,000*	0*	1,851,000*
1976	745,014	266,000*	0*	2,470,000*
1977	725,000*	239,000*	0*	2,956,000*
1978	700,000*	253,000*	0*	3,403,000*
1979	675,000*	268,000*	0*	3,810,000*
1980	650,000*	284,000*	0*	4,176,000*

* Estimated projections based on current data and trends.

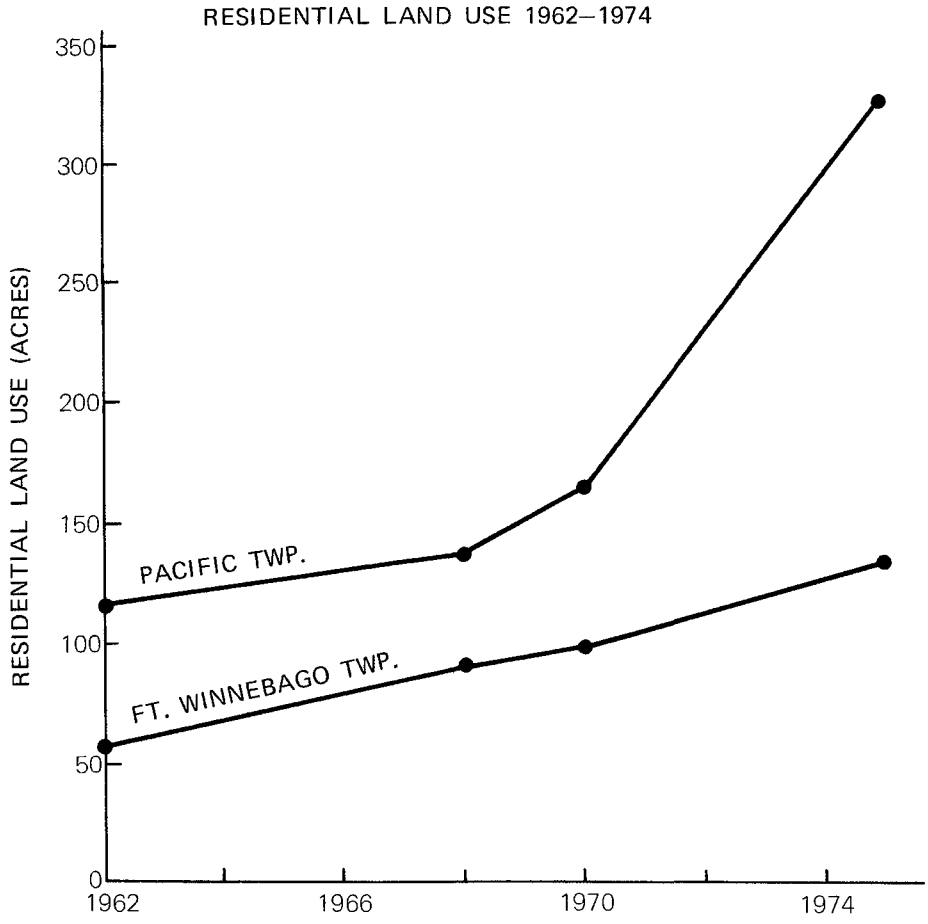


FIGURE 19—*Land use pattern changes as a result of the construction and operation of the Columbia Generating Station in Pacific township compared to Fort Winnebago township*

MASS BALANCE APPROACH

The mass balance approach can be recognized as an essential tool for summing up and following the materials through a complex system and determining where they go. It appears that the atmospheric transport mechanisms for the gases and fine particulates are so efficient in leaving this site that one cannot define the magnitude of the area in which the deposition and effects will eventually take place. These effects are added increments to ecosystems already receiving pollutant loadings from other sources. If the added materials are responsible for unacceptable environmental degradation, then additional controls will have to be imposed to prevent their release. Acid rain impacts are starting to appear as an important remote impact and may be expected to spread and intensify as more coal is burned and sulfur and nitrogen oxides increase the loading of already stressed ecosystems.

Beyond the issue of how best to study or assess the effects of a large coal-fired generating station, there is also the larger question of how to make the results of these studies known in siting future power plants. Obviously, assessment of the trade-offs requiring the technological fixes to minimize the adverse ecological impacts is a complex of comparative impacts. Perhaps more efficient flue gas scrubbers should be employed rather than a tall stack for removing sulfur and nitrogen oxides, gaseous metals (including mercury), halogens (fluorine, chlorine, bromine, iodine compounds), and polycyclic aromatic carbon compounds. The nature of the emitted flyash particles suggests that total particulate removal rather than 99.5 percent may be justified in the future. Actual field evaluation of water quality criteria may show that aquatic systems may be less sensitive to ash basin effluents than laboratory derived criteria have predicted.

These questions and many others will be answered if the resources needed to complete the research program and generate the needed answers are forth-coming.

ACKNOWLEDGMENTS

The information in this report is derived primarily from the research conducted by the faculty and staff of the University of Wisconsin, Madison. Special thanks are due to Professors Orie Loucks and Philip Helmke of the University of Wisconsin, Madison who provided most of the material for this report. Many additional important findings are contained in the reports listed in the bibliography and are not summarized here only because of time and space constraints. Thanks are also due to B. Halligan for drawing the figures and T. Highland for typing the manuscript and D. Mount, K. Biesinger, L. Heinis and L. Anderson for reviewing it.

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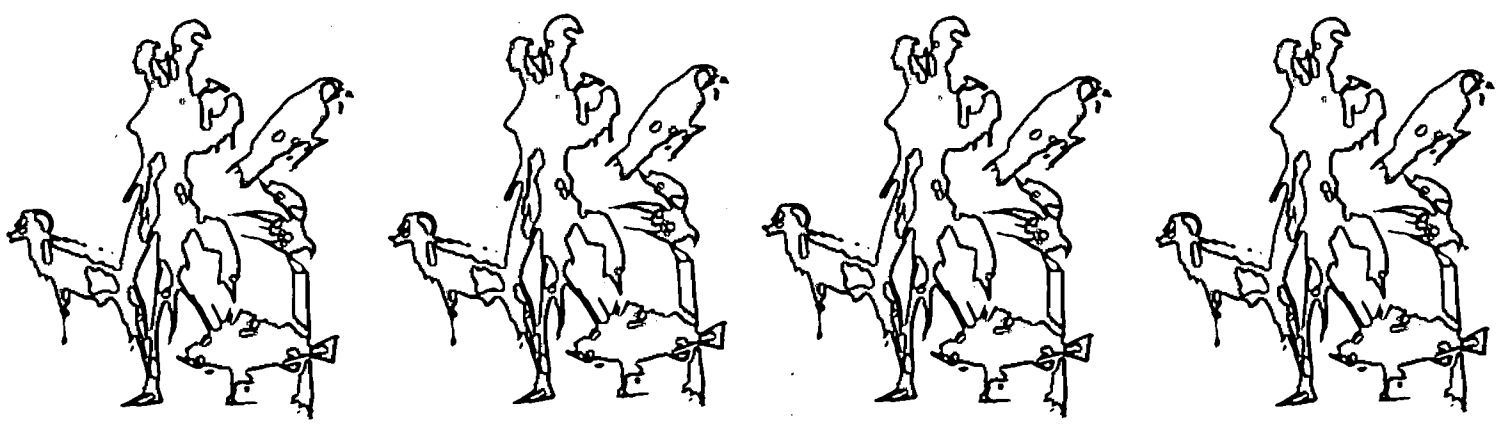
panel discussion



TRANSPORT PROCESSES AND ECOLOGICAL EFFECTS PANEL DISCUSSION

Allan Hirsch, Ph.D.
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John M. Neuhold, Ph.D.
Utah State Ecology Center
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Division of Environmental Planning
Tennessee Valley Authority

A. Paul Altshuller, Ph.D.
Environmental Science Research Laboratory
U.S. Environmental Protection Agency

(Additional comments by presentation speaker Dr. Pueschel)

DR. HIRSCH: We have just heard four excellent papers describing research findings related to transport process and ecological effects. Each of these four papers contributes significant insights and findings. Yet, relating research findings to regulatory controls is probably one of the most difficult aspects of environmental management.

We have heard that over the long run many of these ecological impacts resulting from long-range transport could be extremely significant. However, predicting environmental transport, transformation, and ecological effects of pollutants is extremely imprecise. It is often very difficult to predict the actual ambient levels with any great degree of accuracy. It is even more difficult to assess the ecological effects of those ambient levels, particularly effects of a subtle or a long-term nature. With changing technologies and changing pollutants, precise prediction certainly is not going to become any easier. Yet, in making regulatory or control decisions, we have to be precise. We must quantify the emission standards or the effluent limitations precisely in order to establish meaningful, realistic regulatory programs. That is the dilemma. On the one hand, no matter how good the research, we continue to have difficulty in predicting ambient levels with precision, and even more difficulty in predicting impacts, particularly long-range or subacute, with precision. On the other hand, we need to be very specific about regulatory requirements when a plant is being sited and a standard is being set.

From a management standpoint this dilemma has already been reflected in national pollution control policy. Perhaps the most clear-cut example of this is in the 1972 water pollution legislation, which put heavy emphasis on effluent and technology base controls, recognizing the difficulty of basing a regulatory program on ambient conditions. Even there, however, if we look at the 1977 amendments, we have achieved a basic level of effluent control and are now becoming concerned about the residual ambient impacts.

It seems, therefore, that the basic issue before us today is what all this means for the future of energy research. Do the data tell those concerned with the planning or allocation of resources to energy research programs anything about the direction and emphasis of future research efforts? The issues are similar to those posed by the health effects panel this morning. Should we continue trying to refine our understanding of the effects of trace contaminants on aquatic ecosystems or of sulfur oxide discharges on terrestrial systems and vegetation? Should we continue to emphasize the development of better transport models? Or should we instead say that we are only going to be able to marginally improve this predictive capability with additional research and that we are not really able to apply very well what we know now in the regulatory process? Should our research focus on developing strategies for environmental management, adaptive systems of controls by which we can rely more heavily on monitoring, feedback, and adjustments in control mechanisms, with less dependence on up-front prediction of impacts as a basis for specifying the control or management program? What mix of all these should we have in our research programs?

DR. NEUHOLD: Two points made in the presentations are worthy of note. The first involves the complexity of the transport phenomenon itself to the point of impact on living organisms. The second is the importance of ecosystems in the entire process, Heretofore, most of our effects work has concentrated on two areas: human health effects and effects on individual organisms. Ecosystems, however, are composed of populations of many diverse organisms, which perform various functions. We depend upon our ecosystems for food, fiber, and many other vital resources. The estimated 2½ percent reduction in the production of Scandianavian forests is appalling, yet we can look forward to similar reductions in this country.

Although our predictive ability is improving, it is by no means at a point yet where we can be very specific about levels of toxicants in the atmosphere or in the environment in general. Developing a strategy to handle toxic levels either at emission or at ambient sites is extremely important. Concentration of emissions or concentrations in the ambient environment are variable. In the mountainous areas of the western United States, for example, because of the peculiar air shift patterns, it

is not feasible to rely on simple emission standards. Even if the emission standards are very low, we must be aware that at times of temperature inversions ambient levels may be extremely high.

Our immediate need to utilize available sources of energy, such as coal, while awaiting development of cleaner sources, forces us to have flexible policy relative to both ambient and emission standards. What we now consider to be conservative levels, in terms of human health or organismal effects, may prove to be too high to avoid ecosystem consequences of a long-term nature.

DR. AUERBACH: Simply stated, on one side is the environmental scientist with a lot of environmental information that he claims is bad. On the other side is the technological scientist, who claims there is no demonstrated cause and effect at all. In the middle is the regulator, asking what he should do. In many ways the problem is analogous to the human health problem, in that we are dealing with morbidity rather than mortality in the ecological context. We are trying to perceive and measure effects which can be considered only at the morbidity level in our various ecosystems.

It is obvious that we are dealing here in an area of ill-defined risk. We must look at the potential costs if we do nothing about this risk. In terms of damage to our renewable resource, food, and fiber structure, the potential cost is very great. This is a transcontinental problem covering an increasingly larger area. We don't want to lose ground while we are upgrading the measurement system to report to the regulators the consequences of the impacts of pollutants.

Ecosystem degradation is a difficult concept, because the landscape is composed of multiple species. In the time span of observation that most of us are used to, we don't see the subtle changes, the shifts in species, which over a longer term may result in the landscape's performing less well. This presents a challenge.

From the regulatory point of view, the emphasis is on a flexible system by which, as the information develops, new modes of regulation may be instituted. For example, the 1977 Air Amendements approved the new concept of offset mechanisms, acknowledging that regions have a limited capacity to receive pollutants, and new polluting agents must be treated in a manner which in some way offsets the old polluters. This concept may not yet apply to transcontinental problems such as acid rain, but it is a step in the right direction.

Similarly, with regard to emission standards we are waiting to see how well the best applicable control technology (BACT), mandated to go in over the next 10 years, will work in ameliorating the impacts of gaseous air pollutants. Because of the constantly changing nature of the air mass, measures such as emission budgets or emission fees are not appropriate. Offset mechanisms may be the solution. Potentially, NEPA could be applied to siting processes and combined with the regulatory system to avoid detrimental effects on a continuing basis.

In long range terms, we need to explore methods other than straight combustion of coal to produce the energy we need. We need to explore methods which produce fewer direct gaseous effluents, and we need to couple this with better degrees of control.

DR. JONES: If, in balancing the need for regulatory certainty with the inherent uncertainties of environmental science, we neglect the environmental impacts, particularly as they apply to health and welfare, then we are neglecting the basis for the Clean Air Act and other regulations. The problem with many of our regulations is that they do not have a good scientific basis to begin with, and that is, at least in part, a monetary consideration. We are currently spending perhaps $25 million or $30 million a year on environmental effects projects. At the same time, regulatory decisions are having to be made which may cost a single agency or power producer $500 million a year. Our regulations have far outstripped our predictive capabilities as far as transport, transformation, dispersion, and impacts are concerned. The Clean

Air Act Amendments mandate prevention of significant deterioration, and non-attainment will require the use of models to predict very small increments of air quality. If we are unable to accurately predict these increments of air quality, growth and energy production could be significantly reduced. We need, therefore, to pay considerable attention to obtaining the data and information with which to validate and refine models.

A second consideration is to put more effort at this time into doing a thorough evaluation of new environmental control or production technologies so that we understand the associated problems before we commit ourselves. We know we have effective and workable environmental controls. Applying some of our past experiences could prevent us from getting into the sorts of difficulties we had, for example, concerning hydrocarbon regulations for automobiles. Another example may be the problem of sulfate reduction through SO_2 control at energy sources and power plants. It is possible that scrubbers, particularly wet scrubbers, may actually intensify the sulfate problem. Some attention is now being paid to that particular problem, but a further problem may exist in that the reduction in sulfate levels may not be proportional to the reduction in sulfur dioxide levels. We may expend tremendous amounts of money in trying to achieve 90 percent control and still not reduce sulfates to desirable levels. One of our current problems lies in developing a thorough understanding of the kinetics of the reactions that lead to sulfate production. The rate-limiting steps may be based on urban pollutants, and scrubbers may not be an effective solution.

We need to spend more time looking at new pollutants, nitrates in particular. It now appears that nitrates contribute significantly to the acidity of rainfall, yet in 1974 the problem was attributed to sulfur dioxide emissions from power plants. Controlling oxides of nitrogen is going to be a much bigger problem. It may mean more stringent controls on automobile emissions and more extensive controls on power plant emissions. If we don't consider these things now, we may end up with our power plants producing electricity just to run control equipment.

DR. ALTSHULLER: I would like to discuss briefly how research and development may lead rather than lag regulatory decisions. An example of the impact of research in this respect shows up in the 1977 Clean Air Act Amendments. We see there, for the first time, the recognition by Congress that in the case of ozone one must consider the problem on a regional rather than an urban or local basis, and a call for developing guidelines for regional ozone models. This may be just the tip of the iceberg. If we consider sulfates, nitrates, and perhaps organic aerosols, with respect to acid precipitation, we see that, although there may be a thin basis of research, all of these may involve long-range transport and regional-scale problems. In contrast, therefore, to what could be called the classical air pollution situation, in which concern is with local effects and local impacts of such things as carbon monoxide or SO_2, our concern will increasingly be on a more regional basis.

To individual communities this presents the problem of ascertaining where pollution comes from and in what proportions. Stated very simplistically, the methods for obtaining this information, are monitoring and modeling. On a regional basis, monitoring becomes increasingly difficult because at best one has at rather high cost a thin service network which does not answer the critical question of what is being transported aloft from elsewhere into the area. There is, therefore, increased need for the development of reasonable models, and an understanding of transport transformation rates and deposition is essential to this development. Fortunately, we do not have to understand each individual species, as a lot of meteorology has a common effect on all the species.

In terms of chemistry, the problem becomes more complex. It is interesting to correlate the summertime sulfate peaks, in both air quality and acid precipitation; the summertime ozone peaks; and the summertime peaks of nitrites—organic nitrate and nitric acid—which are indicated by data, albeit sparse, from both the United States and Japan. We heard earlier about the biological interactions of sulfate and ozone on animals and of SO_2 and ozone on plants. There are interactive patterns, and they seem to be more abundant during the summer months. The reasons for

this are extremely complex, but they are inevitably photochemical reactions: the radical species which convert SO_2 to sulfate also convert nitrogen oxides to nitrate convert and form the ozone and the organic aerosols. The effects of these various pollutant combinations suggest that, since we cannot focus our attention everywhere, we should direct our research toward the summer rather than the winter phenomena.

Finally, we must also remind ourselves that new energy sources interact with urban sources, particularly in terms of health effects. We need to really understand the interactions between surface and near-surface urban sources and elevated sources as they affect air quality. This further complicates the problems in monitoring and modeling because again there is the problem of separating the local urban contribution from that which is imported.

DR. PUESCHEL: One of the severe handicaps in predicting the effects of pollutants, specifically pollutants from coal combustion to produce energy, is our failure to identify properties of certain pollutants which relate uniquely to their origin as well as to their effects. A case in point is visibility, which by act of Congress is an air quality standard in the western United States and which EPA has responsibility for regulating. Professor Wilson finds a strong correlation between visibility in the eastern United States and the sulfate concentration. This could be the case, but Dr. McNelis has also pointed out that in the western United States, specifically in Utah, a reduction of visibility by a factor of three is not related to an increase in sulfates. The particles change. These, by virtue of their shape and elemental composition are either nitrates—and in addition to the acid rain problem, there is a correlation indeed between nitrates and visibility—or polymerized hydrocarbons from perhaps two sources. These sources are the combustion of gasoline in automobiles, known as smog, and the vegetation. The hypothesis for particle formation by hydrocarbons from trees was postulated as early as 15 years ago. This is an example of a cause and effect relationship which must be understood before considering any regulatory measures for power plants which operate in the vicinity. Research is needed to increase our capability of detecting specific properties to establish this cause and effect relationship.

questions & answers

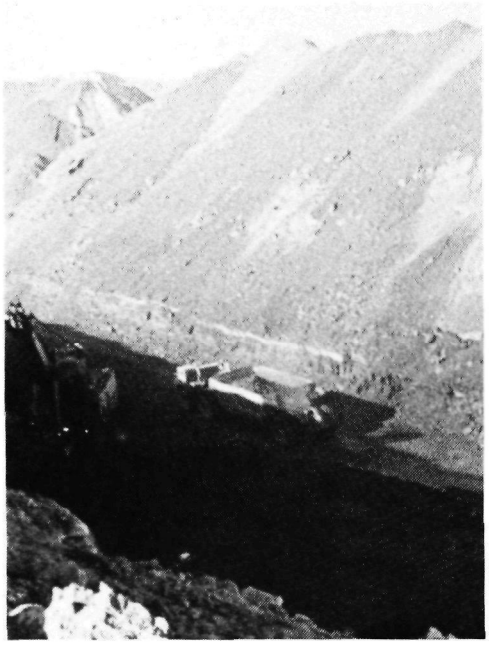
Dr. Edward S. Rubin
Carnegie-Mellon University

QUESTION

The panelists' discussions this afternoon have been exclusively about power plant pollutants, particularly SO_2 and SO_4. Could the panel discuss the contribution, particularly in the eastern United States, of the other types of urban area pollutants that Dr. Altshuller referred to? For example, for residential, commercial, and industrial activity a lot of oil is used, that also releases SO_2 at lower elevations. Obviously that has significant regulatory overtones.

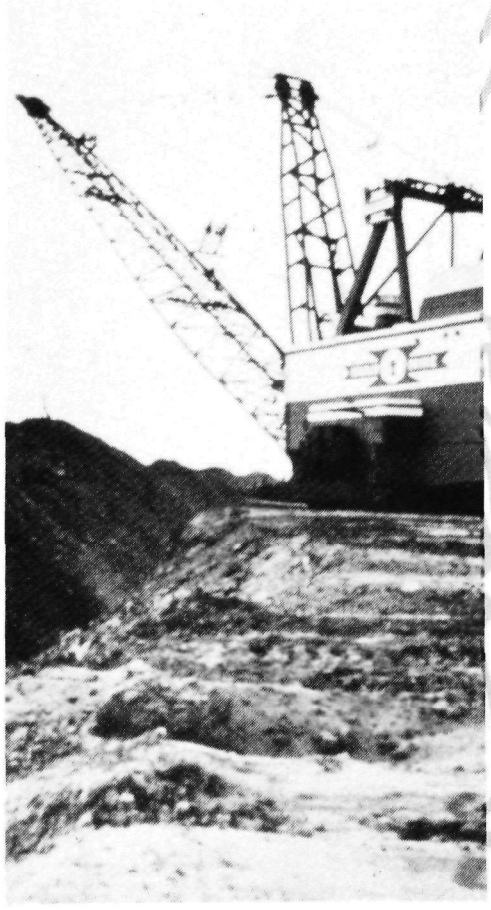
RESPONSE: Dr. Stanley Auerbach (Oak Ridge National Laboratory)

In general, the EPA and other agencies have done analyses based on ambient SO_2 standards. Their projections show foci of SO_2 around certain urban areas in the eastern United States. They are very clear. The decided peaks in ambient SO_2 are of particular interest to the human health people. What we don't know is how these urban areas contribute to transcontinental and regional areas. On an ambient basis they are very, very pronounced.



mining methods and reclamation

chapter 4



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MINING METHODS AND RECLAMATION

METHODS FOR THE CONTROL OF ENVIRONMENTAL DAMAGE CAUSED BY MINING ENERGY PRODUCING MATERIALS

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A DESTRUCTIVE PROCESS

By its very nature the extraction of fuel is a destructive process. Environmental degradation is bound to occur. In figure 1, the numerous emissions produced by the extraction process are illustrated. These environmental insults can be divided into several major categories: solid waste handling and disposal, water discharges, air discharges, noise, and aesthetics.

Mining is the largest producer of solid waste in the United States. Not only must large volumes of rock and soil be removed to extract a fuel, but additional large volumes are produced when the material is processed. The handling and disposal of this solid waste is the major cause of drastically disturbed lands. When improperly disposed, ground and surface water pollution, fugutive dust, landslides, and aesthetic problems result.

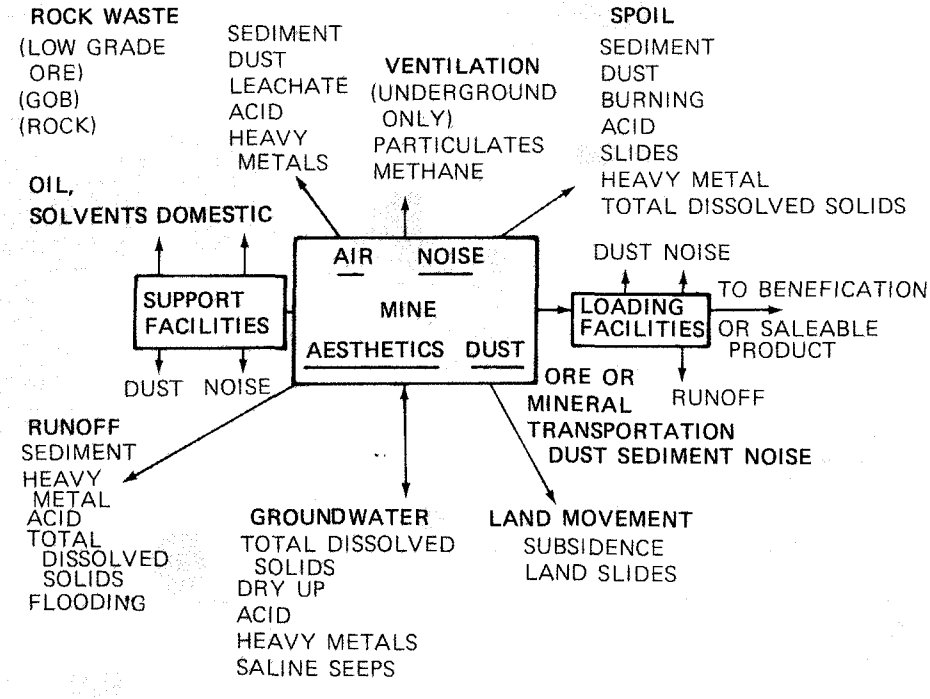


FIGURE 1—*Emissions from extraction process*

During mining and beneficiation, environmental problems occur from the runoff from the disturbed area, water in the pit area, dust and noise from blasting, extraction, haulage, storage, and grinding; and oil, solvents, domestic and other waste from the support facilities.

ABANDONED INACTIVE MINES

In addition to current mining operations, there exists a legacy of abandoned/inactive mines. A 1969 Congressional study reported that inactive coal mines were the source of 78 percent of acid mine drainage.

Pollution control from mining is strongly related to whether the mine is active or inactive. Active mining operations are under the regulation of some state and/or federal agencies and a responsible party; i.e., the mine owner is available. In the case of the inactive mine, responsibility and ownership are often unclear, regulations and laws are not available, and funds for pollution control are unavailable or must come from the public sector.

ENVIRONMENTAL PROBLEMS

The principle environmental problems associated with the mining of coal are sediment, mine drainage, subsidence, and fugitive dust. For the purposes of this discussion, these terms are defined as follows:

- Sediment means the undissolved organic and inorganic material transported or deposited by water.
- Mine drainage is water discharged from the mine site. Acid drainage is water with a pH of less than 6.0 discharged from an active or abandoned mine and from areas affected by coal mining operations.
- Subsidence means the settling or sinking of the land surface due to drainage or underground mine roof falls.
- Fugitive dust means those airborne particulate emissions that are generated at ground level as a result of equipment activity or material transfer.

SEDIMENT

Sediment in water reduces light penetration and alters the temperature which directly affects aquatic flora and fauna. Fish production is hindered because food organisms are smothered, spawning grounds destroyed, and pools filled. Sediment places an additional burden on treatment plants and increases cost as well as lowering aesthetic and economic values. Sediment deposit in navigable streams must be removed at a high cost. Streams filled with sediment have reduced carrying capacity and are subject to flooding.

The mechanisms of soil erosion by water consist of soil detachment by raindrop impact and water scoring and transportion by surface flow. Sediment yield can best be described by the Universal Soil Loss Equation (USLE) which combines the principal factors that influence surface soil erosion by water. These factors are precipitation pattern and intensity; soil erodibility based upon the soil characteristics such as texture, organic matter, clay content, and chemical properties; length of slope; steepness of slope; cropping and management which takes into account the vegetative cover, seeding method, and soil tillage; and erosion control practice such as terraces and diversions.

MINING METHODS CONTROL SEDIMENT

A study by Collier and others showed the average annual sediment production from a surface-mined watershed was 42 tons/acre, more than 1,000 times higher than an unmined watershed. Curtis studied three watersheds in Kentucky and found the sediment yield to range between 0.84 and 1.27 area-inches per area disturbed. He found little correlation between sediment yield and the amount of land disturbed and concluded that methods of mining and handling the overburden are major factors controlling sediment yield. He also noted that the highest sediment yields were measured during the first 6 month period after mining. This indicates the need for more attention to activities during and immediately following mining and the importance of an adequate cover of vegetation and of establishing control structures as quickly as possible after mining ceases.

POTENTIAL EROSION

The current state-of-the-art provides methods that can minimize the effects of erosion. Mining methods such as haul-back, and mountaintop removal/valley fill, when properly executed, can significantly control potential erosion. Engineering formulas are available for the design of sedimentation ponds to catch sediment before leaving the mine site. Areas that have been mined should be reclaimed as soon as feasible in order to hold the soil in place and provide a good plant media. Revegetation techniques are either available or are being developed to reclaim mined areas in all areas of the country. In all cases, a soil technician or agronomist should determine the proper species to be planted, the fertilizer and soil admendment requirements, the necessary mulch, and where possible topsoil should be applied. Prime concern in the selection of the cover crop is that of immediate cover followed by a native species that will perpetuate natural cover.

There are still some problems that exist with the ultimate design of sediment ponds. These include the application of erosion practices to mining situations and the final development of sediment pond technology.

ACID MINE DRAINAGE

One of the most damaging waterborne contaminants from coal mining operations is the acid generated from the exposure of iron sulfide minerals found in the coal and overburden. Not only does the acid directly impact stream biota, eat away metal structures and destroy concrete, but as a result of the low pH, other ions such as heavy metals, become solubilized and are carried into water courses. These ions are often toxic to aquatic life and render the water unusable for domestic, municipal, and industrial use. In 1969 it was estimated that in excess of 10,000 miles of streams have been degraded by acid mine drainage from active mines by industry and improved surface mining techniques. The quantification of the impact of acid mine drainage in terms of dollars loss has never satisfactorily been accomplished.

EXPOSED PYRITE ROCK

The removal of overburden often exposes rock materials containing pyrite (iron disulfide, FeS_2). The oxidation of pyrite results in the production of ferrous iron and sulfuric acid. A further reaction then proceeds to form ferric hydroxide and more acid. As noted in table 1, the products of these various reactions are iron, sulfate, acid, and the various heavy metals that may be associated with the host pyrite such as Cu, Zn, Al, and Mn. Organics have also been found in mine drainage. These are shown in table 2.

TABLE 1
Typical acid mine drainage

Parameter*	Mine # 1	Mine # 2	Parameter*	Mine # 1
pH	5.0	2.8	As	0.01
Acidity, $CaCO_3$	640	470	B	0.5
Alkalinity, $CaCO_3$	17	0	Cd	0.001
Ca, $CaCO_3$	370	210	Cr	0.05
Mg, $CaCO_3$	110	93	Hg	0.0003
Fe, Total	300	93	Cu	0.01
Fe, Ferrous	270	0	Ni	0.20
Na	480	2	Se	0.001
Al	15	31	Zn	0.25
Mn	6	4	PO_4	8.6
SO_4	3040	610		
T.D.S	4320	1050		
Conductivity	3760	1190		

* All units mg/l (liter) except pH and conductivity (micromhos/cm).

NOTE: In-house EPA data.

TABLE 2
Organic priority pollutants found in coal drainage

methylene chloride	1,1,2,2–tetrachloroethene
chloroform (trichloroethane)	1,2–trans–dichloroethylene
bis (2-ethylhexyl) phthalate	di–n–butyl phthalate
benzen	1,1,1–trichloroethane
toluene	trichlorofluoromethane

TABLE 3
Acidity figures for Appalachian area coal mines–1969

Source	Acidity 1,000 lb/day	Percent
Underground, Active	614	19
Underground, Inactive	1,712	53
Surface, Active	28	01
Surface, Inactive	361	11
Combined, Active*	60	02
Combined, Inactive*	238	07
Other	245	07
	3,258	100

*Includes sources where underground could not be separated from surface.

A UNIQUE POLLUTANT

Acid mine drainage (AMD) is a unique pollutant because acid generation and discharges continue to occur after mining has ceased. The most comprehensive survey of the magnitude of acid mine drainage discharges was reported in 1969. The results of this survey are shown in table 3. Underground mines contribute over 70 percent of the acid mine drainage. Inactive mines are also a major contributor.

The acid mine drainage problem is essentially a regional one. Most of the problem lies in the Appalachian Region. Acid discharges are also found in the Interior Region such as in the states of Indiana, Illinois, and western Kentucky. Except for some isolated situations, acid mine drainage is not a problem in the western states because the coal and overburden are low in pyrite and have a high alkaline content.

Control technology for the elimination of acid mine drainage can take one of two forms. Steps can be followed during the mining operation to prevent the acid from being formed. If this is not possible, numerous techniques are available to treat acid that is being produced from a mine.

OXYGEN CONTROL

All techniques for preventing acid formation are based on the control of oxygen. There are two mechanisms by which oxygen can be transported to pyrite–conductive transport and molecular diffusion.

The major convection transport source is wind currents that can easily supply the oxygen requirement for pyrite oxidation. Wind currents against a steep slope provide sufficient pressure to drive oxygen deeper into the spoil mass. Therefore, a factor to consider is the degree of slope after regrading. This is especially important on slopes subject to prevailing winds, since the wind pressure on the spoil surface increases as the slope increases.

Molecular diffusion occurs whenever there is an oxygen concentration gradient between two points, e.g., the spoil surface and some point within the spoil. Oxygen will move from the air near the surface of the spoil, where the concentration is higher, to the gas or liquid-filled pores within the spoil, where it is lower. The rate of oxygen transfer is strongly dependent on the fluid phases and is generally much higher in gases than in liquids. For example, the diffusion of oxygen through air is approximately 10,000 times greater than through water. Therefore, even a thin layer of water (several millimeters) serves as a good oxygen barrier.

OXYGEN BARRIERS

The most positive method of preventing acid generation is the installation of an oxygen barrier. Artificial barriers such as plastic films, bituminous, and concrete can be effective, but they have high original and maintenance costs and are used only in special situations. Surface sealants such as lime, gypsum, sodium silicate, and latex have been tried, but they too are high in cost, require repeated application, and have only marginal effectiveness.

The two most effective barrier materials are soil, including nonacid spoil, and water. The minimum thickness of soil or nonacid spoil needed is a function of the soil's physical characteristics, soil compaction, moisture content, and vegetative cover.

Vegetation not only serves to control erosion, but after it dies, it becomes an oxygen user through the decomposing process. This further aids the effectiveness of the barrier. The organic matter that is formed also aids in holding moisture in the soil.

WATER BARRIER

Water is an extremely effective barrier when the pyritic material is permanently covered. Allowing the pyrite to pass through cycles where it is exposed to oxidation and then covered will worsen the AMD problem. Water barriers should be designed to account for water losses such as evaporation and should include at least 30 centimeters (1 foot) of additional depth as a safety factor.

Additional measures to control AMD are water control and inplace neutralization. Water serves not only as the transport media that carries the acid pollutants from the pyrite reaction sites, but it erodes soil and nonacid spoils to expose pyrite to oxidation. Facilities such as diversion ditches that prevent water from entering the mining area and/or carry the water quickly through the area can significantly reduce the amount of water available to transport the acid products. Sediment and erosion control are needed both during and following mining. Terraces, mulches, and vegetation, used to reduce the erosive forces of water are effective measures to prevent further pyrite exposure. These measures usually are performed during reclamation.

Alkaline overburden material and agricultural limestone can be blended with hot acidic material to cause inplace neutralization of the acid and assist in establishing vegetation. In some cases, grading directs acid seeps to drain through alkaline overburden. These techniques are more applicable to abandoned surface mines than to current mining, where proper overburden handling should prevent acid formation. The major exception may be those situations where an underground mine was breached and an acid discharge formed.

TREATMENT PROCESS

Certain discharges from extraction process cannot be controlled at the source and, therefore, must pass through some type of treatment process. This is usually the case at an active mine because specific discharge criteria imposed by the state and federal government must be met. Inactive/abandoned mines present another situation, because, although treatment may be the only acceptable method to prevent environmentally damaging emissions, no party or funds are available to take over the long term commitment of treatment.

EPA has developed effluent guidelines for most of the mining industry. These guidelines, in general, recommend limits on the concentration of acidity and heavy metals that can be discharged. Typical values are presented in table 4.

INPLACE NEUTRALIZATION

Neutralization is almost the exclusive treatment process used by industry today. The neutralization process provides the following benefits:

- Removes the acidity and adds alkalinity.
- Increases pH.
- Removes heavy metals. The solubility of heavy metals is dependent on pH; that is, up to a point, the higher the pH, the lower the solubility.
- Ferrous iron, which is often associated with acid mine drainage, oxidizes at a faster rate to ferric iron at higher pH's. Iron is usually removed in the ferric form.
- Sulfate can be removed if sufficient calcium ion is added to exceed the solubility of calcium sulfate; however, only in highly acidic acid mine drainage does this occur.

SHORTCOMINGS

Some shortcomings of the neutralization process are:

- Hardness is not reduced and may be increased.
- Sulfate is not reduced to a low level and usually exceeds 2,000 mg/1.
- The iron concentration usually is not reduced to less than 3-7 mg/1.
- A waste sludge is produced that must be disposed.

Although several alkaline agents have been demonstrated to be successful in treating acid mine drainage, lime has been almost universally accepted by the industry.

Other treatment methods have been developed that produce a very high quality of water. The two methods that have proven most successful are reverse osmosis and ion exchange. The major drawback of these methods are their high cost and problems associated with disposal of the waste products.

SUBSIDENCE

The mining of a substantial quantity of underground material such as coal creates a void which in turn often produces a condition of instability within the rock leading to the collapse of the overlying rock into the void often creating surface subsidence. Subsidence begins as soon as the supports or pillars left in the

TABLE 4
Typical effluent guidelines for the mining industry

	Maximum for Any 1 Day	Average of Daily Values for 30 Consecutive Days Shall Not Exceed
pH	6–9	
Fe	1–7 mg/l	0.5–3.5 mg/l
Cu	0.1 mg/l	0.05 mg/l
Zn	0.4–1.0 mg/l	0.1 – 0.5 mg/l
Pb	0.4 mg/l	0.2 mg/l
Total Suspended Solids	30–70 mg/l	20–35 mg/l
Hg	0.002 mg/l	0.001 mg/l
Cd	0.10 mg/l	0.05 mg/l
Cn	0.02 mg/l	0.01 mg/l
Al	1.2 mg/l	0.6 mg/l
As	1.0 mg/l	0.5 mg/l
Mn	4.0 mg/l	2.0 mg/l

mine are no longer able to support the overburden weight. This condition may occur during the mining operation or may not occur until many years after mining has been completed and the pillars slowly decay to the critical failure point. Once the overlying material falls into the mine void, then cracking and caving proceed upward over a finite period of time often reaching the surface and causing considerable damage.

EFFECTS OF SUBSIDENCE

Earth movements at the surface may result in many varied types of damage. Buildings are more severely affected by the compressive and extensive strains associated with subsidence than they are by the actual settlement. Highways, bridges, water and gas lines may be sheared, twisted, or broken by strains and slope changes produced by subsidence. Sewage lines are especially susceptible to changes of slope that can locally reverse their direction of flow. Effects upon the natural environment can also be quite dramatic. Natural drainage patterns can be changed resulting in formation or occasional destruction of swamps. Surface streams often are intercepted by subsided areas or induced rock fractures resulting in flow into deep mines and loss of surface waters. In severe cases, groundwater supplies may be intercepted and drained into underlying deep mines.

MAGNITUDE OF PROBLEM

No definitive national analysis of the amount of land affected by past mine subsidence or of the annual or total property damage has been made. However, an appreciation of the magnitude of the problem can be gained from the experience of the Coal and Clay Mine Insurance Fund of the Commonwealth of Pennsylvania. Although only a small portion of undermined and developed land in Pennsylvania is insured (about 7,500 policies in effect), nearly $1 million is paid out annually in damage claims. Approximately 2,800 separate subsidence incidents involving damage have been reported for the anthracite fields of Pennsylvania alone. The U.S. Bureau of Mines has estimated subsidence costs, both surface damage and control costs, for a 12-county area in Western Pennsylvania for the year 1968 at $295,000 with an additional $4.3 million of coal left in place to minimize potential surface damage. These figures would be much higher under current economic conditions.

Each instance of subsidence is unique. Although the surface appearance of subsidence features can vary greatly, occurrences can generally be classified as pothole, linear, or regional.

The President's 1973 energy message encouraged the use of domestic coal to meet the needs for energy. Since low sulfur coal lying in close proximity to the ground surface is economically attractive to energy producers, much of the near-surface coal resources in the West are important. The emphasis on use of western coals has been reiterated by private and federal sectors with increasing frequency.

WESTERN STRIPPABLE RESERVES

According to U.S. Bureau of Mines estimates, the western coal fields contain more than 60 percent of the strippable coal reserves in America. It has been estimated by the federal government that, in 1985, 1.09 billion metric tons of coal must be mined to meet the demand in the industrial, power generation, synthetic gas, and export sectors of the market. This amount will double the coal production of 544 million metric tons for last year. To achieve a total production of 1.1 billion metric tons, nearly 300 million metric tons will have to come from western coal fields to supplement the estimated 850 million metric tons derived from the traditional coal-producing regions of the East and Midwest. Comparing that figure with last year's production from western states of approximately 54 million metric tons, one begins to grasp the scope of potential coal development in this area of the nation. Although characterized by low Btu and high ash content, western coal contains very little sulfur, and the large size of the coal fields makes them attractive to the huge industrial plans that could result from future growth i.e., gasification and liquefaction processes.

While the adverse impacts of coal mining in the eastern United States have been well documented and intensively researched, relatively little is known concerning the potential degradation that may result from large scale mining in the arid West.

SALINE WATERS

Suspected water pollution problems are salinity, sediment, and groundwater disturbance. To date saline waters have not been critical; however, preliminary results indicate that saline discharges as high as 23 kg/meter of spoil can be produced. The treatment of saline waters, beside holding and evaporation, requires advanced methods such as reverse osmosis, ion exchange, or distillation that are costly and at this time are not economically justified.

Some coal seams are aquifers and are a principle source of freshwater. Mining may result in alteration of groundwater distribution by aquifer disruption. Presently the magnitude of the aquifer disruption problem has been limited and methods to mitigate the problem are just now under study. In addition, if solid wastes from power plants and gasification plants are to be returned to surface mines where aquifers were present, additional groundwater pollution problems may be created.

Western overburden material is of young geologic age and subject to excessive erosion. Stabilization of the spoil, as quickly as possible after grading, is required to minimize sediment discharges. Flash flooding and wind erosion constitute major hazards in damaging soil loss. Possible air pollution problems involve fugitive dust from extraction, loading, hauling, and support facilities. In addition, emissions from spontaneous combustion of coal seams and waste materials could cause considerable air quality degradation.

One of the major drawbacks to western reclamation is revegetation. Climatic conditions are extreme. Seventy-five percent of the western coal fields receive less than 50 cm. of annual precipitation. In addition to limited precipitation, seasonal temperatures can vary from -51° to 49° C, only short frost-free periods are available, wide variations are present in overburden material, and adequate topsoil is lacking.

Water is the key to any successful reclamation program in the West. Ample moisture at planting and during establishment is critical. Techniques for acquiring additional moisture are being developed. These include studies on surface manipulation, irrigation, and mulching and the impact of these practices on surface and groundwater quantity and quality.

OCCUPATIONAL INTERESTS

The people of the West generally express concern over expanded extraction in terms of their own occupational interests. Not everyone is fearful about the effects of developing the coal. There are people who view the development as something good. They see increasing coal development in terms of an expanding economic base, new jobs, better services, and a chance to broaden cultural horizons. Many ranchers and farmers are worried about competition for land and water and about the conversion of present and potential agricultural water supplies to industrial usage. Some believe that mined land cannot be reclaimed nor shallow aquifers rebuilt. A general concern shared by most people is the impact of air pollution on range vegetation, crops, and abundant wildlife resources. The several Indian tribes in the region are concerned over the impact of coal development on or near their reservations in terms of water rights, resources, and cultural values.

Offsetting this rather gloomy picture, however, is a general (although cautious) optimism that the environmental impacts of western strip mining, both during and after mining, can be reduced to acceptable levels by suitable planning and operating technologies. In short, mined lands can be reclaimed. Reclamation as an add-on technology will no longer suffice. Rather, environmental factors must be considered during premining planning; reclamation must be an integral part of the mining process. This fact manifests the realization that the environment is best protected by designing (and using) new mining technologies (methods and equipment) that consider reclamation objectives as well as production goals. Such technologies cannot be developed solely by mining engineers nor solely by geologists, hydrologists, and agricultural scientists. Instead, an interdisciplinary approach is necessary.

OIL SHALE

Oil shales occur in both the western and eastern parts of the country in large volume. Estimates of the recoverable shale oil run into the hundreds of billions of barrels. Recently, western oil shales have received considerable attention due to renewed commercial interest as well as government sponsored research and demonstration projects.

Western oil shale is actually a marlstone containing an organic material known as kerogen. In order to extract the oil, the rock must be heated to temperatures above 450° to 550° C, causing the kerogen to undergo pyrolysis yielding an oil product. Various mining methods have been devised to extract or prepare the oil shale for retorting.

OIL SHALE SURFACE MINING

Large scale open-pit mining was originally proposed for federal oil shale lease tract "Ca" in support of a commercial size retorting operation. The scale of the pit would be comparable to large copper and iron ore mines. Environmental problems could include large scale temporary disruption of the local environment, destruction of groundwater aquifers, fugitive dust, and reclamation associated with open pits. In addition, water requirements for dust control and revegetation could be extensive.

Large scale room and pillar underground mining has been proposed by several potential commercial developers including Union, Colony, Superior, and Paraho. The volume of material mined by underground methods would be substantially less for an equivalent shale oil production than with the use of open pit mining. The overburden would not have to be disturbed and the richest kerogen-bearing zones would probably be selectively mined. Surface disturbance would be far less and fugitive dust could be more easily controlled than for surface mining. However, substantial environmental impact may still occur to the groundwater system. Caution not to vent fugitive dust to the atmosphere must be taken. Mine drainage must be properly controlled and the retorted shale disposed of in an acceptable manner. Surface subsidence or fracturing between aquifers could occur unless the mine geometry was carefully engineered to avoid these problems.

SHALE *IN SITU* MINING

True *in situ* mining involves heating the shale inplace in the ground and extracting the oil through boreholes without employing conventional mining methods. Modified *in situ* mining differs from true *in situ* in that conventional underground mining techniques are used to remove approximately 20-25 percent of the rock in order to rubbilize the shale and retort the remaining shale in the ground. Both processes involve a mineral preparation phase in which permeability to air flow in the shale is increased by explosive fracturing or through the use of fluids or gases under pressure. The environmental impact of these mining methods may at first appear to be the least of any method since most of the waste is left underground. However, true or modified *in situ* mining necessitates retorting within the ground and hence the associated risk of groundwater contamination by leachates from the retorts. At the same time the retorts themselves and the fracturing necessary to achieve retort permeability may interconnect different aquifers reducing groundwater quality. Surface effects such as subsidence, gas leaks, and thermal pollution have not been assessed for these methods.

Tar sands are rock materials, usually sand or sandstone, which have part of the void space filled with viscous hydrocarbons. It has been proposed to mine tar sands by using either surface mining or *in situ* methods. Most U.S. tar sands occur in Utah where the environmental impacts of mining would be much the same as for western oil shale development. In terms of commercial interest and available technology, the tar sands industry seems well behind the oil shale industry. Environmental solution found for the oil shale industry may later be applicable to the tar sands industry.

URANIUM EXTRACTION

There are three primary mining methods that are used to extract uranium. These are surface mining, underground mining, and *in situ* leaching also known as solution mining. Regardless of the mining method used, several environmental problems are associated with the extraction of uranium.

The uranium content in extracted ore is approximately 0.2 percent. The remaining 99+ percent of the extracted material becomes waste spoils or tailings which require proper disposal. The open air storage of the spoils produce opportunities for substantial fugitive dust emissions. *In situ* mining of uranium using a leaching process risks the contamination of surface and groundwaters by the leachate. The mining of uranium, therefore, has the potential to produce air, water, and solid waste disposal problems.

FUGITIVE DUST

Most fugitive dust production in uranium extraction results from surface mining activities. Removal of topsoil and overburden, blasting, and hauling of overburden and ore are the activities most responsible for generating fugitive dust. The environmental impact of fugitive dust generated by uranium extraction is considered most serious in areas adjacent to the mines. The dust emitted to the atmosphere is predominantly silica, with trace quantities of uranium, thorium, and sulfates. Additional compounds and elements associated with the soils and ores of a particular area may also be present. Though it produces a small total impact, dust is easily picked up by moving water, thereby contributing to surface water contamination.

The *in situ* recovery process for uranium has existed for several years but has recently experienced a rapid growth. Increased costs associated with surface and underground mining have now made the *in situ* method economically competitive.

Typically, *in situ* uranium mining is initiated by drilling five holes, four of which are approximately 50 feet apart in the form of a square. Centered inside the square is the fifth hole. A leaching solution is injected into the four corner holes by use of a pumping mechanism. The uranium in the ore body is dissolved into the leaching solution. The uranium containing solution is pumped upward through the fifth hole and is recovered at the surface. The rate of solution extraction exceeds the rate of solution injection. This facilitates a continuous flow and minimizes the likelihood of solution back up and escape into the groundwater. The uranium is extracted from the solution, allowing the solution to be recycled. Holes are drilled on the periphery of the five-hole solution mining system in order to detect, and thereby minimize, the escape of the leaching solution into the groundwater.

The major environmental problem associated with solution mining is the potential loss of leachate which could result in the contamination of both groundwater and surfacewater. The opportunity for contamination arises not only through the natural mixing of the leachate with the groundwater, but also from the active migration of the solution in both horizontal and vertical direction. The magnitude and effect of such losses are unknown at the present time, but the possibility certainly exists. Where ammonium carbonate is used as the solubilizing agent, groundwater pollution from nitrates may occur. It is not yet clear if the extracted area can be totally reclaimed by a flushing process.

URANIUM MILL TAILINGS

In 1974, over six million metric tons of uranium mill tailings were generated. The tailings consisted of approximately 80 percent sand and 20 percent slimes. Tailings created by the processing of uranium ore are discharged to tailings ponds for disposal. Here, solid wastes settle to the bottom of the pond and any liquids present are recycled, evaporated, or infiltrate into the ground. Excess liquid is discharged to surface streams. From an environmental standpoint, complete recycle appears the most beneficial method. However, some milling practices preclude large scale recycling because of the buildup of undesirable constituents in and around the tailings pond. Several environmental problems may result from the tailings pond method of discharge. Tailings may contain such contaminants as radioactive materials, nitrates, sulfates, organic chemicals, and toxic trace elements. Water percolating through the tailings may pick up these contaminants, carrying them to ground and surface waters. Studies in New Mexico have shown that groundwaters have become contaminated by selenium contained in tailings ponds. This problem is most severe when tailings ponds are constructed in permeable soils. The use of a clay sealant and other pond liners which will retard the flow of water into the ground offer some control over groundwater contamination.

FEDERAL/STATE REGULATIONS

There are state and federal regulations that directly impact the mining of energy producing materials. The most significant of these regulations directed toward environmental regulation are summarized in the following paragraphs.

The Environmental Protection Agency is currently identifying and must report to Congress on those facilities defined under Section 169 of the Clean Air Act Amendments of 1977 as major emitting facilities. This definition applies to facilities with the potential to emit 250 tons per year or more of any air pollutant which could contribute to deterioration of air quality. The report to Congress will also

examine the air quality benefits of including such a facility in the category of a major emitting facility as well as administrative aspects of regulating such a facility. Mill tailings and associated mining and milling facilities that are considered major emitting facilities will be subject to fugitive dust control by Best Available Control Technology (BACT). However, it is envisioned at this time that fugitive dust emissions will not be subject to an air quality assessment to determine the increment of air quality that these emissions consume.

UNDERGROUND INJECTION CONTROL PROGRAM

Where the effluent from a tailings pond is disposed of by underground injection or where the effluent is pumped to a shaft or worked out mine area for disposal in the ground, that effluent will be subject to the underground injection control (UIC) program. The requirement for the underground injection control program appears in Section 1421 of the Safe Drinking Water Act 1974. The proposed regulations dealing with UIC, which first appeared for public comment in the *Federal Register* in 1976, have since undergone extensive revision.

The Federal Water Pollution Control Act (FWPCA), Section 307, requires that the Environmental Protection Agency publish and periodically update a list of toxic pollutants. These pollutants are to be subjected to effluent limitations based upon the application of Best Available Technology Economically Achieveable (BATEA). Prior to June 1976, the Environmental Protection Agency had devoted little time to establishing effluent limitations for toxic substances in water. However, on June 7, 1976, the Environmental Protection Agency signed an agreement which settled four lawsuits brought against the Agency by the Natural Resources Defense Council and the Environmental Defense Fund. These suits were aimed at forcing the Agency to expand the list of toxic substances to be regulated under Section 307(a) of the Act, to promulgate final 307(a) standards which had been previously proposed, and to promulgate previously proposed pretreatment standards. In reaching a settlement, the Agency agreed to promulgate 307(a) standards for six of the nine pollutants for which standards had been proposed previously and to complete rulemaking for existing sources of pretreatment standards for eight industrial categores. However, in exchange for expanding the 307(a) list and for near term promulgation of additional pretreatment standards, the Agency agreed to review and revise by the end of 1979 best available technology (BAT) standards for 21 industrial categories, including the coal industry, with a primary focus on a list of 65 toxic or priority pollutants.

PRIORITY POLLUTANT LIST

The Settlement Agreement list of 64 toxic or priority pollutants was composed of compounds and classes of compounds. These classes were then expanded into sublists of specific representative compounds to remove any ambiguities in the study efforts. Thus, the toxic or priority pollutant list actually contains a total of 129 chemicals (114 organics, 13 heavy metals, cyanide, and asbestos). A list of the organic pollutants found in coal mine drainage is shown in table 2.

The Ore Mining and Dressing and coal industry are in the group that must have effluent limitation standards by December 1979. The Effluent Guidelines Division is undertaking research to examine treatment of tailings pond liquors from uranium mills, assuming all ponds are lined. This research will examine the economic, environmental, and technical aspects of (1) total containment, (2) recycle of liquor, and (3) effluent release following best practical treatment. In the latter case those pollutants identified in the consent decree will be addressed.

Recent amendments to the Federal Water Pollution Control Act have extended compliance by industry in meeting effluent limitations to 3 years. The 1972 Act had set compliance at 1 year after effluent limitations were established.

BEST MANAGEMENT PRACTICES

Section 304e of FWPCA allows the Administrator to publish regulations (Best Management Practices) to control non-point sources of toxic or hazardous pollutants. Such Best Management Practices (BMPs) will supplement any effluent limitations for a class or category of point sources. These BMPs will apply to control of plant site runoff, spillage or leaks, and drainage from raw material storage. However, it must be determined that these pollutant sources are associated with the industrial manufacturing or treatment process within such categories or classes of point sources and that significant amounts of such pollutants are contributed to navigable waters.

Definition of BMPs is also being undertaken by the Effluent Guidelines Division of EPA and it is envisioned that tailings will be subjected to Best Management Practices.

WASTE TREATMENT MANAGEMENT PLAN

The Federal Water Pollution Control Act, in particular, Section 208 of that Act, requires the preparation and implementation of a areawide waste treatment management plan. This plan is developed for areas which have been identified by the Governor of a State for exhibiting substantial water quality control problems. While the Act is relatively broad in specifying what the areawide plans shall contain, it specifically references the need for a process which would identify mine related sources of pollution and methods to control those sources of pollution. The plan also requires the development of a process to control deposition of wastes which could effect water quality in the area and a process which would control the disposal of pollutants on land or in subsurface excavations in order to control ground and surface water quality.

The Resource Conservation and Recovery Act (RCRA) will subject mining waste, for example, tailings, to a rigorous study. Specifically, Section 2008f requires that a "comprehensive study of the adverse effects of solid waste from active and abandoned surface and underground mines on the environment be performed." This study will examine the effects of solid waste on humans, water, air, health, welfare, and natural resources. The study will also examine the adequacy of currently used measures to prevent or reduce the adverse effects of mining wastes. The study, currently under contract, will specifically analyze:

- The source and volume of discarded material generated per year from mining.
- Present disposal practices.
- Potential dangers to human health and the environment from surface runoff of leachate and air pollution by dust.
- Alternatives to current disposal methods.
- The cost of those alternatives in terms of the impacts on the mine products costs.
- Potential for use of discarded material as secondary sources of mine product.

The Act also requires the Administrator of EPA, as he deems appropriate, to review studies and activities of other agencies dealing with mining waste in order to avoid duplication of effort.

FEDERAL AND STATE PROGRAMS

If no actions are taken by the federal or state governments to control subsidence problems from future mining, then it is likely that present problems will be compounded and eventually remedial action will become necessary by government agencies. A 1976 U.S. Bureau of Mines report indicated that four backfilling demonstration projects were currently in progress for abandoned mine subsidence control with an estimated cost of $7 million. The U.S. Bureau of Mines estimates that it will be involved in three to five subsidence control projects (for abandoned mines) per year for the next 5 to 10 years. Presently there is no federal program to control creation of future subsidence problems. Only one state, Pennsylvania, has enacted legislation specifying the separate responsibilities of surface owners and mine operators for subsidence damage. Under Pennsylvania law, which applies only to the bituminous fields, a mine operator is responsible for damage to surface structures that were in existence prior to implementation of the law (1966). Surface structures built after 1966 in subsidence-prone areas can be protected by purchasing coal support from the mine operator.

NEW MINING LAW

The new surface mining law, Public Law 95-87, of August 3, 1977, addressed the subsidence problem in a general manner under Section 516(b)(1) which states in part,

> "Each permit issued under any approved State or Federal program pursuant to this Act and relating to underground coal mining shall require the operator to—adopt measures consistent with known technology in order to prevent subsidence causing material damage to the extent technologically and economically feasible, maximize mine stability, and maintain the value and reasonable foreseeable use of such surface lands except in those instances where the mining technology used requires planned subsidence in a predictable and controlled manner: Provided, that nothing in this subsection shall be construed to prohibit the standard method of room and pillar mining."

In order to adequately address the subsidence problem, a concerted effort is needed by all levels of government (federal, state, and local) to coordinate the surface development with the extraction of the coal so that maximum use can be made of each resource without conflicting with development of the other.

SURFACE MINING ACT

On December 13, 1977, the Department of the Interior, Office of Surface Mining Reclamation and Enforcement published in the *Federal Register* a set of interim rules and regulations titled the "Surface Mining Reclamation and Enforcement Provisions," more commonly known as the surface mining act. Some of the major sections of these rules and regulations are general and specific performance standards for the surface mining of coal, general performance standards for underground mines, and a program that will allow for the reimbursement to states to assist them in meeting the standards of this Act and to encourage the states to build strong reclamation and enforcement programs.

A great deal of controversy arose following the publication of this Act. Much of the discussion centered on the design criteria for sedimentation ponds and temporary diversion structures. As a result of these objections, the Office of Surface Mining Reclamation and Enforcement issued on February 27, 1978, Interim Final Rules and Notice of Public Hearing. These rules modify the design criteria for sedimentation ponds to allow for greater flexibility and to accommodate more diversity of the terrain and other physical conditions.

Work is presently ongoing to develop the final rules and regulations for this Act. It is anticipated that they will be published in the *Federal Register* in the fall of 1978.

FUTURE COAL NEEDS

There have been many estimates made as to the amount of coal that will be required in the future. These range from only a minor increase up to those who feel that coal production will more than double by the year 2000. All agree that coal production must increase. The source of this increased production will come from two major sources—eastern underground coal mines and western surface mines.

Eastern surface mines will continue to supply large amounts of coal. However, recent improvements in mining techniques such as haul back, mountaintop removal and valley fill, and the new surface mining act should significantly reduce the environmental problems created by surface coal mining.

The problems are not so simple for underground coal mining. One of the most significant problem is that created by subsidence.

SUBSIDENCE DAMAGE CONTROL

Although there is no simple or universal solution to all of the problems caused by subsidence, various means are available to control surface damages from future mining. Two basic approaches must be coordinated and applied to each situation. The first approach involves controlling the mining activity while the second involves controlling the nature of surface development. The specific subsidence damage control measures most suitable depend upon the extent of surface development that would be threatened by subsidence. For a heavily built up area underlain by mineable coal, the subsidence control measures must be aimed at preventing surface subsidence by controlling the mining operation to minimize surface disturbance. For nondeveloped areas the emphasis must be placed upon delaying surface development until the coal resource is extracted and the area has undergone subsidence and stabilized.

Future mining of high and medium density development areas in a manner which would result in future subsidence could have a major economic impact which would be unacceptable in terms of both individual impact and impact on the general welfare of the community. Mining technology presently exists which would generally permit recovery of approximately 50 percent of the coal while substantially reducing surface subsidence.

SURFACE SUPPORT

Conventional room and pillar mining can be modified to provide surface support in many cases by accepting much lower extraction ratios with careful attention to design, size, and spacing of support pillars. This method has been used successfully in Western Pennsylvania where present law requires the mine operator to provide surface support for some structures. Panel and pillar mining likewise can be adapted to minimize subsidence damage and is compatible with longwall mining. Shortwall mining techniques can also be adapted to provide surface support. The critical considerations in utilizing these methods involve abandonment of adequate coal for support (about 50 percent), adequate pillar size so that deterioration of pillars will not cause subsidence, and careful design of pillar placement to sup;ort the overburden. Other techniques have been proposed to reduce the impact of subsidence by minimizing the compressive and extensive strains that do most of the damage. These methods include extraction face control measures to control the propagation rate of the subsidence trough and harmonious extraction methods based on the principal of overlapping compressive and extensive strains to achieve a cancellation effect. In addition, various backfilling measures such as hand packing, mechanical backfilling, hydraulic backfilling, and pneumatic backfilling can be utilized to reduce the amount of surface subsidence. Although backfilling may appear to be an attractive subsidence control measure, the high costs involved, at least one to four dollars per ton of coal mined under favorable conditions, pose a serious question of economic viability.

LAND OWNERSHIP AND RIGHTS

Although methods exist to permit mining of a portion of the coal under developed areas without inducing subsidence, it it not likely that mine operators will voluntarily abandon a large percentage of their mineral resource unless they are required to provide surface support. The key to the problem is the recognition that land ownership and rights can be divided into three estates: surface rights, mineral rights, and surface support rights. Each of these can be held in separate ownership. Unless the surface property owner is assured the right of surface support it is likely that future mining under developed areas will produce substantial damage similar to that which has occurred in the past. If the mine operator must provide surface support then approximately 50 percent of the mineral must be abandoned which raises a key policy issue in terms of meeting the Nation's energy needs.

UNDEVELOPED COAL AREAS

For situations where mineable coal exists under sparsely or undeveloped areas the solution is simpler in concept but may prove equally difficult to implement. Future development of these areas should be controlled to preclude high or medium density development which may be subjected to future subsidence. It is recommended that, prior to approval of any surface development in areas underlain by coal, the potential for future mining and subsequent subsidence be reviewed. It is suggested that, in areas where mineral rights have been severed from the property rights, the property owner should be required to certify the specific status of the rights to surface support prior to subdivision or land development for which any state or local permit may be required.

Just as it is impractical to allow development to occur in areas where future mining may present a real threat of subsidence, it is equally impractical to consider that mining should be allowed to occur in a manner that the resultant subsidence potential is of a nature which cannot be defined in terms of time and extent. Regulation of the mining industry should be established which will avoid the creation of a potential subsidence problem. The principal problem presented with regulation of development in such cases is that it is presently impossible to predict when subsidence may occur. This precludes development of the land for an extended period unless very expensive stabilization measures are implemented. Two general approaches to mining techniques should be considered.

TWO GENERAL TECHNIQUES

- Mine in a manner that will not cause immediate or long-term subsidence problems.
- Mine in a manner which would result in immediate and complete subsidence.

Under the first approach it would probably be necessary to limit extraction to 50 percent or less, based on current generally accepted engineering principals. Under the second approach of total extraction or near total extraction, it would be necessary to ensure that the surface is left in or returned to a usable state. Flexibility in such regulation must, however, be maintained since physical problems may exist which would preclude implementation that would achieve the desired result. Trade-offs and alternative approaches must be accommodated to effectively deal with individual case situations.

OTHER POTENTIAL PROBLEMS

There are a number of other potential environmental problems that could develop due to underground coal mining. Drift mines, particularly those operating up the dip of the coal seam, have the potential for producing large amounts of acid mine drainage. This drainage does not necessarily drain out through the mine opening where it would be necessary to treat it. Some can build up in the abandoned workings and by moving down the interface between the coal and surrounding strata, find its way to the surface of the hillside as seeps and contaminates surface waters.

Underground mining operations, due to their high initial capital investment, must be extensive in order to provide the operator with a profit. Large underground openings can intercept numerous groundwater aquifers. These aquifers could be major sources of municipal water supplies. Even though the water would be pumped to the surface so that it could again enter the water supply, its quality could be significantly reduced.

As the coal sources near the surface become more depleted, it will become increasingly necessary to mine coal from much greater depths. The discharges from these mines could contain greater quantities of TDS than the discharges of mines located nearer the surface. This is caused by the greater thickness of overburden that the water would percolate through.

WESTERN & EASTERN PROBLEMS DIFFER

Many of the environmental problems associated with western coal mining are significantly different than those encountered in the east. These differences are caused by major variations in both the climate and in the soil conditions.

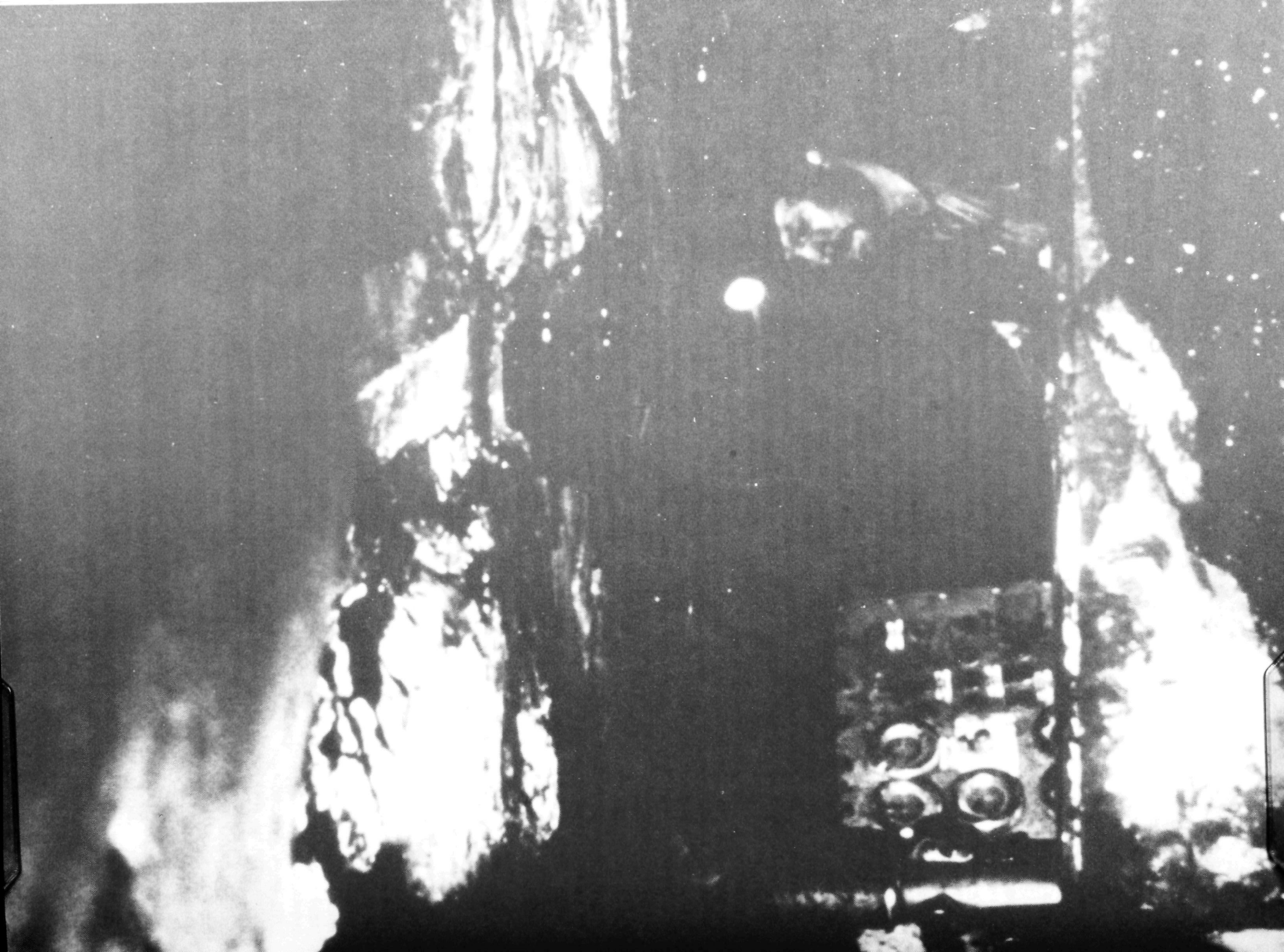
Most of the coal mined in the western United States is found in semi-arid or arid areas. The result is that fugitive dust is a much greater problem in the west than in the east. Haul roads produce large amounts of dust both from the normal traffic and naturally by the windy conditions that are often encountered. This problem could become increasingly important as more and more mines open within a relatively small area.

In many cases, western coal seams are major aquifers. Utilizing the methods presently used to extract western coal, i.e., large area type operations, aquifer disruption could become a serious problem. Methods need to be devised whereby the aquifer could be restored with no resulting loss in groundwater quality.

The soils in the west are generally alkaline rather than acidic; therefore, AMD is generally not a problem in the west. However, the alkalinity does cause its own type of environmental problem. The salts in the soil are very soluble. As the overburden is broken and overturned, these salts become very susceptible to leaching. The salts become concentrated, seriously contaminating the water with TDS. This water can become so brackish, that it is no longer useful, even for irrigation.

ALASKAN COAL PROBLEMS

The potential environmental problems associated with Alaskan coal could be immense. The mineable reserves in Alaska are tremendous. It has been said that the Alaskan coal reserves outstrip all those in the lower 48 states combined. Much of



the coal in Alaska is not flat lying but rather is steeply dipping. This alone can create numerous problems. Very little is known concerning the effects that mining will have on the permafrost and tundra. It appears certain that new mining methods will have to be developed to protect the fragile Alaskan environment if this coal is to be developed in an acceptable manner.

UNDERGROUND COAL GASIFICATION

Advancing technology can create new or different environmental problems. It is likely, that in the future, in situ coal gasification may become a significant source of energy. A detailed description of the various underground coal gasification processes being investigated is beyond the scope of this paper. However, all processes follow the same general procedure. Contact with the coal seam is made by drilling several boreholes from the surface. The permeability of the coal seam (to air flow) is then increased, and the seam is ignited and burned within a controlled temperature range, causing pyrolysis of the coal and release of the product gases. Air or oxygen must be injected through boreholes to support the combustion, while product gases are generally removed through separate boreholes. EPA is presently involved in supporting research to determine the possible environmental effects of underground coal gasification. At the present time the major environmental implications of underground coal gasification involve the following:

- air emissions
- groundwater pollution
- subsidence
- thermal pollution

For any of the mining methods, the disposal of spent or processed shale must be considered since essentially all of the shale mined ends up as a spent shale disposal problem. Possibilities for disposal include surface disposal in huge mounds or as valley fills, returning the spent shale to the mine (surface pit or underground mine) or in the case of modified *in situ*, slurrying the surface retorted spent shale for reinjection into the retorts.

SURFACE DISPOSAL

Surface disposal of spent oil shale is probably the most commonly postulated disposal method. However, numerous environmental problems must be solved. The spent shale must be cooled, transported to the disposal site, and properly contoured. These activities are capable of producing substantial quantities of fugitive dust unless proper control measures are taken. Once in the disposal area, the shale must be compacted and eventually revegetated. The shale must be leached to remove the salts and/or covered with a sufficient depth of soil to prevent the roots from reaching the spent shale. EPA studies on revegetation of oil shale indicate that problem areas that may be encountered include inadequate leaching of salts prior to planting, resalinization due to the upward movement of salts into the soil cover, initial high pH on the shales, saline runoff from revegetated shale, and the concentration of some toxic trace elements in the vegetation. In addition, a hazard exists for contamination of surface and groundwaters by leachate from the spent shale. One EPA study has indicated that the permeability of spent shale, even though it has been compacted, may be rather great. This result is much different from the early predictions that after compaction the spoil would be impermeable.

Disposal of spent oil shales in underground mines eliminates the revegetation problem but may increase the risk of contaminating groundwater supplies. Very detailed studies of the specific disposal site would be necessary to determine the risk of water leaching through the spent shale and moving into the groundwater system.

Disposal of spent shales by reinjection into the modified *in situ* retorts may complicate an already serious pollution question. Modified *in situ* retorts, as commercially proposed, intersect several permeable zones in their 300- to 7,000-foot height. Addition of surface retorts shale waste may increase the production of leachates which has ready access to the groundwater flow system. Once in the groundwater system the contaminates may also affect surface streams which are fed by groundwater recharge.

URANIUM EXTRACTION PROBLEMS

Uranium extraction in the future will present environmental problems of greater magnitude than present extraction unless adequate control technology is

developed. The rising price of uranium ore will make profitable the extraction of lower grade ore. Exploitation of the lower grade ore implies that more waste spoils and tailings will be generated per unit of ore mined. The increased wastes may produce several detrimental effects on the environment. More land will be disturbed to produce a given amount of uranium. The potential for fugitive dust emissions will increase due to the increased production of spoils and tailings. The proper disposal of solid wastes will require finding sufficient suitable disposal sites and/or reclamation methods to handle the increased tailings and spoils.

GROUNDWATER CONTAMINATION

Groundwater contamination may become a future problem in areas surrounding uranium mines if *in situ* mining and underground waste injection become more common. As stated earlier, losses of the leachate used in *in situ* mining occur due to dilution and mixing with groundwaters. Mixing introduces the opportunity for groundwater contamination by such leaching compounds as sulfuric acid and ammonium carbonate.

Several uranium mills presently dispose of toxic liquid and chemical wastes by deep well injection. These wastes result either from excess liquid that has not evaporated in the tailings ponds or from waste regenerant solutions used by *in situ* mining operations. The disposal zone is usually several hundred feet below the surface. It should be separated from aquifers by impermeable formations to prevent contamination of groundwaters. Little is known about the long-term impacts on groundwaters due to deep well injection. Wastes disposed of in this manner typically have high concentrations of dissolved solids and contain toxic heavy metals such as molybdenum, arsenic, selenium, and uranium. Contamination of aquifers from injected wastes appears to have occurred in New Mexico. The injection of these toxics into the ground presents a real, though presently uncertain, threat to groundwater near the injection site.

COAL EXTRACTION R&D

The Extraction Technology Branch of the Industrial Environmental Research Lab, Cincinnati, is involved in research that seeks to minimize the environmental disturbances associated with the extraction of coal. Disturbances related to coal extraction include air and water pollution and production of solid wastes. A number of the research programs deal with the development of environmentally acceptable methods for mining coal. Projects are underway that will assess mountaintop removal, head-of-hollow fill, steep slope, surface longwall, modified block-cut, and daylighting mining methods.

Other research projects are evaluating various sediment control techniques. These include a project to demonstrate the effectiveness of debris basins and to demonstrate methods to reduce sediment that is generated from haul roads. Another project is applying current technology to improve techniques for surface mine sediment control. The use of a vegetative filter zone to control fine grained sediments is being evaluated.

GROUNDWATER POLLUTION RESEARCH

Four projects are evaluating techniques to minimize groundwater pollution. One project is evaluating the feasibility and effectiveness of using gravity connector wells to improve stream quality by reducing groundwater drainage from abandoned underground coal mines. Another project will assess the economics of intercepting groundwater inflow into an active coal mine, with emphasis on reducing the amount of acid mine drainage. The third project is to establish criteria to locate sources and define the quantities of water that will enter underground coal mines through faults, fractures, etc. The final project will determine the potential for underground coal mines to pollute the groundwater in the vicinity of mining operations. The study will involve detailed evaluation of groundwater conditions as selected sites.

In order to avoid duplication of efforts and to help inform interested persons regarding oil shale research in progress, the working document entitled, "Oil Shale Research Overview" was prepared. The May 1977 edition of this document lists 148 federally-funded oil shale research projects of which 73 are being funded by various EPA offices. The Research Triangle Park Health Effects Research Laboratory of EPA is assessing human exposure effects relationships and evaluating hazards to man under controlled experimental conditions. The Industrial Environmental Research Laboratory, Cincinnati, supports coordinated, interagency oil efforts by administering

an R&D program covering environmental assessment of extraction and process control technology. Current activity by the EPA Duluth Laboratory includes oil shale-related fresh eater ecosystem effects. Region VIII of EPA will develop a comprehensive information profile for major fresh water aquatic environments that could be affected by oil shale development. EPA interagency participation is exemplified by the 42 interagency studies listed in the "Oil Shale Research Overview."

EPA MONITORING RESEARCH

Much of the EPA monitoring research is done at its Environmental Monitoring and Support Laboratory (EMSL) at Las Vegas, Nevada; Cincinnati, Ohio; and Research Triangle Park, North Carolina. Las Vegas activities include western regional air monitoring, groundwater monitoring and techniques development, and overhead monitoring. Cincinnati EMSL stresses water techniques development and quality assurance. Research Triangle Park is developing energy-related air monitoring quality assurance support and air pollutant measurement and instrumentation research.

FATE OF POLLUTANTS

EPA is studying the fate in freshwaters, groundwaters, and air of specific pollutants resulting from oil shale development. The Athens Laboratory is studying the fate of specific pollutants in freshwaters. EPA Region VIII is providing for the maintenance of an air quality monitoring network to continue to define long (5-year) baseline data information.

The environmental research and development results for the near term are expected to be characterization, control technology, assessment and measurement and monitoring protocols for oil shale development. *In situ* processing, extraction, surface retorting refining and combustion are included in current oil shale research activities.

URANIUM EXTRACTION PROBLEMS

Currently, the Extraction Technology Branch has only a limited program dealing with uranium extraction. One project will determine and document for one uranium-bearing aquifer system the interrelationships between aquifer geometry, hydrology, hydrochemistry, and mineralogy, and uranium mineralization and to determine how this natural system will respond to local chemical or physical stresses induced by uranium mining. Another project is evaluating potential problems of toxic elements associated with uranium mineralization and mining in South Texas.

ZERO & NONZERO DISCHARGE

A proposed study will evaluate candidate approaches for treatment and/or disposal of uranium mill tailings that have been discharged to lined tailings pond. Both nonzero discharge and zero discharge options will be considered. A nonzero discharge approach to be evaluated is the release of the tailings pond effluent to surface waters following application of Best Practicable Treatment (BPT) effluent limiations. Zero discharge approaches that will be evaluated include increasing the surface area of the tailings pond for increased evaporation and recycling of the wastewater.

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MINED LAND RECLAMATION

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HISTORY

Many people think of reclamation in terms of establishing vegetative cover. Reclamation of mined land is much more than that; however, in this paper reclamation is used synonymously with revegetation.

Commercial surface mining for coal in the United States began in Illinois just over 100 years ago. Natural revegetation of many of these areas probably began soon after mining ceased, because natural forces continually operate to vegetate disturbed land. For example, many of the 10- to 30-year-old coal surface mines in Alabama have been naturally reforested with loblolly pine and Virginia pine and now produce more commercial softwood timber than the surrounding unmined forest land (1).

Although some surface mines have been revegetated by natural means, the vegetation process can usually be hastened by planting. Among the earliest documented attempts at reclamation is the seeding of sweet clover on spoil-bank ridges by the Wayne Coal Company in Ohio as early as 1918. In 1920, several species of trees were planted on coal mine spoils in Illinois. Shortly thereafter research was started in Indiana to determine the adaptability of various tree species to conditions on spoil banks (2).

EARLY RESEARCH

A formal research program on the forestation of strip-mined land was started in 1937 by the U.S. Forest Service through its Central States Forest Experiment Station at Columbus, Ohio (3). Research was conducted in cooperation with the coal mining industry, state agencies, and agricultural experiment stations. The results of this early research were summarized by Limstrom (4). It involved mostly the evaluation of survival and growth of many different tree species. The value of planting nurse-trees such as black locust and European alder in mixture with other tree species received much attention. Thousands of acres of surface mined land have been successfully forested with species and planting procedures recommended by these early researchers. That research still serves as the basis for many revegetation guides in use today.

Before the 1960s, most of the research and consequently most of the reclamation centered on tree species; there was little concern for erosion and sedimentation. Anyway, most of the sediment from erosion on the ungraded spoil dumps was trapped in the depressions between the mounds. Herbaceous cover was considered a hindrance to the establishment and growth of planted tree seedlings.

HERBACEOUS COVER

Beginning in the early 1960s more and more emphasis was given to the quick establishment of herbaceous cover for erosion control and for esthetic purposes. This new emphasis was coincident with greatly expanded surface mining activity in the Appalachian region, where water runoff and erosion produce severe sedimentation problems. Subsequently, the use of herbaceous vegetation for ground cover and erosion control increased to the extent that for the past 10 years or so relatively few trees have been planted. Diversified plantings of grasses, legumes, shrubs, and

tree species are still needed to provide for a variety of future uses of the land. Reforestation is anticipated as a result of natural plant succession in much of the eastern United States, especially where an herbaceous cover is established for erosion control without further management.

As early as the mid-1940s some research on the use of herbaceous species in reclamation was reported (5). Subsequent trials and other research have been conducted by the Forest Service, Soil Conservation Service, Agricultural Research Service, and various state experiment stations. The results of these experiments have been incorporated into revegetation guides published by federal, state, and private agencies.

Many plantings have been made by industry-related groups such as reclamation associations and coal producers' associations, and by many individual mining companies. These plantings may also be used in evaluating reclamation success.

RECLAMATION TECHNOLOGY

Reclamation technology has made significant advances in the last 30 years with the most rapid developments coming during the past decade. Accomplishments have come about through the joint efforts of the many concerned individuals representing governmental, educational, and industrial interests. Acceptance of environmental issues as priority national problems permitted enactment and revision of laws regulating surface mining activities. Increased interest led to increased appropriations which permitted expansion of research relating to mined land reclamation.

Reclamation should begin with an evaluation of the overburden, including all soil and rock above the coal seam. In addition to economic and legal factors, chemical, physical, and biological factors must be considered in planning reclamation procedures. Acceptable reclamation usually means burial of undesirable overburden material in the spoil bank and adequate protection of the affected area from siltation, chemical pollution, and mass failure.

The chemical and physical properties of spoil determine the magnitude of the reclamation effort needed and the degree of success that can be attained. Some spoils require only grading and minimal treatment to allow successful revegetation. To be productive, others require many tons of lime and large quantities of mulch or organic additives in addition to fertilizer. On some spoils, saving and replacing topsoil is the best way to restore productivity. Surface water pollution resulting from severe erosion and movement of acid and soluble salts into streams is also a serious problem in surface mining. Mass failure of spoil banks can completely negate previously successful reclamation efforts, for landslides often occur after spoil grading and revegetation have been accomplished.

SPOIL DIFFERENCES

Society has had long and successful experience in dealing with earth surface materials. However, there are extremely important differences between these materials and the typical spoil. Unlike normal agricultural soils, most mine spoils are made up of freshly broken rock fragments. A reclamation plan not only has to deal with this material as it is now, but also of even greater importance, must consider what the material will become in the future as weathering reactions progress. The nature of these reactions profoundly influences all aspects of the reclamation effort.

If chemical processes do not provide nutrients of sufficient quantity and quality for plant growth, fertilizer must be applied. If, on the other hand, these reactions produce excessive acidity or toxic elements, appropriate amendments must be utilized. Water-soluble products can enter the surface and ground water of the area. Particulate matter formed by both physical and chemical breakdown of large fragments is highly erodible and may cause severe siltation in nearby streams. Engineered spoil banks and slopes may become unstable because of changes in the properties on which their initial design was based.

WEATHERING PROCESSES

The nature and extent of the weathering processes and the time required to reach relative equilibrium with the surface environment depend on such characteristics of overburden strata as mineralogy, geochemistry, fabric, and texture as well as upon methods of handling and placing the excavated materials. Many

materials found in sedimentary rocks are chemically unstable in the earth's surface environment. Pyrite, a common mineral in coal-bearing sediments, is one of the more important of these unstable materials, for the oxidation of pyrite forms soluble iron salts and sulfuric acid. This is the major source of acid mine spoil and acid mine drainage. In addition, these highly acid solutions can break down other minerals that are resistant to weathering. A common result is high concentrations of soluble aluminum and manganese. These are notoriously toxic to most vegetation. In some areas, toxic levels of heavy metals such as copper, nickel, and zinc are also produced (6).

CHEMICAL ANALYSIS

Chemical analyses can be used to determine the elements present in the strata from which spoil is formed. However, simply because an element is present does not necessarily mean that it will become available after disturbance of the overburden; consideration must be given also to such factors as its mode of occurrence and its potential to react with other weathering products. These factors can be evaluated by correlation of chemical analyses with petrologic analyses. A petrologic analysis should include at least determination of mineralogy, porosity and permeability, grain-size, and fabric. Knowledge of these characteristics along with the inorganic and organic geochemistry of the overburden will enhance the ability to predict weathering reactions as well as the mobility and concentrations of elements of interest after exposure of overburden material in spoil banks (7).

Studies of heavy metals in spoils have indicated that sedimentary organic material may play an important role in both the physical and chemical properties of spoil. It is generally accepted that organic matter is vital in the development of fertile soil, but to date, investigation of fossil organic matter in overburden as a source of such beneficial material in spoil has been totally neglected. The sediments comprising coal overburden contain various amounts of organic matter. Because of its pronounced capacity for absorption, cation exchange, and formation of organic-metal complexes, this organic matter strongly affects the trace metal assemblage of the sediments of which it is a part (8,9,10,11). It is probable that this organic matter influences the reactions and mobility of these elements during weathering of the enclosing rock and therefore affects both stream pollution and plant growth.

PHYSICAL FACTORS

Physical factors affecting success of reclamation are commonly related to color and particle size of the spoil. Color of the materials directly influences spoil temperatures through the absorption of solar energy. High temperatures can impede seedling emergence and alter the growth of surviving plants. Temperatures on the surface of dark-colored spoils may become so high that plant tissue contacting spoil fragments is killed. The upper 15 cm of black shales may have temperatures up to 10°C higher than light colored spoils on south facing slopes. Surface temperatures as high as 64°C were measured in Pennsylvania (12).

Emergence of some grasses is stopped at a soil temperature of 47°C while others may withstand temperatures to 52°C (13). Once a vegetative cover is established, the tendency toward excessive soil temperatures is moderated. Mulch can be used effectively to regulate surface temperatures.

The physical characteristics of mine spoil as a rooting medium are frequently quite different from those of naturally developed soils. Spoil is an unorganized mass of material derived from any or all of the strata overlying the coal bed. Particle size affects soil aeration and moisture efficiency. Thus, it is an important consideration in reclaiming surface mine spoils.

FINE SPOIL PARTICLES

The proportion of fine particles (less than 2 mm in diameter) varies among spoils from about 20 percent to 80 percent by weight (14, 15). Southwestern spoils commonly contain more than 50 percent clay by volume. Many spoils contain 25 percent to 40 percent fines. Both herbaceous and woody vegetation have been successfully established on spoil within this range. However, in spoils with chemical properties that limit plant growth, the coarse spoils yield better growth than spoils of finer particles because lesser amounts of toxic elements are available from the smaller surface area of the coarse fragments. Spoils devoid of fine particles in the

surface layers are extremely difficult to vegetate directly with seed. Surface layers of coarse fragments dry out rapidly.

MOISTURE CONDITIONS

Fortunately, moisture conditions of many spoils are relatively favorable for plant growth. Variations in micro-relief may aid in water infiltration and percolation. Because the moisture conditions are more favorable at some depth below the surface, it is important to speed the growth of seedlings during cool, rainy periods so that roots penetrate to depths where moisture is available. In some cases this means selecting species noted for deep rooting, applying fertilizer to promote rapid initial growth, and applying mulch to maintain moisture near the soil surface until seedlings are established.

Some spoils having a high proportion of silt and clay are prone to crusting, which results in a pavement-like surface. This compact surface layer must be broken before seeding.

Bulk densities of spoils are frequently higher than those of adjacent undisturbed soils. However, in time, densities will become more favorable to vegetation growth and development through freezing and thawing, accumulation of organic matter, and root penetration.

Usually the reclamation specialist does not attempt to correct physical problems, but, rather, tries to live with them. A premining analysis of the overburden could be used to schedule movement, mixing, and placement of the materials so that the most desirable material is left on or near the surface as the plant growth medium. This applies to chemical as well as physical properties of overburden.

SPOIL CHEMISTRY

The chemical nature of strip-mine spoils is extremely variable depending upon chemical properties of the different strata in the overburden. Some spoils range in chemical reaction from extremely acid to alkaline. Some are relatively fertile; others are completely deficient in one or more essential plant nutrients. In the Southwest, coal mine spoils are normally alkaline, with a pH of about 8.0. They often contain over 1500 ppm of sodium.

Along with organic matter and nutrients, another prime factor in soil fertility is the presence of a flourishing and varied population of microorganisms. The absence of such a micro-flora and fauna in fresh spoil is probably the single most important deficiency in most areas as far as establishing protective vegetation is concerned. Therefore, enhancing the establishment of an adequate population of benefical microorganisms in spoils is very important. It is likely that with proper placement of overburden strata, fossil organic matter will provide a source of usable carbon for pioneering species of organisms that can be followed by proliferation of relatively normal heterogeneous populations.

Microbial associates have been shown to play a key role in establishing plant species on problem spoils (16, 17, 18, 19). For example, Marx (20) has shown that pine seedlings planted on acid mine spoils survived and grew well when inoculated with an ectomycorrhizal fungus, *Pisolithus tinctorius.* Rhizobia that will effectively nodulate legumes can mean the difference between success and failure in vegetating problem spoils. Some strains of Rhizobium bacteria have been found more efficient than others in nodulating legumes on mine spoils (21). However, there still are many voids in our understanding of the microbiological requirements for successful surface mine reclamation. The conditions listed below are known to be associated with the mycorrhizal fungi and will help point up the need for continued physiological investigations of interactions of these symbionts and plant growth and development.

ADAPTABILITY

About 95 percent of the world's present species of vascular plants belong to families that are characteristically mycorrhizal. Of these, about 5 percent are ectomycorrhizal. The endomycorrhizae are found on the remaining species of herbaceous and woody plants (22). Ecological adaptability for the above associates is dependent upon the evolution of metabolic pathways which will enable them to withstand environmental stress. Of literally hundreds of possible associates which may be adapted for strip mine reclamation, only a few have been investigated and

fewer still have been demonstrated to be useful under such conditions. The more completely we understand the ecology of mycorrhizal species on adverse sites, the more intelligent may be our selection and evaluation of species for reclamation.

NITROGEN LEVELS

In the majority of revegetation efforts, either leguminous or nonleguminous nitrogen-fixing plant species have been used to increase the level of nitrogen in the spoil material. With few exceptions, isolates that have been examined have shown the nitrogen-fixing species to be endomycorrhizal as well. In a recent publication on the interactions between growth, phosphate content, and nitrogen fixation in mycorrhizal and nonmycorrhizal legumes (23), the mycorrhizal plants showed more extensive nodulation, increased nitrogenase activity, and higher levels of phosphate in the early stages of plant development. Later when the significant mycorrhizal effect on growth was apparent, the total nitrogen and phosphorus per mycorrhizal plant were also higher. But nitrogenase activity and phosphate content as measured on a dry weight basis showed no significant differences between mycorrhizal and nonmycorrhizal plants. The mycorrhizal enchancement of phosphate uptake and nitrogen fixation apparently precedes the favorable effect on growth. Studies of this nature would be extremely valuable to our understanding and evaluation of nitrogen-fixing species for reclamation.

Symbiotic associates of herbaceous species help increase plant yields which, in turn, have the desirable effect of adding organic matter to the spoil. The mycorrhizal associates contribute a large fraction to the soil biomass and aid in the establishment of a microbial succession that performs vital functions in the carbon cycle. Under the new regulations, mulch is to be used on all regraded and topsoiled areas. The favorable growth conditions obtained by Vogel (24) using bark mulch as an aid to plant establishment indicate that various types of vegetative residues should be investigated in conjunction with degradative and/or cellulose-modifying microbial species. Many of the successional species are capable of cellulose degradation and an increase in their populations would aid in the creation of a nutrient-rich fraction from the vegetative residues.

WESTERN RECLAMATION

Reclamationists in the west face some problems quite different from those in the east. Scarcity of water is of major consequence, but spoil chemical characteristics are important, too. Many western spoils are high in exchangeable sodium and salinity levels are significant. Sometimes boron, molybdenum, or magnesium levels are high enough to cause problems. Nitrogen and phosphorus are nearly always deficient for plant growth.

Power et al. (25) reported up to 50 percent displacement of exchangeable sodium within 3 years after spoil was treated with gypsum. Doering and Willis (26) showed that essentially all exchangeable sodium can be removed very quickly with calcium chloride, but soluble salts formed by reactions must then be leached with several feet of water before vegetation can be established.

Reclamation in the west hinges on management of available water. Mulches can be used effectively to conserve moisture. Irrigation should be used whenever possible to aid plant development at critical times.

As the world's petroleum resources decline, oil shales will increase in importance as a source of hydrocarbons. Recovering this resource will involve mining extensive areas. For example, oil shales containing an estimated 600 billion barrels of oil and considered suitable for commercial development occupy about 17,000 square miles of Colorado, Utah, and Wyoming. Problems of reclaiming spoil material from overburden removed during strip-mining for oil shales are similar to those from strip-mining of coal in the western United States.

SPENT SHALE PROBLEM

The major reclamation problem of oil-shale mining involves the spent shale left after recovery of the oil; this applies to shale mined by underground methods as well. Coal is used almost in its entirety, but only a small percentage of the volume of mined shale is recovered as oil. It is estimated that for each 1.5 million tons of shale mined, 1.3 million tons of spent shale would have to be disposed of. Depending on the recovery process used, the physical properties of the spent shale range from clinker-like to dust-like, and each has its own special problems. The

chemical problems are even more serious; they include high levels of salinity, low organic matter, and low levels of available plant nutrients. The high salinity makes leaching almost imperative for reclamation, but this is hampered by a shortage of water in an arid climate. Efforts to utilize topsoiling have been hampered by capillary rise of salts into the added topsoil.

SUITABLE PLANTS

Considerable research has been done, both in the greenhouse and in the field, to find plant species suitable for reclaiming oil shale. It has been demonstrated that only a few salt-tolerant species can be successfully established on unleached spent shale. Where capillary rise of salts can be stopped by compaction or by interposing a coarse rubble layer, topsoiling broadens the choice of species. The number of adaptable species increases with increasing soil depth, up to approximately 1 foot of topsoil. Little toxicity is associated with spoils from oil shale mining, but because of the scarcity of water in this region, soluble salts will continue to be a major obstacle to revegetation.

Perhaps the most significant advance in oil-shale technology is *in situ* oil recovery. In this process, the shale is fractured and the oil recovered from it while the shale is in place. If it proves successful, this method will eliminate the need to handle and dispose of the billions of tons of waste material and the major reclamation problems now anticipated will be eliminated.

Vegetation can be successfully established on mine spoil if certain practices are followed. Some of the more important considerations will be discussed.

SEEDBED PREPARATION

A suitable seedbed was shown by Vogel (27) to be necessary for the rapid and successful establishment of seeded vegetation on mine spoils. On plots that were roto-tilled before seeding, vegetative cover was established faster and was denser at the ends of the first and second growing seasons than it was on plots that were not tilled. Tillage was more beneficial for seedings made between April 1 and October 15. The main advantage of tillage is that it breaks up the crust on the surface of the spoils and increases the number of microsites favorable for germination of seed and growth of the plants. Seeding on freshly graded spoils would provide the same advantages as tillage at lower cost. Requirements for seedbed preparation are more stringent in the dry western regions. Specialized implements are needed such as the rangeland drill for placing seed in furrows, or pitters and gougers that create depressions to conserve soil moisture.

The amendments to be discussed are lime, fertilizer, and mulch.

pH FACTORS

The chemical properties that most often influence the establishment and growth of vegetation on strip-mine spoils are related to chemical reaction and imbalances in plant nutrients. Acidity or alkalinity is a very useful criterion for predicting the capacity of spoil to support vegetation. Its intensity is expressed as pH—a measure of the concentration of hydrogen ions present. Most spoils in the eastern United States are in the acid range (below pH 7.0), while most spoils in the western states are alkaline.

Some plant species are more tolerant than others of acid conditions just as some species are more tolerant than others of alkaline conditions. Nearly all plant species will grow in spoils with a pH above 5.5 and below 8.0. A more limited number will grow when pH is between 4.5 and 5.5 or above 8.0. Few species can tolerate spoil below pH 4.5 and fewer still will grow where pH is below 4.0. In some of the western areas, species tolerant of alkaline conditions must be selected.

There are problems in establishing vegetation on acid spoils. Toxic levels of aluminum and manganese are soluble at low pHs and become harmful to plants. Roots of many plants will not grow into materials with toxic levels of soluble aluminum. Thus plant growth is stunted because the roots do not take up nutrients.

LIME

Some things can be done to ameliorate acid spoils. Amendments such as organic matter, fly ash, and topsoil may be added, but lime is the most used. Topsoiling is considered the most economical way of treating alkaline western spoils.

The most common practice now is to apply enough lime to raise pH to 5.5. At this pH, manganese and aluminum become less soluble and are less available in forms toxic to plants. Also, phosphates and other nutrients become more readily available to plants at the higher pH.

Studies have shown that rock phosphate can be used successfully in reclaiming spoils when the pH is below 4.5 (28). Rock phosphate contains calcium as well as phosphorus.

FERTILIZER

Most surface mine spoils are deficient in one or more essential plant nutrients. Nitrogen is almost universally lacking; phosphorus is limited in most spoils but is adequate in some. Potassium levels generally are adequate for the establishment of vegetation.

A deficiency in nitrogen severely limits establishment and growth of herbaceous species, especially grass. Thus, the addition of nitrogen fertilizer is essential.

Further applications of nitrogen fertilizer may be avoided by planting or seeding nitrogen-fixing plant species. Legumes are used for this purpose, although the long-lived legumes usually take more than 1 year to get established. This means that annual legumes or grasses must be used for the initial quick cover needed to control erosion.

MULCHES

Various mulches can be used during the critical period of seedling establishment to improve the microclimate and help conserve soil moisture. Among the many materials that have been tested for use on surface mine spoils are pulp fiber, grain straw, hay, wood chips, wood bark, leaves, and some chemical binders.

Generally wood pulp fiber is mixed with seed and fertilizer and applied with a hydroseeder. The amounts of this mulch usually used (900-1100 kg/ha) are inadequate to reduce erosion significantly. Also, it is doubtful that they have a significant effect on moisture conservation.

Straw at 2200 to 3400 kg/ha, distributed evenly over the surface after seeding, can aid in the successful establishment of vegetation on spoils. However, it is often necessary to hold the straw in place with a binder or to run over it with a disc or crimper. Hay falls into the same category as straw. Both may retain seed which can result in a volunteer stand of vegetation. However, seed of some weeds may be undesirable.

Wood chips are good because they stay in place on the spoil. However, efforts to establish vegetation with wood chips as a mulch have been disappointing.

Shredded tree bark applied at the rate of about 94 cubic meters per hectare has been found to be quite effective in conserving moisture, retarding runoff and erosion, and providing microclimatic conditions favorable to plant establishment and growth. Leaves, too, have been found to be a valuable mulch. They can be applied with a blower or with a regular farm manure spreader. Leaves must be disced into the spoil to hold them in place.

Naturizer is a trade name of a mixture of composted municipal waste and sewage sludge. Initial tests indicate its use on surface mine sites may be beneficial both as a way to dispose of waste products and as an aid to mined land reclamation.*

CHEMICAL BINDING AGENTS

Many chemical binding agents have been developed over the past few years and many of them are purported to work well in erosion control. Additional

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*The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable.

research is necessary to support these claims. When used alone these chemicals cannot serve all the functions required of a mulch; i.e., they cannot provide moisture conservation, stabilize the soil, and moderate surface temperature. Neither do they provide any plant nutrients.

Sewage sludge and effluent have been used successfully in efforts to vegetate some problem spoils. Much research is underway into the use of these and other waste materials in reclamation.

TOPSOILING

Topsoiling is now required on nearly all surface mine disturbance in the United States. The so-called topsoil is removed from the area about to be mined and stockpiled for later spreading on the graded site. Almost all the unconsolidated overburden may be classed as topsoil. In many cases the importance of topsoiling cannot be disputed, but in some cases another stratum in the overburden may have more desirable characteristics as a plant growth medium than topsoil. In these cases the best material for plant growth should be placed on the surface.

For a long time, most seedings of mine spoil in the Appalachian region were made in the spring or fall, with spring generally being preferred. Many people believed that even in a humid region it was impossible to vegetate mine spoils by direct seeding in the summer. Vogel (27) has shown that a vegetative cover can be established by seeding selected mixtures of temporary and long-lived herbaceous species anytime between March 1 and October 15 in eastern Kentucky. Results of his study have been applied with success to other areas in the Appalachian region. In early spring and fall, initial cover was best achieved with Balbo rye or annual ryegrass. Pearl millet, sudangrass-sorghum hybrid, and weeping lovegrass provided quickest cover from mid-May to mid-July. Kentucky-31 fescue and sericea lespedeza became the primary cover on the areas after two or three growing seasons.

In humid regions, barren areas should be seeded anytime mining is completed between March 1 and October 15. The seed mix can be changed to fit climatic conditions throughout this period. Seeding temporary species for quick cover with the permanent species is desirable in most situations. The temporary species provide cover sooner than the permanent species, but are later replaced by the permanent ones.

In any seeding, the species selected often is less important than adherence to good vegetation practices; i.e., preparation of a suitable seedbed, application of sufficient fertilizer, and, when necessary, application of lime and mulch.

In the southwest it is important to seed when moisture conditons are best. For example, fourwing saltbush should be planted only when the probability of summer thunderstorms exeeds 50 percent and existing soil water stress is less than 2 atmospheres of tension.

CLIMATE

The amount and distribution throughout the year of rainfall are strong factors in the establishment of vegetation. In the east rainfall usually is not a problem, but in the west and southwest it may be the limiting factor in plant establishment. Although water is recommended for areas that receive less than 200 mm of precipitation, it can likely be beneficial for areas receiving much more precipitation.

Species of vegetation for use on surface mine spoils should be selected according to the time of year, type of spoil, purpose of seeding or planting, and the expected future use of the land.

QUICK COVER

One of the first considerations is to establish a quick cover for erosion control. In the east this generally means a mixture of herbaceous annuals and perennials. Some woody species may be desirable. When temporary quick-cover species are mixed with permanent species, there is a chance that the temporary cover will prevent or retard the development of a satisfactory stand of the permanent cover. It is important to limit the amount of seed of the annual or quick-cover species to prevent this.

Many experiments have been conducted to determine the adaptability of various herbaceous and woody species for vegetating strip-mine spoils. Some species

PREFERRED PLANT SPECIES

have been selected for their tolerance to acid conditions; others have been selected specifically for use on alkaline spoils. Many species of grasses are well suited to surface mine reclamation, because they are adapted to a wide range of climatic and spoil conditions. Some species are desirable because germination is usually rapid and growth is quite good during the first growing season.

Many plant species have been tried with varying degrees of success in the United States. For each of the major coal producing regions there are preferred plant species in each of four major categories: grasses, forbs, shrubs, and trees. The grasses and forbs may be further classified as temporary, semipermanent, or permanent. Temporary species are used to give quick cover for site protection; semi-permanent species are reasonably persistent perennials; permanent species are those expected to persist for many years.

Annual grasses can be used for quick cover and as companion crops with slower developing perennials. Some species are better adapted to spring seeding, others should be seeded in the summer, and still others in the fall.

Leguminous forbs are considered essential in ground-cover mixtures. Associated plants generally benefit from the nitrogen fixed by the legumes. Annual legumes germinate quickly and provide good cover within a few months. Perennial leguminous forbs often are more difficult to establish; many have hard seed coats or other specific dormancy requirements that delay germination. The availability of soil phosphorus is generally more critical for the establishment of legumes than for grasses. Seeding rates of companion grass species should be carefully regulated to prevent excessive competition and possible failure of the legumes. Each species of legumes must be inoculated with specific strains of Rhizobium to stimulate nodulation to insure the nitrogen-fixing activity.

Shrubs for reclamation plantings have not been emphasized although they have significant value for site protection, wildlife food and cover, and esthetics. Possibly in the future more emphasis will be placed on the use of shrubs.

TREES

Trees have generally been a mainstay of reclamation efforts. A few tree species can be directly seeded but most are normally established by planting seedlings. Many species are adapted to surface mine spoils, but species native to the area are usually recommended. Unfortunately, high value tree species are usually the most difficult to establish on spoils. Grass and legume ground covers generally reduce tree growth, at least in the early stages. In later years legumes may enhance growth. Black locust, autumn olive, and bristly locust are nitrogen fixers and can be beneficial as nurse trees for other tree species.

Revegetation practices in the United States are determined or influenced mainly by legal requirements for surface mining and reclamation. The seeding of grasses and herbaceous legumes to establish a cover for erosion control and for esthetics is generally recommended. Once the herbaceous vegetation is well established it can be used for pasture and hay. Good forage species usually are used for vegetating mine spoils—for example, smooth broomgrass and alfalfa in Illinois and tall fescue and annual lespedeza in southern Appalachia. Livestock grazing is becoming a commonplace land use on vegetated strip mines even in the mountainous areas of Appalachia. Unfortunately, the tendency is to overgraze or start grazing before the vegetation is well established, which hinders the development of adequate cover.

The land use in effect at time of mining often influences the choice of revegetation practices. For example, prime agricultural land in the flatlands of Illinois is reclaimed for immediate return to row crop production.

REFORESTATION

On the other hand, forested land is usually not replanted to forest species. Some states require that woody species be planted in addition to the herbaceous species on steep slopes and other sites not intended for agricultural use. Normally the planting of woody species is optional for the landowner or mining company. The legal requirements in some states unintentionally discourage tree planting

because they permit release of vegetation bonds as soon as the requirements for the herbaceous vegetative cover are met.

BLACK LOCUST

Black locust is still the most commonly used tree species. It is especially popular for use on steep slopes because it can be established by direct seeding in mixture with herbaceous species. Locust seedlings respond to fertilizer, especially phosphorus, as herbaceous legumes do, and first-year seedling heights of 30 cm or more are not uncommon. Unpopular doghair stands of locust sometimes develop where seeding rates are excessive. European black alder and autumn olive are other nitrogen-fixing woody plants that are used as nurse plants or site improvers and for wildlife habitat.

Red pine, white pine, and hybrid poplar have been successful in the northern Appalachian coal fields. European white birch has been the most successful tree species on extremely acid spoils in Pennsylvania. Virginia pine has been widely planted in the middle and southern Appalachian region, and loblolly pine is often planted or direct-seeded in southern Appalachia. Most species of pine are tolerant of acid spoils, especially in association with the acid-tolerant mycorrhizal associate, *Pisolithus tinctorius* (20).

Tree planting now is rare in the midwest even though reforestation studies showed that high value hardwoods can be produced on spoils. This is due in part to political and social pressures that favor agricultural uses of all surface-mined lands. Also, hand planting of tree seedlings costs more and entails more labor-related problems than seeding of herbaceous species. Another reason for choosing agricultural uses over forestry is the greater and quicker economic return from the reclaimed land. Yet, some of the 30- to 50-year-old hardwood stands, especially of black walnut, in Indiana and Illinois demonstrate the economic potential of growing forests on mined lands.

QUICK COVER VS. TREES

There is a need to establish a quick cover for erosion control at the same time that trees are planted, but the herbaceous vegetation may adversely affect survival and growth of the planted trees. Some people recommend seeding the herbaceous species one year and planting trees the next. Others suggest using herbicides to kill patches of herbaceous vegetation where tree seedlings will be planted. A more practical method is to plant trees and herbaceous species at the same time. The herbaceous cover should consist mainly of legumes because the growth of trees usually is enhanced by legumes but suppressed by grass (29). When seeding must be done in late spring and summer, an herbaceous cover can be established with summer annuals. These will die in the fall and provide a mulch over winter. Trees and perennial herbaceous species can be planted the following spring.

On areas that can be traversed with farm machinery, early competition of herbaceous species with trees can be avoided by planting the herbaceous species and trees in alternate strips. To further assure their establishment and early growth, tree seedlings should be inoculated with the appropriate mycorrhizal fungi.

Revegetated surface mines can provide excellent wildlife habitat and water-based recreation, as is shown on many old strip mine sites. Present revegetation practices in the east often provide poor wildlife habitat because they use mainly a few species of grasses and legumes such as tall fescue and sericea lespedeza that provide little food or diversity of habitat.

LEGAL REQUIREMENTS

Perhaps the most significant piece of legislation relating to surface mining and reclamation was the Surface Mining Control and Reclamation Act of 1977 and subsequent interim regulations pertaining to that law. Since the act was passed in August 1977, many states have enacted legislation that conforms to the federal requirements.

Some of the specific legal requirements for reclaiming surface-mined land will be discussed.

Reclamation options often depend on how the overburden is handled and placed during the mining operation. Controlled placement of spoil should result in

improved slope stability and should provide the best possible conditions for vegetation establishment and growth.

The importance of overburden analyses must be emphasized since overburden characteristics play a large part in determining the future land use. Knowledge of the chemical and physical characteristics of the overburden can be helpful in designing spoil movement and placement systems for minimizing environmental damages and maximizing future land use options.

Topsoiling is required unless alternate methods are approved. Topsoiling refers to the practice of removing the A, B, and C horizons individually or in combinations before mining, then redistributing these materials on the mined area to prepare the site for vegetation establishment. Where prime farmland is mined, requirements relating to topsoil removal, storage, and replacement are more stringent.

Topsoiling is a questionable practice on steep slopes in many areas in Appalachia where the soils are shallow and infertile. An alternative is to use selected portions of the overburden materials. According to regulations the decision to substitute overburden materials for topsoil must be supported by chemical and physical analyses and field or greenhouse trials. The intent of the regulations relating to topsoiling is to provide the best medium for plant establishment and growth.

NUTRIENTS/AMENDMENTS

Nutrients and amendments must be applied as indicated by soil tests and vegetation requirements. However, not all standard soil tests are applicable to surface mine spoils. Greenhouse and field tests usually are required to verify the accuracy of soil tests. Fifty pounds of nitrogen and 40 pounds of phosphorus per acre are considered minimum on most spoils for establishment of herbaceous vegetation. Lime can be used to neutralize acidity. Lime should be incorporated at least 6 inches deep to be most effective. Rock phosphate also is an effective amendment in some acid spoils.

Regulations require prompt vegetative cover capable of stabilizing the soil surface with respect to erosion and productivity levels compatible with approved land uses. Grasses are usually more reliable for early site protection. Legumes are important in reclamation because of their nitrogen-fixing ability. Mixtures of grasses and legumes in the proper proportions are often used for reclamation.

A number of state laws require trees or other woody plants on steep slopes or areas having a high potential for erosion. Tree planting or seeding will continue since wood production will continue to be the land use for many areas after mining. Regulations require that where forest is to be the future use, trees adapted to local site conditions and climate be selected. Trees are to be planted in combination with an herbaceous cover of grains, grasses, legumes, forbs, or woody plants to provide variety, succession, and regeneration capability in the area.

SITE PREPARATION

Requirements are that any disturbed areas which have been graded be seeded with grains, grasses, or legumes for temporary cover to control erosion until the permanent cover is established. This requirement forces operators to plant or seed the freshly graded spoil and thus benefit from the fresh seedbed. It may be necessary to do further seedbed preparation to enhance the establishment of the permanent cover.

Mulches must be used on all regraded and topsoiled areas. Straw and hay are the most widely used mulching materials, and they are among the most effective. Shredded hardwood bark is also an effective mulch. Processed wood fiber and reprocessed paper products are used rather extensively as mulch in Appalachia because they can be applied with seed and fertilizer from a hydroseeder.

Federal law requires that all disturbed areas be restored in a timely manner to conditions capable of supporting the uses they were capable of supporting before any mining, or to higher or better uses as specified and approved.

The short-term success of reclamation is definitely determined by criteria set up by regulatory authorities. Usually the standards require a minimum ground cover

density within a specific time period. The number of woody seedlings per acre may be stipulated for steep slopes. Supplemental seeding, fertilizing, liming, mulching, and planting may be required to achieve the minimum performance standards. Once reclamation meets all legal requirements, the performance bond is released, and the land manager may then do whatever is required to achieve the desired land use objectives.

We must be careful that, through legislation and regulation, we do not foreclose land use options for surface mined land. Laws and regulations should be flexible enough that the land owner or land manager has some input as to the proposed future use of the land.

TOPSOILING

Although topsoiling may be an attractive reclamation practice on some sites, its full potential cannot be realized without additional research. What are the effects of storage on physical, chemical, and biological properties of topsoil? Would topsoil be more effective if blended with selected overburden materials? Could microbiological activity be improved through blending? What about chemical and physical properties? What is the optimum depth of topsoil over coarse textured but non-toxic spoil, and over extremely acid material?

Chemical binders used with or without wood fiber have received some interest recently as soil stabilizers. The potential of these materials for binding soil particles and retarding erosion has not been demonstrated.

There is little documented information regarding the productivity of surface mined lands. It is believed that under proper management many sites could be very productive. We need to start research into the management of reclaimed land so that we can document site productivity.

LAND USE OPTIONS

In many cases there may be more than one use that can be made of land mined and reclaimed. There is need for work aimed at defining various land use options available to the land owner or mine operator. Reclamation activities should be designed to provide maximum land productivity over the longest term.

Although it may be desirable from the ground cover standpoint to plant trees together with an herbaceous cover, it is not always practical to do so. For example, we don't yet know what combinations of species are compatible. Some specific questions to be answered are: Do trees perform better in association with grasses, legumes, or mixtures of these? Should trees and herbaceous cover be established at the same time or should tree planting be delayed a few years? Should only native species of trees be used? Older hardwood plantings have been found to be fairly successful, yet we are having trouble getting hardwood plantations established now. Why?

To meet specific land use goals some effort should be aimed at selecting and testing superior plants for mined land reclamation. This means selecting not only the best species but, perhaps more important, genotypes within species.

Studies should be made to determine the best combinations and patterns of vegetation as well as the best surface configurations on mined land to benefit wildlife. Research must also be done to find the best ways to mine and reclaim land with the least adverse impacts on visual resources.

Reviews of past work show that despite the availability of much information on how to establish vegetation, there are many areas where technology is lacking. Additional studies on plant establishment are needed for refining current practices and restoring biological productivity through a better understanding of soil-plant-animal relationships.

WASTE AS SOIL AMENDMENTS

Some studies already show benefits that may arise from using various waste materials as soil amendments. More research is needed in this area so that we may be better able to dispose of waste materials in such a way as to enhance land productivity.

Federal law requires that surface mining and reclamation be conducted so as to maintain the present hydrologic balance. Research is needed in all phases of the

water cycle in relation to surface mining and reclamation activities to safeguard our water resources.

EROSION

General observations tend to support the belief that replaced topsoil erodes faster than does spoil material on similar sites. A serious consequence of this erosion is the permanent loss of the topsoil as a medium for plant growth on strip-mined areas. Another consequence is stream siltation. Ways must be developed to control erosion on surface mined lands.

The federal regulations extend the time of responsibility of a mine operator for successful revegetation. With what types of vegetative cover and under what management practices can an operator be sure of complying with this requirement? The vegetation bond represents capital not really producing anything.

It is very important to avoid introduction of toxic or harmful elements and compounds into the food chain. Toward this end there is need to carefully evaluate the quality of forage, feed, and food crops produced on surface-mined lands, especially where waste materials are used in the reclamation process.

Spoil instability is still a major problem. This includes not only surface erosion but subsidence, piping, sliding, and slumping. Proper water control both on the surface and within the spoil mass is not to be ignored. Mining methods, earth moving operations, and overburden placement schemes must be evaluated as they relate to stability. Techniques must be developed for selecting the mining and spoil handling systems most appropriate to each situation.

Information contained in this part of this paper was taken from materials supplied by the various agencies and departments. The material was abstracted and rearranged in the format required of the paper. In some cases not all the material furnished was used. Some of the research reported here was conducted cooperatively with the EPA and supported in part by interagency environmental agreements.

FOREST SERVICE

The Forest Service has been involved in mined land reclamation research in the eastern United States for over 30 years. Its program was expanded in the early 1960's with a mission to develop practical methods of reducing damage to the environment and forest resources during surface mining operations and to rehabilitate mined areas for the production of quality water, timber, wildlife, recreation, range, and esthetic benefits. Other reclamation research is being handled in the west under the SEAM program.

In 1946 and 1947 the Central States Forest Experiment Station began experiments basic to the formulation of planting guides and recommendations for reforesting surface mine sites. Many plots were established throughout the surface-mining areas in Ohio, Indiana, Illinois, and western Kentucky as well as in eastern Missouri, Kansas, and Oklahoma.

PERFORMANCE EVALUATION

The Northeastern Forest Experiment Station initiated studies in cooperation with Southern Illinois University and the Ohio Agricultural Research and Development Center in 1976 to evaluate the performance of these plantations. Of the 23 species observed, outstanding growth was noted in black walnut, cottonwood, chestnut oak, red oak, sweetgum, and yellow-poplar.

Height of hardwoods at several locations was greater than 70 feet (21.3 m). Several individual cottonwoods, red oaks, and yellow-poplars were taller than 90 feet (27.4 m). Black walnut, yellow-poplar, red oak, and silver maple performed better in plots where black locust was used as a nurse tree than where locust was not planted. Over 60 different species of volunteer trees were observed. Many woody vines as well as herbaceous and shrubby plant species were common.

Tree growth was suppressed where trees were planted with a grass cover, but it was enhanced by lespedeza, a legume. This indicates that trees and a herbaceous cover comprised mostly of legumes can be established together without adversely affecting the trees.

TEST PLOTS

Large scale test plots using equipment and methods which are operationally practical were established by the Rocky Mountain Forest and Range Experiment Station in the summer of 1977 on the McKinley Coal Mine in northwestern New Mexico. Treatments included incorporating straw at 8 metric tons per hectare, contour furrowing with and without straw, and checks. Initial observation in October of 1977 showed good germination of the seeded wheat-grasses on all areas. An unusually wet period shortly after seeding in August produced good germination even in unmulched areas. Chemical and physical spoil properties were more favorable than normal in this area because of the age and source of the exposed materials.

At present, the most promising species to plant on mine spoils in the southwest are alkali sacaton, western wheatgrass, fourwing saltbush, and Indian ricegrass. Good stands of alkali sacaton have resulted when pure live seed was applied at a rate of 3 kg/ha. Drilling is by far the most common method of planting seeds on reclaimed areas in the southwest. The rangeland drill has worked best. Fourwing saltbush seedlings should be planted in areas that will be flooded periodically. It is best to wait until the probability for sizable (10 mm plus) summer thunderstorms exceeds 50 percent, and soil water stress is less than 2 atmospheres of tension. Transplant plugs of western wheatgrass were field planted successfully. Investigations in New Mexico have shown advantages of using mulch to establish perennial species. Straw spread at a rate of 2,240 kg/ha and rototilled into the top 8 cm of spoil was effective in the establishment of fourwing saltbush transplants and seeded alkali sacaton on mine spoils. Some type of supplemental water is recommended for areas receiving less than 200 mm of precipitation. When an overhead sprinkler system was used to apply 254 mm of water in the first growing season, an average of 86 alkali sacaton seedlings per m^2 became established.

WATER QUALITY DATA

There is a need for water quality data from small Appalachian watersheds that will explicitly show changes in water quality attributable to strip mining. Most existing data are from large watersheds in which it is impossible to isolate the effects of strip mining from the effects of deep mining, settlement, and farming.

Work is under way to establish water quality data bases for small first-order watersheds throughout Appalachia, on unmined watersheds, newly strip-mined watersheds, and old strip-mined watersheds. The data base, once established, can be used as a basis for evaluating both short-term and long-term effects on streams of different kinds of strip mining and reclamation. It can also serve as a frame of reference for future studies on these and nearby watersheds.

Sampling sites have been established for each of these three watershed conditions in 135 Appalachian counties where there is an appreciable amount of surface mining. These counties reach from northern Pennsylvania to central Alabama. Monthly samples are collected and analyzed for common ions, specific conductance, pH, and for 12 to 28 trace elements.

Preliminary analysis indicates a wide scatter in the chemical data. Water from some streams draining recent and old strip mines was scarcely distinguishable from that from nearby unmined watersheds, and in three streams it was actually a little better. A comparison of 58 pairs of old and new mined watersheds showed that in 37 instances the drainage from the newly mined area was better than that from the old mined area. Twenty-one of the old mined watersheds had better quality water than the newly mined areas.

Data from Bear Branch watersheds showed that for a major storm on April 3-4, 1977, flow from well reclaimed surface mined watersheds peaked lower than that from an unmined, forested watershed.

NONMINE WASTE USE

Plots have been established in northeastern Alabama, western and eastern Kentucky, and West Virginia to study the use of nonmine wastes as amendments in reclaiming surface mine spoils. Many of these plots have been instrumented with recording water runoff gages, erosion transects, suction lysimeters, and samplers for collecting surface runoff at different stages of flow. The surface and ground water samples are analyzed for the common dissolved constituents plus 12 trace elements. Soil samples collected periodically are analyzed for various dissolved, extractable, and

exchangeable constituents. The vegetation on each plot is periodically photographed and evaluated.

MULCH USE

Findings to date indicate that in general the response to a given mulch is highly dependent upon season of year, aspect, slope, and type of the mulch. Bark, hay, straw, wood chips, and hydromulch, in that order, all effectively promoted the growth of legumes in Alabama and western Kentucky. From 66 percent to 89 percent plant cover was established under bark and hay at two sites as contrasted to 22 percent and 34 percent cover on the controls. Straw was the best mulch at a third site, but was least effective at one of the other sites.

Shredded hardwood bark, limestone chips, hydromulch, composted garbage, and a paper-nylon blanket were used on an outslope plot near Elkins, West Virginia. After one growing season, the bark and composted garbage ranked highest for legume growth and plant distribution; hydromulch resulted in the poorest legume growth. Grass density and growth were better where limestone chips, composted garbage, and paper-nylon blanket were used. Best erosion control was achieved with the paper-nylon blanket; bark ranked a close second.

Studies installed in 1977 have confirmed data from previous studies that indicate that mulching increases survival of planted hardwood seedlings. Individual seedlings were mulched with one bushel of shredded hardwood bark. This provided a depth of about 10 cm for a radius of 38 cm from the stem. Survival of the mulched trees was 36 percent higher than that of the unmulched trees. Survival of yellow-poplar and cottonwood was not enchanced by mulching.

PLANTING METHODS

Data from old and new studies indicate that planting methods may present problems. In 1978 a study was installed to compare trees planted using a planting bar, mattock, power-auger hole backfilled with spoil, and power-auger hole backfilled with top soil. Shredded hardwood bark mulch also is being evaluated. To minimize human error, highly experienced personnel were used. Every phase was under control from lifting the trees in the nursery through the final planting. Since all conditions were optimal, differences in survival and subsequent growth should be due to the method of planting or to the mulch.

Data collected on the effectiveness of topsoiling as a reclamation technique indicate that herbaceous plant root structures are well branched and fully occupy the available growth space of the topsoil. However, with subsequent growth into the spoil material the root structure changes into single strands with little or no branching.

Blackberry seeds showed different responses to seven different minespoils under greenhouse conditions. The largest of three Kentucky seed size-classes germinated best and survived best on all minespoils tested. Although yields showed no consistent correlation with the chemical or physical factors for the minespoils, pH, potassium, organic carbon, and silt fractions gave the highest r-values.

Experimental vegetation plots have been established on coal spoils in Montana, Wyoming, and Utah. A study was installed to determine appropriate rates and frequency of fertilizer application for establishing various species of grasses, forbs, and shrubs. Direct seeding is being compared with planting containerized seedlings. The effects of four different types of spoil on plant growth are being tested in the field. Various treatments of topsoil, bark-wood fiber compost, and hay mulch have been applied on plots in the Alton, Utah, coal field. Superior shrubs and grasses are being developed to provide plant materials more suitable for hostile spoils in the semiarid west.

SHEAR TESTS

Direct shear tests give acceptable estimates of the shear strength parameters of surface mine spoils. If plans for mining operations are based upon results of such tests, reclaimed areas in the future should be more stable than those reclaimed in the past.

At least 14 species of small mammals were found on reclaimed surface mines in Kentucky. The species composition and densities were related to the reclamation

plants initially used, and to the current successional stages of plants on the minespoil and surrounding plant communities. Three species of mice were shown to be active vectors of the endomycorrhizal fungi on recently reclaimed minespoils.

SPENT OIL SHALES

Spent oil shales present a more difficult challenge for revegetation than coal mine spoils. A greenhouse bioassay study was completed using five nonmine waste amendments on leached and unleached TOSCO spent shale. Sewage sludge had more beneficial effects on plant growth than did fiber, straw, sugar beet pulp, or cow manure. Sewage sludge apparently ties up the sodium salts in spent shale. Field plots were established in the oil shale areas of Colorado and Utah. Different depths of topsoil were applied to spent shale, and test species of grasses and shrubs were grown under irrigated and nonirrigated conditions. There was little difference in growth on the topsoil-treated shale, but irrigation was beneficial on raw shale. Soil covering of 1 foot or more gave better plant growth than did shallower soil coverings. Other studies are designed to compare fall seedings with spring-planted containerized stock and to assess the significance of snow accumulation behind standard snow fencing. One study showed that plants grew better on shale covered with topsoil or subsoil than when mulched with rock or straw without topsoil.

The Department of Agriculture conducts a grant program in energy-related reclamation and environmental effects research through its network of universities and State Agricultural Experiment Stations. Grants are solicited under specific guidelines for work on high-priority research topics. Following are some results from the first group of reclamation grants funded by Cooperative Research.

On the Black Mesa mine in Arizona a study by the University of Arizona showed coal mine spoil to be highly productive under irrigation. The project is also using soil pitting to enhance rainfall use.

SOIL FORMATION

Studies conducted by Montana State University in the Colstrip area show that soil formation can be easily detected in 50-year-old sites. The key properties of the profile are carbonate movement, clay movement, organic matter build-up and root development.

In another study in Montana, field tests of mixtures of grasses show that planting a low number of species components is preferable to highly complex seed mixtures. Good density was achieved when slender, western, and thickspike wheatgrass were used in equal proportions of 645 live seed per square meter. A second promising mixture for minespoils is green needlegrass, fourwing saltbush, prairie sandreed, and switchgrass. Introduced species germinated best. Prechilling significantly improved speed of elongation of the seedlings in all species. Millet and slender white prairie clover are promising for some uses.

New Mexico State University tested field plantings of Indian ricegrass and fourwing saltbush on the Navajo mine and the San Juan mine. The plantings were not adversely affected by NaCl or Na_2SO_4 salts; in fact, they were enhanced at 50 to 100 meq of Na per liter of soil saturation extract. Indian ricegrass was also tolerant of boron salt in the growth medium. Galleta grass is sensitive to boron. An extensive collection of shrubs and grasses is still under test. At least 13 species look promising for use in reclamation.

SLUDGE AMENDMENTS

Sewage sludges used as soil amendments were found by Ohio State University researchers to vary significantly in toxic heavy metal content. Newark sludge was a valuable amendment. Bellaire sludge was somewhat toxic due to N, Mn, and Zn. Tall fescue grew well with moderate loading rates of both sludges. The leachate from treated lysimeters showed that Bellaire sludge leaches out Mn, Al, Ni, and Cd. The cadmium content in leachates varied from 6 to 94 micrograms/liter which might be a deterrent to its use as a soil amendment. Topsoiling was effective on two sites. Grass predominated on acidic sandstone soils and legumes on limestone soils.

Utah State University scientists showed success with container-grown desert shrubs in large pots. Field planting of shrubs was generally better in spring than in fall for fourwing saltbush, shadscale, and cuneate saltbush. Fourwing saltbush is one

of the best reclamation species. To stabilize soil and promote runoff and water harvesting, two commercial products, Soil Seal and Aerospray 10 proved to be effective for more than 1 year. Polyvinyl acetate (product 3011) applied to shallow basins increased water retention and also promoted runoff when sprayed on slopes.

HYDROLOGIC MODEL

A computerized hydrologic model for predicting infiltration, soil erosion, and water quality has been modified by Iowa State University for use in mine management. Drainage systems for minelands have been designed on the basis of hydraulic conductivity data. A study of piezometer water levels in the disturbed substratum is being used to chart groundwater changes in reclaimed areas.

The University of Kentucky has characterized the geologic conditions at four shale and sandstone sites and evaluated the potential of spoil materials as growth-support media for grasses and legumes. They report that the phosphorus status of the soil and its potential acidity are key parameters. Water holding capacity and infiltration are also factors related to the geology of the site which determine what plant species can be employed. One of the best for difficult sites is tall fescue.

At North Dakota State University, these computer models are operational: 1) Agricultural Sector Simulation Model, 2) River Model, 3) Environmental Quality Model, 4) Economic Model, 5) Coal Development Model, 6) Demographic Model, 7) Government Model. A new model simulating coal mining, conversion and land reclamation is being developed with links to the above models. The system, RIMAS, will provide information and maps to determine baseline conditions and to predict impacts of energy development.

ORNAMENTAL PLANTS

Research underway at the University of Virginia showed that woody ornamental plants can be grown commercially on minesoils. Vegetables also produce high-quality yields when grown with sawdust and with black plastic. Water deficiency of coarse spoil is controllable by mulches.

A project conducted by West Virginia University classifies minesoils on the basis of their internal characteristics. All are called *Spolents.* In the next lower category Great Groups are set apart on the basis of soil temperature and moisture regimes. Subgroups are distinguished by their lithology. Families are defined by particle size, mineralogy, soil reaction, and soil temperature. Topsoils have also been classified.

Atmospheric pollution from burning coal is caused by SO_2 gas which produces sulphurous acid upon contact with moisture. At the University of Wyoming, sensitive indicator plants have been found and the response of the native flora and crop plants has been measured under controlled atmospheric conditions. Two promising indicators are bracken fern and ponderosa pine.

Science and Education Administration—FR, formerly the Agricultural Research Service (ARS), is involved in research aimed at restoring and enhancing agricultural productivity. Much surface mined land will be returned to some form of agricultural use. The following information was extracted from the annual report on soil, water, and air science research (of SEA-FR) compiled for 1977.†

REACTIONS TO SALT

Research at Mandan, North Dakota, is concerned with the stage of plant development in relation to how species respond to salt. Response of eight perennial forage species to Na and Mg as well as to total salt concentration in two mine spoils was evaluated. Evaluations were made at three stages of plant development: germination, emergence-establishment, and growth. Results show that species respond differently to similar salt levels and ion concentrations. Stage of plant development was also important in how species responded. Greatest effects were apparent during

†The research workers in the soil, water, and air sciences of SEA-FR publish the results of their investigations in the open literature as quickly as sound scientific judgment warrants. The above-mentioned annual report provides a brief overview of the scope of their activities and examples of recent findings, some of which have not been released for publication.

the period of emergence and stand establishment. If the character of the soil-spoil complex is known before mining, seeding mixtures can be selected, the specific response of certain species can be better managed, and adverse reactions can be limited.

SAMPLE COLLECTION CONSEQUENCES

Studies are being conducted on the effects that overburden sample collection methods have on the results of chemical analyses. Water with high salt content and drilling mud used as a drilling fluid in sampling overburden may result in contamination of the sample. Sodium absorption ratio (SAR) is the preferred method for characterizing the sodium status.

Five cm of topsoil added to sodic spoils and seeded to native grasses in 1970 produced over 1200 kg dry matter/ha in 1976, compared with about 200 kg/ha for spoil without topsoil. A good sod of western wheatgrass and green needlegrass developed even though sodium had migrated into the applied topsoil, raising its SAR from about 1 to over 8. Similar sodium migration was seen in other experiments where greater thicknesses of soil materials had been added. Data indicated that upward sodium migration will probably occur for 15 to 30 cm above the soil-spoil interface. Upward sodium migration can be reduced or eliminated by applying gypsum to spoils before covering them with soil material. Likewise, gypsum treatment can reduce SAR in the first 30 cm of spoil by 30 to 50 percent over a period of 3 to 4 years. A minimum of about 75 cm of soil material needs to be returned to sodic spoils to restore full production potential—at least for spring wheat, alfalfa, crested wheatgrass, and several native grasses. If upward salt migration, restricted internal drainage, erosion, compaction, etc., are of significance, this minimum requirement needs to be increased. However, less thickness is required if higher quality spoils are present. Even with highly sodic spoils covered with soil, plant roots penetrate 30 cm or more into the spoil and utilize any water stored there. Reclaimed spoils usually require fertilization with N and P.

SPOIL CHARACTERIZATION

Other research at Mandan involves characterization of spoils. Overburden samples have been collected and analyzed from a number of coal fields in western North Dakota, and more intensive sampling has been done in the Underwood coal field. At several mine sites, spoils have also been sampled to the depth of mining. Spoil properties vary widely from site to site, and it appears that characterization will need to be site-specific within each permit area. Variation with depth in smoothed spoils is relatively low. Electrical conductivity of smoothed spoils after mining is often higher than that of unmined overburden. A series of experimental plots was established at four mine sites in which succession of native grass species is being studied, both with and without topsoil over the spoils. Vegetation the first year consisted primarily of annual weeds. In the fall of 1974, perennial grass seed was introduced by mulching plots with native prairie hay. This resulted in the initiation of a large number of perennial native grasses and forbs. To date prairie junegrass predominates on all plots. This technique seems to have potential for hastening natural succession.

SPOIL TEST SITE

At University Park, Pennsylvania, 6 m depth of strip mine spoil has been excavated, transported to Klingerstown, and reconstructed in two, 2 m diameter x 4 m caissons. The caissons have been instrumented with lysimeters, tensiometers, water and temperature access tubes, a groundwater well, and O_2 diffusion chambers. Conductivity, pH, acidity, Ca, Mg, and SO_4 analyses have been carried out at each foot of depth in the spoil. Concurrently, physical properties such as hydraulic conductivity and particle size distribution were measured. Soils surrounding the spoil area and mine soils in the spoil area have been described, classified, and analyzed in detail. The Ohio State University model of acid production from a drift mine has been adapted to describe acid production in caissons of strip mine spoil. At 10 randomly chosen sites on the experimental area, values of hydraulic conductivity, bulk density, porosity, and field capacity have been determined on the top 20-30 cm of the profile. Results show the Lower Kittanning spoil to have a lower bulk density, but higher conductivity, porosity, and field capacity than surrounding soils. Preliminary comparison of microlysimeter data with standard pan data suggests that evapotranspiration on strip mine spoil may be approximated with standard pans.

CLIMATOLOGICAL TESTS

Water measuring flumes, sediment samplers, rain and snow gages, and other climatological instruments have been installed on a mined and an unmined watershed near Steamboat Springs in northwestern Colorado. Stage recorders and sediment samplers have also been installed at three sites on Fish Creek, which drains the overall mined area. This instrumentation will allow evaluation of the effects of surface mining on water quality and quantity.

Water samples from the watershed sites and Fish Creek sites have been analyzed for EC, pH, HCO_3, Cl, NO_3, SO_4, Ca, Mg, K, and Na for the period May 5 to October 4, 1976. Using EC as an indicator of overall quality, the analysis indicated a recurring pattern of increased EC in one mined area, but revealed strong effects from local inflows, suggesting natural spatial variation in water quality. A numerical, physically-based model, capable of simulating water and sediment movement rates on a watershed during a storm, has been shown to simulate data from a natural rangeland watershed accurately.

GREENHOUSE STUDIES

Greenhouse studies at Beltsville, Maryland, have shown a slight improvement in legume yields on acid mine spoils when the commercial inoculant "Implant" was used instead of conventional inoculation. Another greenhouse test showed that while 175 MT/ha sludge compost gave the highest forage yields, the spoil pH was raised to only pH 3.5. Additions of 35 MT/ha of fluidized bed material (FBM, a by-product of a new coal burning process) with 175 MT/ha compost gave a similar yield, but raised the spoil pH to about 6.5. The neutralizing value of FBM can be increased by pulverizing it to 100-mesh size. The neutralizing value of FBM in a pH 2.6 strip mine spoil is approximately one-half that of $CaCO_3$.

SITE APPLICATIONS

Subsoil applications of lime and rock phosphate to strip-mine spoils by means of a special subsoiling machine promoted root growth of tall fescue to a depth of 55 cm. Surface applications of lime and rock phosphate permitted root penetration to a depth of only 35 cm. The deep-placement technique has been used for subsoil placement of composted sewage sludge in studies of the effects of vertical mulch.

Analysis for 14 elements of plants growing on reclaimed mine spoils in the east shows that they would meet the nutritional requirements of animals. Se concentration was above 0.1 ppm while control plants had less than 0.1 ppm. Fly ash is a source of Se available to plants. It is also a source of Mo which could reach toxic levels if Cu concentrations remain low. In the west, grasses from mine spoils were generally low in Cu, Zn, K, Ca, and Mg. Sagebrush contained more than 4 ppm Se, which could be slightly toxic. Fluoride concentrations have ranged from less than 1 ppm to 100 ppm.

At Blacksburg, Virginia, studies using special crops show a need for mulch as well as fertilizer. Two-year mean yields with specialty crops of tomatoes and October beans indicated the need for mulch and adequate amounts of nitrogen. The highest tomato yields (30 MT/ha) were obtained from Big Boy and Supersonic varieties with high nitrogen (336 kg/ha) and sawdust mulch. Overall average yields from sawdust were 20.8 MT/ha, from straw 17.6, and from no mulch 12.3. The highest shelled October bean yield of 4.3 MT/ha was obtained from the high fertility level and sawdust mulch. Yield increases of 50 percent to 70 percent resulted from the use of sawdust as a mulch. Concentrations of elements in leaf tissue and edible fruit were for the most part within the normal range established for these vegetables.

SEEDING GROUND COVER

Seedling growth in rough surface conditions offers quicker ground cover and minimizes erosion. Forage harvested from hydroseeding on a rough surface averaged yields of 4025 kg/ha compared with 3930 from the agricultural seeder. Nurse crops caused a wide range in density of grasses, legumes, and bare ground as follows: hairy vetch 55 percent, 39 percent, and 6 percent; rye 40 percent, 23 percent, and 36 percent, respectively. From a fertility and species-persistence study, yields in the sixth harvest year were: bromegrass 5540 kg/ha, orchardgrass 3800, Ky 31 fescue 3475, and timothy 5150. Forage yields from rock phosphate averaged 4450 kg/ha, and from lime plus superphosphate 3760 kg/ha.

Rock phosphate continues to be one of the better amendments on distrubed soil materials having a pH below 5.0. Third year plant density counts indicated the persistence of special-purpose legumes. Treatments seeded with sericea averaged 65 percent and with crownvetch 75 percent; Kobe lespedeza and red clover dropped to 15 percent. Of interest was the high density of ladino clover, averaging 79 percent. Yields (dry weight basis) favored species mixtures of sericea lespedeza and Ky 31 fescue, and sericea and weeping lovegrass, which averaged 6270 kg/ha.

CULTIVAR YIELDS

Yields of five buckwheat cultivars grown on low-pH strip mine spoils in Morgantown, West Virginia, and on low-fertility marginal land soils averaged 1345 kg/ha from marginal lands or approximately 5 times the average grain production on reclaimed strip mines. Nitrogen and P increments did not stimulate yield on marginal soils, but nitrogen application promoted a small yield increase on strip mine soils. Buckwheat samples from field locations did not contain hazardous levels of Pb, Cd, Cr, Ni, Cu, or Co. However, greenhouse buckwheat forage from mine spoils amended with fly ash contained increased concentrations of several essential elements but phytotoxic levels of B. Plant concentrations of Cu, Ni, and Cd exceeded normal amounts. Tufcote and Midland bermudagrasses have been successfully maintained on low pH strip mine spoil over a 5-year period using complete fertilizer and lime or raw rock phosphate as soil amendments. After 5 years, highest yields were obtained at the highest lime rate (8 MT/ha) or with 4 MT/ha of raw rock phosphate. Bermudagrass forage quality was sufficient for grazing beef cattle but not for producing dairy cows. Aluminum and Mn content of bermudagrass forage was decreased by applications of lime, whereas P levels were significantly increased by applications of raw rock phosphate. The magnesium levels in forage from mine spoils were extremely low (0.05 to 0.10). Spoil pH was increased from 3.5 to a high of 6.5 with 8 MT/ha of lime. Raw rock phosphate (2 MT/ha) increased the pH to approximately 5.

Also near Morgantown, erosion of steep outer slope areas on low pH strip mine spoils was successfully controlled by use of several species including tufcote bermudagrass, tall fescue, and redtop. Lime or combinations of lime and raw rock phosphate were essential for good establishment and growth of all species.

MICROBIOLOGICAL RESULTS

Microbiological examination of disturbed and undisturbed soils on strip mine sites indicated that numerous heterotrophic soil microorganisms resided in the rhizosphere of plants on mine spoil treated with lime or sewage sludge, but no longer existed in unvegetated spoils. Nearly 150 isolates of bacteria, actinomycetes, and fungi have been collected from vegetated strip mine areas and are currently being identified. Analytical procedures for elemental analysis of plant material, soil, and water using an induction coupled plasma quantometer (ICPQ) have shown that its detection limits for AL, B, Ca, Cd, Co, Cr, Cu, Fe, Mg, Mn, Mo, Ni, P, Pb, Sr, and Zn are as good as, and in most cases better than those of atomic absorption. Detection limits of Na, Se, and K were somewhat poorer than with atomic absorption. Methods for sulfur determination in plants and mine spoil material have been developed using a Leco IR 33 sulfur analyzer with careful control of operating procedures.

VEGETATION CONCENTRATION MECHANISM

Spray irrigation was used to test the efficiency of vegetation as a concentration mechanism for the nutrients and toxic metals contained in polluted leachate from a municipal solid waste sanitary landfill. Vegetation from six forage grasses and six native woodland species was analyzed before and after application of 140 to 155 cm of leachate containing 500 ppm Ca; 150 to 200 ppm Na and Fe; 50 to 100 ppm of Mn, K, Mg, and N; 2 to 5 ppm of Al, Sr, Zn, and P; and less than 0.5 ppm of Ni, Co, Cr, Cu, Pb, and Cd. Measurements of chemical oxygen demand (COD), specific conductivity, and pH in sprayed waste water were 5,000 mg/liter; 3,000 micromhos/cm; and 5.3 to 5.5, respectively. Leachate applications appreciably increased Fe, Mn, Cl, and S in most forages and woodland species. Lime treatments prevented excess Mn accumulation. Reed canarygrass contained higher levels of micronutrients than other forages. Micronutrients in sourwood and orchardgrass stands were depleted by leachate irrigation. Seasonal factors affected uptake of Na, Fe, Mn, Zn, K, and Co in grasses. Volunteer Pennsylvania smartwood contained up to 9,000 ppm Mn after irrigation with leachate. Heavy metals in grasses and woodland species ranged from 10 to 30 ppm Cd; 1.0 to 7.0 ppm Ni; 3.0 to 6.0

ppm Pb; and from 0.5 to 1.5 ppm Cr and Co. Aeration appreciably reduced the odor and COD levels of leachate.

SLUDGE APPLICATION RATES

Studies to determine the effect of rates of sludge application on extremely acid strip mine spoils (pH 3.2) have produced significant yield increases from tall fescue, crambe, and other crops. Fescue forage was analyzed to determine quality aspects as affected by harvest date and season of the year. Significant increases in plant composition of Zn, Cd, Ca, and Mg were noted from applications of sewage sludge. However, significant decreases were noted for B, Mn, Fe, Al, and Pb. Significantly higher levels of Pb, Cu, Cr, Fe, Zn, Al, and N were found in winter-harvested than in summer-harvested forage. Higher cadmium content may be the main factor limiting forage quality where sewage sludge has been applied. Cadmium concentrations in forage range from 0.9 ppm from conventional fertilization on strip-mined areas to a high of 1.4 ppm where 224 MT/ha of sewage sludge were applied. Crambe, an oil seed crop, showed significant increases in seed yield from application of sewage sludge on low pH strip-mine spoil. An application of 10 MT/ha of composted garbage on a newly seeded strip-mine spoil produced significantly better tall fescue stands than treatments with lime or fluidized bed waste plus a complete fertilizer. Old stands of fescue are better after 3 years on plots receiving garbage mulch and sewage sludge than on plots receiving conventional fertilizer and lime treatment. Fescue yields from older studies on strip mine spoils increased with increasing rates of sludge to 224 MT/ha. Garbage mulch plus lime also increased yields.

Studies were conducted at two locations to determine effects of sewage sludge application rates on movement of various elements through an acid strip mine spoil profile. Significant increases in soil pH at depths of 30 cm were found after application of sludge. Calcium, Mg, P, K, Cu, and Zn were moved into the soil profile, possibly by chelation with organic matter from sludge. Soil microbial studies comparing plots treated with sewage sludge with conventionally fertilized strip mine spoil indicated a much better soil microflora after treatment with sludge.

SEEDLING ESTABLISHMENT

Seedling establishment of crested wheatgrass, western wheatgrass, and fourwing saltbush was good at the Shirley Basin uranium mine site, and fair at the Rosebud coal site in Wyoming. Residue production from spring-seeded barley averaged about 1120 kg/ha. Grass mixtures were seeded into the barley stubble in November. *Artemisia vulgaris,* an introduced herbaceous sage, was found to have an average protein content of 27 percent, and an *in vitro* digestability of 65 percent. Phosphorus, Ca, Ma, and K contents of the plant material were within the optimum range for cattle nutrition. Specific conductivity was usually below 2.0 mmhos/cm and no sodic conditions were evident. All study sites were low in plant available P and N; therefore, 56 kg N per hectare and 56 kg P per hectare were applied.

Plantings of woody species were expanded to include additional locations at surface-mined sites at Kemmerer and Hanna, Wyoming, and at Oak Creek, Colorado. Eighty-three woody species are now under test. Additional species were added to the 1-year plantings at Gillette, Shirley Basin, and Glenrock, Wyoming. Of the 83 species, only 18 planted at more than one location were not browsed by wildlife. Major wildlife species causing damage were antelope and deer.

At Peoria, Illinois, translocation of Zn, Mn, Cu, Pb, Cr, Cd, and Hg was studied in corn plants grown on strip-mine soil amended with anaerobically digested sewage sludge. In the seven plant tissues analyzed, metal concentrations were generally highest in the leaves and roots and lowest in the grain and cob. Concentrations of all metals except Mn and Hg increased in tissues as a result of sludge application.

SOIL CONSERVATION SERVICE

The Soil Conservation Service has been involved in plant development work for a long time. Many of the plants that are proving most effective in revegetating surface-mined areas were selected by the SCS at one of its 20 plant material centers around the country. In recent years, the SCS has greatly accelerated its activities in evaluating, selecting, and encouraging the commercial development of plant materials for surface-mined lands.

The SCS system of classifying mine spoil has provided a method for evaluating plants and correlating their adaptation and performance with site conditions to project the results of their use on similar sites elsewhere. Technical guides have been developed with information on the adaptation of plants, recommended mixtures, seeding rates, and seeding times.

In addition to its plant materials work, the SCS has just completed an inventory of land disturbed by surface mining in the United States as of July 1, 1977. The inventory covers the status of land needing reclamation, land not requiring reclamation, and total acreages of land disturbed. Disturbed land is classified by commodities mined. The report shows a total of 5.7 million acres disturbed as of July 1, 1977. Of this, over 3.8 million acres have not been reclaimed. This includes over 2.7 million acres mined before there was any legal requirement for reclamation. Approximately 1.9 million acres have been reclaimed either by natural means or through efforts of mining companies and landowners.

DEPARTMENT OF ENERGY

The Department of Energy's Land Reclamation Program (LRP) was initiated in 1975 to conduct integrated research and development projects to coordinate, evaluate, and disseminate the results of reclamation research. Close cooperation with academic institutions and other agencies to transfer pertinent information and avoid duplication of effort has been a primary goal. The major effort is to develop ways of ameliorating the environmental impacts of coal extraction. Current field and laboratory research efforts have been directed toward providing solutions to problems related to land reclamation.

At the Big Horn Mine, Tongue River, Wyoming, scientists are investigating the formation, transport, and ultimate environmental effects of mine-related pollutants in the Tongue River watershed in Wyoming and Montana. The study will focus on defining the effects of current strip mining practices and regulations as well as upon predicting impacts on water quality.

PLANT MOISTURIZATION

The purpose of a study at the Jim Bridger Mine, Rock Springs, Wyoming, is to investigate and evaluate alternative systems that can provide additional moisture to plants used in revegetating mined land in the arid west. A new snowfence system has been designed and deployed that has promise for increasing the water available to vegetation. Two years' data indicate that plant-available moisture may be increased by 20 percent to 50 percent.

Other research at the Jim Bridger Mine is identifying principles of adaption and survival of native species under stress. Plants are being tested and analyzed for productivity (biomass), population dynamics (species mortality and distribution), and energy allocation strategies (how a plant assigns its energy resources to growth, reproduction, and defense).

ACID STUDY

A cooperative research/demonstration activity with the State of Illinois at Goose Lake State Park is designed to investigate the process of acid production and its transport into adjacent ponds and groundwater systems. This study is focused on the groundwater system, including recharge, flow patterns, flow rates, discharge, and chemistry, in the spoil materials and surrounding undisturbed areas. Information will be gathered on (a) the chemical characteristics of groundwater in acidic mine spoils, (b) the subsurface transport of potential pollutants to the ponds and surrounding land area, (c) the magnitude of impacts to groundwater quality due to the initial mining, and (d) the long-term effects of reclamation on groundwater, hydrology, and quality. Additionally, oxygen diffusion rates into the spoils are being studied under various surface treatments to determine whether pyrite oxidation is controlled by reclamation. Forty groundwater monitoring wells have been emplaced in the reclaimed spoil material adjacent to undisturbed land to measure groundwater transport of pollutants.

REFUSE SITE

An abandoned 34-acre refuse area in south-central Illinois is the location of a comprehensive reclamation/demonstration project. The refuse site has caused pollution and sedimentation problems in nearby streams and also may have contaminated the local groundwater system. The groundwater system and streams,

and runoff from the gob pile, have been monitored before, during, and after the reclamation in an attempt to understand the changes in water quality brought about by reclamation. Additional research has been initiated at this site to investigate the cost and effectiveness of selected reclamation techniques. In particular, the growth of various plants in different concentrations of cover material and unamended and treated gob is being evaluated in both field and laboratory experiments.

WESTERN REVEGETATION

A joint study with Utah International Coal Company at the Navajo Mine is concentrating on the breeding and selection of plant species and varieties for use in the revegetation of lands disturbed by mining in the arid west. The objective of this study is to develop plants suitable for reclaiming mine spoils in harsh environments characterized by drought and spoil salinity. Seed and transplants from similar environments were collected throughout the west for cytological studies, hybridization, and cloning. Examinations have shown that most *Atriplex* species contain chromosome races. This fact will assist in interpreting and utilizing adaptive differences noted in native populations and in identifying the most promising crosses in breeding studies.

At the Jim Bridger Mine in Wyoming and the Macoupin County refuse reclamation/demonstration site in Illinois, research has been established to study the use of reclaimed mine land by wildlife. Study areas have been designated where species composition and density on reclaimed areas can be compared with those in adjacent native ecosystems. A second study is focusing on the impacts small mammals will have on early success of vegetation establishment. Early data suggest that small mammals have a significant deleterious effect on reclamation.

COSTS AND BENEFITS

Essential to any reclamation program is the identification and quantification of factors responsible for variations in costs and benefits of the reclamation effort. A project is underway to assess the realtive costs and benefits of alternate reclamation procedures to determine possible methods of reducing overall costs while maintaining acceptable end results.

Another project is set up for developing data and information systems regarding techniques, technologies, and research in the field of mined land reclamation, and the dissemination of such information. This activity is coordinated with DOE's Energy Information Administration. This effort is focusing on designing and implementing a land reclamation data acquisition and management system and a comprehensive computerized bibliographic reference library.

For several years EPA has been engaged in studies of both eastern and western coal mine reclamation. Results of the most recently completed studies on reclamation are as follows:

SPOIL MATERIALS

Field experiments were established in western Kentucky on four types of surface-mined coal spoils. Areas were selected to represent the extremes in spoil materials commonly encountered in reclamation. There is evidence that mine spoils may be successfully reclaimed when proper levels of fertility have been restored.

Where a rough surface was created by ripping or subsoiling, yields of mixed legume-fescue forage exceeded 4 metric tons per hectare. These yields were equal to or greater than those of adjacent unmined land. The advantage was obtained at all levels of applied phosphorus. The use of a chisel plow or heavy-duty disc produced a rough micro-relief that also produced significantly greater forage yields than smooth-graded plots.

It was found that phosphorus and water are commonly the limiting factors in obtaining an adequate vegetative cover. Lime must be incorporated to effectively improve the rooting zone of plants. Lime will not move downward, so plant roots are restricted to the zone of lime incorporation.

ACID MINE DRAINAGE

A project was conducted near Elkins, West Virginia, to demonstrate methods of controlling acid mine drainage (AMD) pollution from inactive surface and underground coal mines. Methods included burial of acid-producing spoil and coal refuse, and regrading and revegetation of surface mines.

The subwatersheds primarily impacted by surface mines showed the greatest improvement. Although good vegetation was established on most areas, sulfate and other ions continued to leach from the backfill material for years after reclamation was completed.

Except for a few small areas, a good vegetative cover was established. Grasses exhibiting the best growth were tall fescue, oat grass, orchard grass, and Kentucky bluegrass. Weeping lovegrass was a good nurse crop. Sericea lespedeza, birdsfoot trefoil, and alsike clover were the dominant legumes. Best tree survival and growth was obtained from European black alder. Pines, Japanese larch, and black locust also were successful. With the possible exception of the pines, dense growth of grasses and legumes did not affect survival or growth of the trees. The addition of agricultural lime and fertilizer was largely responsible for the success of vegetation.

RUNOFF EFFECTS

At five active coal strip mine areas in the tristate region of Montana, North Dakota, and Wyoming, a system of intensively monitored microwatersheds was constructed to demonstrate the effects of several soil surface manipulation treatments on control of runoff, chemistry of runoff, soil water flow, aquifer characteristics, and vegetation establishment. Treatments were chiseling and gouging with and without topsoiling and dozer basins with topsoiling.

Topsoiling is a major reclamation tool in the control of surface runoff because it increases infiltration. For all storms observed, topsoiled watersheds had less runoff than watersheds not topsoiled. Erosion at each study site correlated positively with runoff. At this stage of the study it seems apparent that surface manipulation, particularly gouging and dozer basins, is effective in controlling runoff and erosion on many mine sites in the semiarid west.

At two of the study sites a net 10- to 20-cm of water moved from the subsurface zone into the surface 2 m zone in four of the five watersheds during the hydrologic year. If this process were to continue over decades there would be some potential salinization of the surface soil.

Dozer basins should be constructed with a rear-mounted dozer basin implement designed for that purpose. Front-blade equipment produces shallower basins with lower water detention capacity and a very compact impermeable base.

RUNOFF QUALITY

The quality of surface runoff water from spoil watersheds is of major concern. NO_3-N, Mg, Ca, soluble salts, and most trace elements were found in low concentrations in runoff water. Mn and Fe concentrations often exceeded federal standards for drinking water, but were probably acceptable for irrigation. Occasional samples contained Cd, Pb, and PO_4-P at levels that exceeded desirable limits. Early results of a study of the quality of runoff as a function of watershed surface manipulations show no trends.

Surface manipulation treatments should be useful for controlling runoff under most conditions in the semiarid west. However, if the conservation of soil water is the goal, it will have variable results. At this stage of research, it is apparent that surface manipulation techniques will be widely applicable, but there will be instances when such techniques will have explicit limitations.

SPENT SHALE DISPOSAL

Disposal of massive amounts of spent shale will be required if an oil shale industry using surface retorting is developed. Field studies utilizing lysimeters to model both low elevation (dry) and high elevation (moist) disposal sites were initiated in 1973 on two types of spent oil shale—coarse textured (USBM) and fine textured (TOSCO). A similar study was initiated in 1975 on Paraho spent directly heated oil shale. The studies were designed to document surface stability and salt movement in spent shales and in spent shales covered with soil after vegetation had been established by intensive treatment and then left under natural precipitation. The Paraho study also provided for trace element analysis of the leachate water and for comparison of water movement through compacted and uncompacted spent shale.

A good cover of native perennial grasses was established on all plots except the low elevation bare TOSCO spent shale, where the cover was dominated by a mixture of annual and perennial grasses. The bare Paraho plots had less than 10 percent vegetative cover. Problems encountered included inadequate leaching prior to planting, resalinization by upward movement of salts into the soil cover over the fine textured TOSCO spent shales, and the initial high pH of the Paraho spent shales. Vegetation from the plots showed higher levels of some trace elements than vegetation grown on native soil. Runoff from all plots was moderately to highly saline. Sediment yields were generally low.

If spent oil shales are to be quickly stabilized with native vegetation they will require leaching, N and P fertilization, and irrigation. Nitrogen application will be required for a number of years to assure a permanent cover.

The infiltration rate on the fine-textured spent shale is very slow, thus the erosion potential may be high. The slow infiltration rate must be considered when stabilization of this spent shale is planned.

RESALINIZATION

Resalinization of leached fine-textured spent shale occurred in these studies. Application of more leach water would move the salt farther down and decrease the resalinization potential. The disposition of the leach water within the spent shale disposal pile must be considered in large-scale operations.

A minimum of 30 cm of soil should be used over unleached spent shale with low pH. High pH [11-12] spent shales require a thicker soil cover. Even with soil cover, irrigation and fertilization are still required for vegetation establishment.

A study of ecological recovery after reclamation of toxic coal mine spoils measures the rate of recovery of a damaged ecosystem in response to intensive remedial treatments. The project involves a problem watershed in which 162 ha (400 acres) of forested land were disturbed in the early 1970s. Unsuccessful reclamation resulted in adverse impacts to the 27.6 km (10.8 sq. mi.) watershed.

Remedial work conducted over a 3-year period was initiated during the fall of 1974. Treatments included incorporation of agricultural limestone to raise spoil pH, seeding with acid-tolerant grasses and legumes to provide a protective ground cover, and planting of trees and wildlife shrubs the following planting season.

Vegetation and aquatic monitoring began in 1975. Data collected through spring 1977 show that total vegetative ground cover increased from 34 percent to 43 percent, and that the mean pH increased from 4.0 to 4.5. Aquatic invertebrate sampling indicates an increase in the number of individuals and taxa in the streams receiving direct treatment. Fish have recovered in portions of the main stream close to two downstream reservoirs. The most evident changes in water chemistry were overall increases in stream pH. Other water quality parameters varied in their responses to the treatment.

PLANNING MODEL

Tennessee Valley Authority (TVA) is currently developing a planning model for assessing the impact of surface mining on the environment. Findings of field studies at 12 sites in the Cumberland Plateau of Tennessee indicate that:

- Most mining results in alkaline drainages with generally low concentrations of metals.
- The most serious water quality problem is erosion and resulting sedimentation.
- Models for daily streamflow, storm flow, and suspended solids have been formulated and at least partially verified.
- Models for stream biota and stream pH have been formulated but not verified.

PEST AND VECTOR FORMATION

Another project involves arthropod pests and vectors produced in pools formed as part of the strip mining process. Monthly biological samples have been collected from nine study ponds (selected on the basis of age) and likely sites for oviposition near the ponds. Seven species of mosquitoes, five of which actively feed on man, have been found. *Anopheles punctipennis* and *Culex erraticus* have been the most prevalent species, and *Anopheles quadrimaculatus*, the malaria vector, was found in significant numbers.

Midges of the genus *Procladius* (Diptera:Chironomidae) are common inhabitants of ponds, lakes, and slow-flowing streams. Larvae with morphological abnormalities were found in ponds formed by strip mining for coal near Brilliant, Marion County, Alabama. Atrophied and deformed antennae, deformed mandibles, and unusual numbers and forms of ligular teeth appeared in about 25 percent of the nearly 200 larvae examined. A search is being conducted for the factor or factors causing the abnormalities; the following are possibilities; crowding, diet, water quality, and nematode parasitism.

SUMMARY

Vegetation can be successfully established on most surface mine spoils if proper mining and reclamation techniques are employed. Overburden must be moved and placed so that the best material for plant growth is on the surface. A suitable seedbed is essential. Amendments must be used to alleviate acidity, provide nutrients, and improve plant-soil-water relations. Seeding or planting must be done at the proper time of the year. Species must be compatible with the area. Species in mixtures must be compatible with each other to assure success in achieving land reclamation goals.

Legislation generally determines the degree of reclamation sought, but technology is not always available to meet regulatory requirements. Sometimes legislative action tends to create new problems through specific requirements which have not been thoroughly researched.

Much research is being done under the auspices of the federal government aimed at reclamation of surface mined lands throughout the United States.

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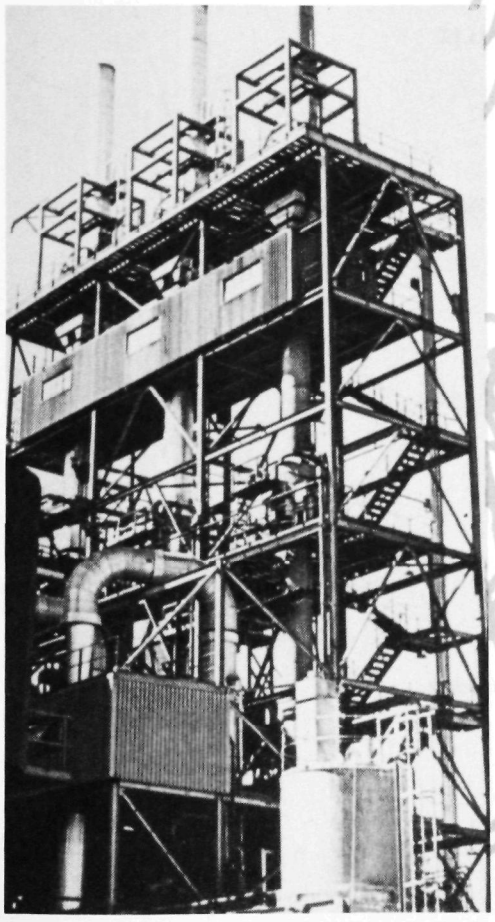

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CONTROL TECHNOLOGY

INTERAGENCY COAL CLEANING TECHNOLOGY DEVELOPMENTS

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Expanding coal production and use is a major goal of our National Energy Policy. A corollary goal is the containment of adverse environmental effects from coal use.

COAL CLEANING

Important in the coal energy cycle is coal beneficiation or cleaning. Coal cleaning removes extraneous mineral matter and mining residue. It is also a cost effective means of removing sulfur from metallurgical coke and boiler fuels used to comply with SO_2 emission regulations.

Coal cleaning processes generate pollutant streams which must be controlled and residues which must be disposed of in an environmentally sound manner. In 1976, more than 370 million tons* of coal were physically cleaned, generating more than 107 million tons of coal cleaning residues. Leachates from improper waste disposal, particulate emissions from thermal drying, and fugitive dust from coal handling pose health and ecological threats.

THREE BASE ELEMENTS

EPA's interagency energy/environmental program is subdivided into three basic elements. The principal objectives of activities under these subprograms are to (a) assess and develop coal cleaning technology for removing pollutant-forming contaminants from coal, (b) evaluate the environmental impacts of coal cleaning processes, and (c) develop improved methods of controlling pollution from coal preparation.

This paper presents an overview of regulatory activities related to coal cleaning, an analysis of future coal cleaning R&D priorities, and a summary of progress on the interagency coal cleaning R&D program.

Research and development activities under the interagency coal cleaning program are responsive to changing regulatory requirements and energy goals. A review of the technical status of coal cleaning and associated regulatory activities will provide the context for the discussion of progress on recent coal cleaning R&D.

AIR POLLUTION REGULATIONS

In accordance with provisions of the Clean Air Act Amendments of 1970, EPA has set primary and secondary ambient air quality standards which regulate pollutant levels to protect human health and public welfare (property and plant and animal life). Ambient air pollutants specified in current EPA regulations relating to coal use include sulfur oxides, nitrogen oxides, and total suspended particulates.

Section 1.11 of the 1970 Clean Air Act Amendments requires that EPA promulgate emission standards for new stationary sources (constructed after the date the regulations are proposed). Since these new source performance standards (NSPS) are based on emissions, the owner/operator may use any control system, but the standard must be achieved without the privilege of variances or exemptions. The Clean Air Act Amendments of August 1977 have significantly modified previous

*English to metric unit conversion factors are given at the end of this paper.

clean air legislation, especially as related to its potential impacts on the use of coal cleaning technology. These Amendments specify that all new stationary sources regulated by EPA must (a) use best available control technology, (b) use a method of continuous pollution control, and (c) achieve a percentage reduction of the regulated pollutants for fossil fuel fired units. Any reduction of a pollutant by post extraction fuel processing may be credited to the percentage reduction requirement.

NSPS FOR FOSSIL FUELED BOILERS

In the near future, EPA will propose revised NSPS for fossil fueled boilers used for electrical energy generation. The regulations now under consideration (a) require an 80- to 90-percent reduction in sulfur between extraction and stack gas emissions and (b) specify that the sulfur emissions cannot exceed 1.2 lb $SO_2/10^6$ Btu of boiler heat input. Emissions below a minimum level (0.2 to 0.5 lb $SO_2/10^6$ Btu) would be exempted from the percentage reduction requirement. Promulgation of these regulations would effectively preclude the use of coal cleaning as a sole method for complying with SO_2 standards in new electric utility boilers.

Other important provisions of the 1977 Clean Air Act Amendments include prevention of significant deterioration of air quality in clean air regions, the siting of sources in nonattainment areas, the periodic review of state implementation plans for meeting National Ambient Air Quality Standards, and the setting of emission standards for potentially hazardous pollutants. The strigency of regulations for nondeterioration and clean air regions may necessitate the use of coal cleaning in combination with scrubbing in order to comply with SO_2 emission standards. Tightening and strict enforcement of emission standards under state implementation plans may expand the market for physically or chemically cleaned coals.

Potentially hazardous pollutants which EPA must consider regulating include arsenic, beryllium, mercury, lead, and polycyclic organic matter, all of which are emitted from coal-fired boilers. If EPA decides that the emission of these pollutants from coal combustion must be regulated, then removal of some of these contaminants before combustion by coal cleaning may be an effective method of control.

WATER POLLUTION REGULATIONS

Federal control of water pollution sources associated with coal production, preparation, and consumption is achieved through the issuance of discharge permits which contain the limits on the effluents discharged. Effluent guidelines are presently based on the best practicable control technology (BPT) currently available and must be based on the best available technology economically achievable (BATEA or BAT) by 1983, except where modified requirements are in order, pursuant to Section 301(c) of the Federal Water Pollution Control Act (FWPCA). Effluent limitations are also being issued for new sources. These new source performance standards, mandated by FWPCA Section 306, are intended to be the most stringent standards applied.

State control of water pollution sources associated with coal preparation is achieved through the issuance of permits independently or under the National Pollutant Discharge Elimination System (NPDES). The permits, which contain limits on the effluents discharged, are issued to each discharger. The objective of such control systems is to achieve or maintain specified ambient water quality standards which are primarily a state responsibility. The Federal laws are intended to aid in the achievement of state standards. EPA, however, retains the authority to veto state plans.

On May 13, 1976, EPA promulgated interim final effluent guidelines for four subcategories of existing sources: coal preparation plants; coal storage, refuse storage, and coal preparation plant ancillary areas; acid or ferruginous mine drainage; and alkaline mine drainage. More than 10 lawsuits were filed challenging these regulations. These lawsuits were consolidated and are now pending before the U.S. Court of Appeals for the Fourth Circuit.

FINAL REGULATIONS

EPA promulgated final regulations on April 26, 1977, which incorporated several revisions to the interim final effluent guidelines published on May 13, 1976. Subpart B of these regulations addresses discharges from coal preparation plants and

associated areas, including discharges which are pumped, siphoned, or drained from coal storage, refuse storage, and coal preparation plant ancillary areas. Included under these regulations are discharges related to the cleaning or beneficiation of coal of any rank including, but not limited to, bituminous, lignite, and anthracite.

LIMITATIONS

The limitations establish the concentration of pollutants which may be discharged after the application of BPT treatment. These limitations differ for discharges that are normally acidic before treatment as opposed to those that are normally alkaline. For acidic conditions, limitations were specified for total iron, manganese, total suspended solids (TSS), and pH. Limitations for total iron, TSS, and pH were specified for alkaline conditions.

On September 17, 1977, EPA published proposed new source performance standards for the coal mining point source category. These limitations establish the concentrations of the pollutants which may be discharged after application of the best available demonstrated control technology. These limitations apply to discharges from facilities which recycle process waste water and differ depending upon whether discharges are normally acidic or alkaline before treatment. Pollutants regulated include total iron, manganese (acidic conditions only), TSS, and pH. The regulations stipulate no discharge from facilities which do not recycle process waste water.

In 1975, EPA was taken to court by several environmental groups who claimed that EPA had not done a complete job in assessing the pollution of surface waters by industry. On June 7, 1976, the courts decided in favor of the environmentalists, and the machinery for a review of effluent guidelines was set in motion.

PRIORITY POLLUTANTS

EPA must first review its BAT guidelines in the light of the priority pollutants. These priority pollutants arose from the court case and amounted to about 65 compounds or classes of compounds which the EPA had failed to regulate, or take into consideration, in their earlier guidelines. The process of naming specific compounds in the classes resulted in a list of 129 priority pollutants. The courts, in this decision, set deadlines for EPA to implement BAT by 1983. The first step is a proposed rule-making by September 30, 1978. By December 31, 1978, after time for comment, EPA is to publish its proposed revised guidelines. Six months later (June 30, 1979) the revised guidelines are to be promulgated. This will give industry 4 years to implement BAT. The recent 4 month strike by the United Mine Workers (UMW) of America has interfered with this schedule. Consequently, EPA, along with the National Coal Association, is preparing to ask the court for a 6-month delay in the deadlines.

The BAT Review is a three phase study—the first two deal with technology; the third, with economics. The technology phases centered on the priority pollutants and are known as the screening and verification phases. The screening phase involves looking for the presence or absence of the priority pollutants; the verification phase involves quantifying and confirming the pollutants found in screening.

ECONOMIC PHASE

During these two phases, economic data are also collected. Factors which would affect the economics of a treatment technology are determined from each site visited for sampling as well as from industry associations. These factors include, plant capacity, plant age, location, type of process, source of raw materials, end use of product, capital cost, capital recovery, and operating costs. This information is combined with wastewater data, flow rates, and concentrations, to assess the impact and cost effectiveness of a treatment technology.

The verification phase was delayed by the UMW strike. Plans are being made to begin the verification phase.

SCREENING PHASE

The screening phase has been completed for the coal mining industry. In the screening phase, 18 coal preparation plants were visited. Of these only two were not sampled—one because the plant was shut down by a strike; and the other because there was no point of discharge.

In addition to the screening tests for the 129 priority pollutants, analyses were made for classic water pollutant parameters and some elements not on the priority pollutant list. Of the 129 priority pollutants, 24 were found in water from preparation plants and associated areas. Some of the pollutants may be artifacts of the analytical procedures. Additional tests will be required to evaluate their authenticity. Also, 12 elements not on the priority pollutants list were found.

SOLID WASTE DISPOSAL REGULATIONS

Solid wastes generated from coal preparation are generally subject to land disposal. Federal guidelines for land disposal of solid wastes are nonspecific in terms of definite quantities which can or cannot be disposed of. All facets pertaining to land disposal sites are covered by requirements to conform to the most stringent water quality standards under the provisions of the Federal Water Pollution Control Act. Leachate collection and treatment systems are required at disposal sites as necessary to protect ground and surface water resources.

Provisions of the Solid Waste Disposal Act were significantly modified by the passage, on October 21, 1976, of the comprehensive Resource Conservation and Recovery Act (RCRA) of 1976 (P.L. 94-580). From 90 days to 2 years was provided for consummation of many of the actions called for by the Act; therefore, details of regulations to be promulgated are not yet available. Some of the general provisions of the Act are:

- EPA must issue guidelines within 1 year, defining sanitary land fills as the only acceptable land disposal method that can be implemented; open dumps are to be prohibited.
- Within 1 year, EPA shall develop and publish proposed guidelines for solid waste management.
- Within 18 months, EPA must propose criteria for identifying hazardous waste, regulations for generators of hazardous wastes, regulations for transporters of hazardous wastes, and performance standards for treatment, storage, and disposal of hazardous wastes.
- Under minimum guidelines to be provided by EPA, the states will manage permit programs.
- Each regulation promulgated shall be reviewed and, where necessary, revised at least every 3 years.

It has not yet been determined whether coal refuse (and combustion ash) will be classified as hazardous wastes. This determination would require implementation of the most restrictive provisions of the Act.

CONTENT OF COAL

Coal is a complex heterogenous substance. In addition to its organic constituents (carbon, hydrogen, oxygen, and nitrogen) coal contains significant quantities of inorganic elements. While these inorganic elements are associated primarily with individual mineral phases in coal, they are also incorporated to a lesser degree in the complex organic coal molecules.

Coals are known to contain nearly all of the naturally occurring elements. Some elements of environmental concern contained in significant quantities in coal are sulfur, arsenic, beryllium, cadmium, copper, lead, mercury, manganese, nitrogen, selenium, and zinc (1).

ORGANIC AND INORGANIC AFFINITIES

Elements of environmental concern may be classified by their relative organic or inorganic affinities. Those with high organic affinities are associated predominantly with the organic coal structure, while those with high inorganic affinities are associated predominantly with the coal mineral phases. Physical and chemical coal preparation partition the elements of environmental concern in to fractions which are associated with clean coal product streams or waste or pollutant emission streams.

The relative amounts of contaminants, the manner in which they are included in the coal structure, and the degree to which they can be removed vary widely with different coals.

PHYSICAL COAL CLEANING

Coal is physically cleaned by crushing run-of-the-mine coal to a point where some of the mineral impurities are released from the coal structure. The mineral and coal particles are then separated by techniques which generally rely upon differences in the specific gravity or surface properties of the particles.

Chemical coal cleaning processes are being developed to provide improved techniques for desulfurizing steam and metallurgical coals. Chemical coal cleaning processes vary substantially because of the different chemical reactions which can be used to remove sulfur and other contaminants from coal. Chemical coal processes usually entail grinding the coal to small particles and reacting these particles with or without chemical agents at elevated temperature and pressures. The sulfur in coal is converted to elemental sulfur or sulfur compounds which can be physically removed from the coal structure. Some chemical leaching processes, such as the TRW–Meyers Process, remove only pyritic sulfur. Other processes, such as that under development by the Department of Energy (DOE), are said to be capable of removing organic and pyritic sulfur.

CLEANING STEAM COAL

Approximately 50 percent of the domestically consumed coal is physically cleaned to remove mineral matter and mining residue. A large portion of metallurgical grade coals are cleaned to remove sulfur. Cleaning operations for steam coals have not previously been designed to remove sulfur for compliance with SO_2 emission standards. The first U.S. steam coal preparation plant, designed to remove sulfur for compliance with state and federal SO_2 emission standards, has just begun operation at Homer City, Pennsylvania. Two other sulfur removing plants are being planned by the Tennessee Valley Authority (TVA). None of these steam coal plants incorporate the advanced beneficiation techniques now used in the metallurgical and mineral industries.

A number of chemical coal cleaning processes are currently under development (2). These processes are being developed to produce desulfurized coals for use in complying with SO_2 emission standards. The Meyers chemical coal cleaning process, which is at the most advanced development stage, is now being evaluated in a 1/3-ton per hour test unit at Capistrano, California. At least eight other processes are in various stages of laboratory development. Many of these are capable of removing both organic and pyritic sulfur. With accelerated development, several chemical processes could be ready for commercial demonstration in 5 to 10 years.

POLLUTANT LEACHATE

Coal preparation plants annually generate more than 100 million tons of waste. Interaction of air and water in pyrite rich coal wastes converts the pyritic sulfur to a dilute sulfuric acid leachate. This leachate may have high concentrations of dissolved trace elements or other potentially hazardous pollutants (3). Drainage of the leachate into ground and surface waters may degrade water quality and affect human health. Current knowledge on the relationships between coal mineral properties, coal trace element concentrations, the effects of weathering on the release of trace elements, and the effects of various technologies in controlling trace element pollution is rudimentary.

Coal and mineral dust, resulting from the handling, transportation, and storage of coal, may contain high concentrations of hazardous trace elements and compounds. Little is known about the composition of these dusts, their effects on human health, and the degree to which dust emissions can be controlled.

Sludges from coal preparation plants present a disposal problem. Some sludges are not easily dried, are thixotropic, and must be contained in storage ponds. Techniques to solidify and dispose of coal preparation plant sludges are in an early stage of development.

SPENT CHEMICALS

Spent chemicals used in chemical desulfurization contain many potentially hazardous trace elements and compounds. Little is known about the techniques which will be needed to neutralize and dispose of these wastes.

DEVELOPMENT DIRECTIONS

A primary short-term market for coal cleaning has been created by SO_2 air pollution control requirements. The degree to which coal cleaning is used to meet these requirements depends upon the specific sulfur emission standards which must be met, the desulfurization potential of U.S. coals, the costs of coal cleaning, and the costs of alternative pollution control techniques. Other applications for coal cleaning include the upgrading of subbituminous coals (principally lignite) and the preparation of coals for synthetic fuel conversion processes. The primary objective of the interagency coal cleaning program has been directed toward the environmental considerations of coal use.

The applicability of coal cleaning for compliance with SO_2 emission standards is contingent upon a number of regulatory and technical uncertainties. Once these uncertainties have been resolved, the use of coal cleaning will be largely defined by market considerations; i.e., a determination of the most cost effective method of coal energy production considering the costs of all pollution control requirements. Near-term applications for compliance with SO_2 emission standards are in doubt primarily because of changing regulatory requirements mandated by the 1977 Clean Air Act Amendments.

PERIODIC REVIEW OF STANDARDS

The 1977 Clean Air Act Amendments require periodic review of emission standards under State Implementation Plans (SIPs). Some regulations will be tightened, especially in noncompliance regions and in areas wishing to offset emissions from industrial growth by a reduction of emissions from existing boilers.

Revised NSPS for utility boilers being considered by EPA require an 80 percent to 90 percent reduction in sulfur between extraction and emission. This would preclude physical coal cleaning as a sole method for compliance with SO_2 emission standards in these boilers. In some instances combinations of coal cleaning and flue gas desulfurization (FGD) may be more cost effective than FGD alone. Cases for which this combination may be the most cost effective strategy cannot be adequately defined because of economic uncertainties. The standards have not been promulgated and a number of potential cost benefits and liabilities associated with coal cleaning have not been quantified. These include (a) the emission averaging time which must be used, (b) the degree to which coal cleaning will reduce coal sulfur variability, (c) the comparable costs for controlling sulfur variability with scrubbers, and (d) boiler operating and maintenance cost benefits resulting from coal cleaning.

EPA also plans to set BACT standards for industrial boilers. The level at which these standards are set will determine the applicability of coal cleaning as an SO_2 emission control strategy in these boilers.

Taking the above factors into consideration, along with the current status of coal cleaning technology, near and long term problems which coal cleaning R&D must resolve may be projected:

NEAR TERM PROBLEMS

- The characterization of coal sulfur variability and the degree to which coal preparation attenuates this variability.
- The desulfurization potential of U.S. coals by physical methods, including techniques which rely on surface properties as well as specific gravity differences.
- The development of improved fine coal cleaning techniques which will provide for maximum pyrite removal with minimum coal energy losses.
- The development of improved techniques for fine coal dewatering and drying.
- An evaluation of the environmental impacts which result from coal cleaning.
- The development of technology to control trace elements in leachant from coal preparation plant wastes.

- A determination of the effects of coal cleaning on boiler operating and maintenance costs.
- The establishment of costs for controlling pollution from coal preparation processes.
- The establishment of costs of alternative strategies for compliance with SO_2 emission standards in industrial and utility boilers.

LONG TERM PROBLEMS

- The characterization of U.S. coals and their mineral and organic contaminants.
- The development of advanced physical/chemical processes for removing inorganic and organic contaminants in coal.
- The development of pollution control techniques for (a) newly regulated pollutants, and (b) developing coal cleaning technologies.

R&D PROGRESS

The interagency coal cleaning program is divided into three major subprograms: 1) the assessment and development of coal cleaning processes, 2) the assessment of environmental impacts from coal cleaning, and 3) the development of pollution control technology for coal cleaning processes. Government organizations involved in the program include the U.S. Environmental Protection Agency, the Department of Energy, the Department of Interior, and the Tennessee Valley Authority. The program budget for fiscal 1978 was approximately $8.0 million. The program is directed for EPA by the Industrial Environmental Research Laboratory, Research Triangle Park, North Carolina. Table 1 summarizes projects active during 1977-1978. Selected projects are discussed in the following sections.

TABLE 1
Active interagency coal cleaning projects (1977-1978)

Project Title (Contract, Grant, or Interagency Agreement)	Organization Directing Work	Organization Performing Work	Objectives
TECHNOLOGY ASSESSMENT AND DEVELOPMENT			
Coal Cleanability (IAG-D6-E685)	DOE(*)	DOE(*)	Determine desulfurization potential of U.S. coals by size reduction and specific gravity separation.
Coal Cleaning Technology Assessment and Development (68-02-2199)	EPA	Versar, Inc.	Evaluate performance and costs of equipment for removing sulfur from coal
Interim Support for Homer City Test Program (68-02-2639)	EPA/DOE(†)	Chem Systems/Pennsylvania Electric Co.	Provide test planning and initial test support for the Homer City Coal Cleaning Demonstration Program.
Dense Media Cyclone Pilot Plant (IAG-D6-E685)	DOE(*)/EPRI/PENELEC/EPA	DOE(*)	Evaluate effects of cyclone design and operation variables on separation on fine coal and pyrite.
Demonstration of Coal-Pyrite Flotation (IAG-D5-E685)	DOE(*)	Heyl and Patterson Co./Barnes and Tucker Co.	Commercial testing and operation of two stage coal-pyrite flotation process developed by DOE(*).
Adsorption-Desorption Reactions in Pyrite Flotation (IAG-D6-E685)	DOE(*)	University of Utah	Evaluate the adsorption-desorption mechanisms which control performance in the DOE(*) two stage coal-pyrite flotation process.
High Gradient Magnetic Separation (IAG-D5-E686)	DOE(*)	General Electric Co.	Evaluate technical feasibility of high gradient magnetic separation for removing pyrite from coal.
Surface Phenomena in Dewatering of Fine Coal (IAG-D5-E685)	DOE(*)	Syracuse Univ.	Evaluate phenomena governing the effectiveness of surfactants in reducing the final moisture content of coal vacuum filter cakes.
Coal Cleaning Test Facility (IAG-D5-E685)	DOE(*)	Birtley Engineering Corp. Williams, Trebilcock and Whitehead	Design a DOE coal cleaning test facility Provide architectural and engineering plans.

continued

* – Department of Energy, Coal Preparation and Analysis Laboratory, Pittsburgh, Pennsylvania

† – Department of Energy, Office of Environment, Washington, D.C.

TABLE 1 (continued)

Project Title (Contract, Grant, or Interagency Agreement)	Organization Directing Work	Organization Performing Work	Objectives
Coal Preparation Plant Computer Model (IAG-D6-E685)	EPA/DOE(*)	DOE(*), U. of Pittsburgh, and Battelle	Develop computer model capable of predicting the performance of coal preparation plants.
Engineering/Economic Analysis of Coal Preparation Operation and Cost (IAG-D6-E685)	DOE(*)	Hoffman-Munter Corp.	Determine the costs of cleaning for eight representative coal preparation plants - from jig plants to complex heavy media plants.
Reactor Test Project for Chemical Removal of Pyritic Sulfur from Coal (68-02-1880)	EPA	TRW Defense and Space Systems Group	Evaluation of the Meyers chemical coal cleaning process in a 1/3 tph test reactor unit.
Microwave Desulfurization of Coal (68-02-2172)	EPA	General Electric	Evaluate the feasibility of coal desulfurization by microwave treatment.
Battelle Hydrothermal Process Improvement Studies (68-02-2187)	EPA	Battelle Columbus Laboratories	Evaluate methods for liquid/solid separation and leachant regeneration.
Evaluation of Chemical Coal Cleaning Processes (IAG-D5-E685)	DOE(‡)	Bechtel	Evaluate relative costs and performances of selected chemical coal cleaning processes.
Hydrodesulfurization of Coal (68-02-2126)	EPA	Institute of Gas Technology	Evaluate desulfurization of coal by mild oxidative treatment followed by devolatilization.
Environmental Studies on Coal Cleaning Processes (IAG-D5-E721)	EPA	Tennessee Valley Authority (TVA)	Evaluate technology for controlling pollution at TVA coal preparation plants.
Cost Evaluations of Coal Cleaning and Scrubbing (IAG-D5-E721)	EPA	TVA	Evaluate relative costs of coal cleaning and scrubbing in complying with various SO_2 emission standards.
ENVIRONMENTAL ASSESSMENT			
Environmental Assessment of Coal Cleaning Processes (68-02-2163)	EPA	Battelle Columbus Laboratories	Evaluate pollution resulting from coal cleaning, transportation and storage. Evaluate coal cleaning as an SO_2 emission control technique.
Trace Elements and Mineral Matter in U.S. Coals (R804403)	EPA	Illinois State Geological Survey	Characterize the elemental constituents and mineralogy of U.S. coals.
Geology of Contaminants in Coal (IAG-D6-E685)	EPA	U.S. Geological Survey	Characterize coal resources west of the Mississippi as to their elemental and mineralogic composition. Evaluate the geologic factors which affect or control coal cleanability.
Trace Element Characterization of Coal Preparation Wastes (IAG-D5-E681)	EPA/DOE(†)	Los Alamos Scientific Laboratory (LASL)	Characterize trace element and mineralogic associations in coal preparation wastes.
A Washability and Analytical Evaluation of Potential Pollution from Trace Elements (IAG-D6-E685)	DOE(*)	DOE(*)	Evaluate partitioning of trace elements in 10 U.S. coals during specific gravity separation.
Evaluation of the Effects of Coal Cleaning on Fugitive Elements (IAG-D6-E685)	DOE(*)	Bituminous Coal Research Inc.	Evaluate partitioning of trace elements during preparation and use.
DEVELOPMENT OF POLLUTION CONTROL TECHNOLOGY			
Control of Trace Element Leaching from Coal Preparation Wastes (IAG-D5-E681)	EPA/DOE(†)	LASL	Determine leachability of trace elements from coal preparation wastes and evaluate pollution control methods.
Control of Blackwater in Coal Preparation Plant Recycle and Discharge (IAG-D5-E685)	DOE(*)	Pennsylvania State University	Characterize black water generated by coal preparation plants and assess potential control methods.
Stabilization of Coal Preparation Waste Sludges (IAG-D5-E685)	DOE(*)	Dravo Lime	Collect coal preparation plant sludges and perform laboratory stabilization tests.

* – Department of Energy, Coal Preparation and Analysis Laboratory, Pittsburgh, Pennsylvania
† – Department of Energy, Office of Enviroment, Washington, D.C.
‡ – Department of Energy, Office of Energy Technology, Washington, D.C.

TABLE 2
SO_2 emission standards for coal fired steam generators

Application	Sulfur Reduction Percent	Emission Limits, lb $SO_2/10^6$ Btu
Existing Boilers (SIP's)	–	0.2-8.0
Current NSPS for Steam Generators	–	1.2
Revised NSPS for Utility Boilers(*)	85(†), (‡)	1.2 Max. 0.2 or 0.5 Floor
NSPS for Industrial Boilers	Unknown	Unknown

(*) Values under consideration

(†) 85 percent minimum for 24 hour average

(‡) A provision of the standard will permit a 75 percent minimum sulfur reduction and an exemption of the 1.2 lb $SO_2/10^6$ Btu level 3 days per month. This provision is to allow for variations in fuel sulfur levels and pollution control device performance.

TECHNOLOGY ASSESSMENT AND DEVELOPMENT

Improved techniques for the preparation of fine coal are needed to enhance sulfur removal and coal energy recovery. The primary objectives of the technology assessment and development activities are to evaluate the potential cleanability of U.S. coals and the performance and costs of commercial equipment which can be used for the beneficiation of fine coal. The development of chemical coal cleaning processes is supported, as is applied research necessary to characterize the basic mechanisms which govern beneficiation processes.

A CONTROL TECHNIQUE

Passage of the 1977 Clean Air Act Amendments provides new emphasis for the assessment of coal cleaning as an SO_2 emission control technique. New regulatory actions in response to this legislation will significantly change the conditions under which coal cleaning can be used as a method of complying with SO_2 emission standards. Studies are now in progress to assess the applicability of coal cleaning in meeting SO_2 emission standards for:

- Existing boilers regulated under state implementation plans.
- Current federal NSPS for coal-fired steam generators.
- Revised NSPS for coal-fired utility boilers.
- NSPS to be promulgated for industrial boilers.

While preliminary in nature, the results of portions of these studies warrant discussion.

Table 2 summarizes the SO_2 emission standards which are expected to be applicable to coal-fired boilers by 1980. Important new considerations mandated by the 1977 Clean Air Act Amendments are the requirements for use of best available control technology and a percentage reduction in the regulated pollutant. Thus, the revised utility boiler regulations and new federal standards for industrial boilers will require a percentage sulfur reduction in addition to an emission limit.

SPECIFIC GRAVITY SEPARATION

An evaluation of USBM data (5) suggests that specific gravity separation conditions now commonly used for coal de-ashing can remove 25 to 55 percent of the pyrite from U.S. coals, using the best available technology (table 3). Moderate reductions in the coal top size and specific gravity of separation to conditions corresponding to best current technology would provide pyritic sulfur reductions ranging from 40 to 80 percent. Assuming that all the coal sulfur were converted to SO_2 upon combustion, burning of these coals would result in SO_2 emission levels ranging from 0.9 to 4.4 lb $SO_2/10^6$ Btu. Although an increased reduction of pyritic sulfur can be achieved at these lower particle sizes and specific gravity of separation, coal carbon or Btu losses would increase to unacceptably high levels unless:

TABLE 3
Coal desulfurization potential by coal cleaning*

	Average Pyritic Sulfur Removed, percent	Average Organic Sulfur Removed, percent	Average Reduction in lb $SO_2/10^6$ Btu, percent	Average Emission Factor, lb $SO_2/10^6$ Btu
Uncleaned Coal	–	–	–	1.1 9.0
Physical Coal Cleaning (PCC)	43 80	–	16 55	0.9 4.4
Chemical Coal Cleaning (CCC)	95	25	48 73	0.6 2.5

* Based on Data from U.S. Bureau of Mines RI 8118 for Averages for Each of Six Coal Regions Assuming Application of Best Available Technology

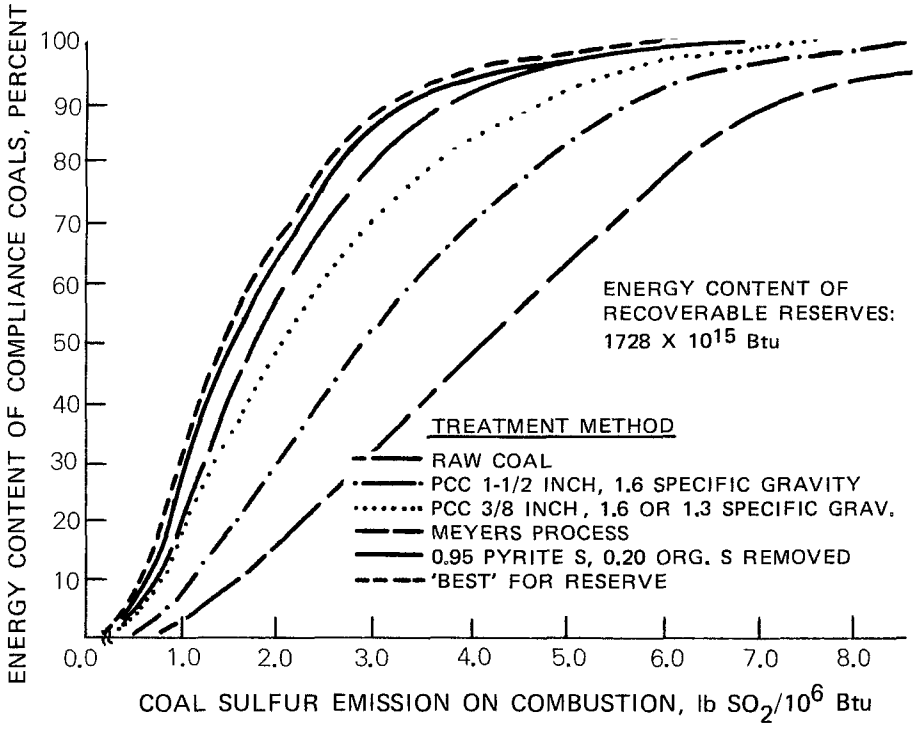


FIGURE 1—*Estimated cleaning potential of northern Appalachian coals*

- The sink or high specific gravity fractions were upgraded (desulfurized) by further processing. Probable operations would include pulverization, specific gravity separation, froth flotation, oil agglomeration, or chemical cleaning.
- The preparation plant was to produce multiple product streams to be used in different boilers.
- High sulfur coals could be used in boilers with FGD or in boilers subject to less stringent SO_2 emissions regulations.

If experiments by Min and Wheelock on Iowa coals are applicable to other U.S. coals, the best combination of physical cleaning techniques is potentially capable of removing up to 90 percent of the pyrite sulfur (5). Combustion of coals cleaned to these levels would produce emissions ranging from 0.8 to 3.5 lb $SO_2/10^6$ Btu.

Chemical coal cleaning processes can remove 95 to 99 percent of the pyritic sulfur and 25 to 40 percent of the organic sulfur. Removal of 95 percent of the pyritic sulfur and 25 percent of the organic sulfur from U.S. coals would result in total sulfur reductions in the range of 53 to 77 percent (4).

SULFUR CONTENT AND REMOVAL VARY

The sulfur content and sulfur removal potential of coal by physical and chemical techniques vary between coal regions and between coal beds in the same region (6). Figure 1 presents the estimated energy content of the recoverable Northern Appalachian coal reserves which can be cleaned to meet various SO_2 emission levels. Less than 5 percent of the raw coal is capable of meeting a standard of 1.0 lb $SO_2/10^6$ Btu. Crushing to 3/8 inch and physically cleaning at 1.6 or 1.3 specific gravity would increase the relative energy content of coals available for a 1.0 lb $SO_2/10^6$ Btu emission standard to more than 20 percent. Chemical cleaning of appropriate coals using processes capable of removing 95 percent of the pyritic sulfur and 20 percent of the organic sulfur would provide more than 620 x 10^{15} Btu (36 percent of total), capable of meeting a 1.0 lb $SO_2/10^6$ Btu standard.

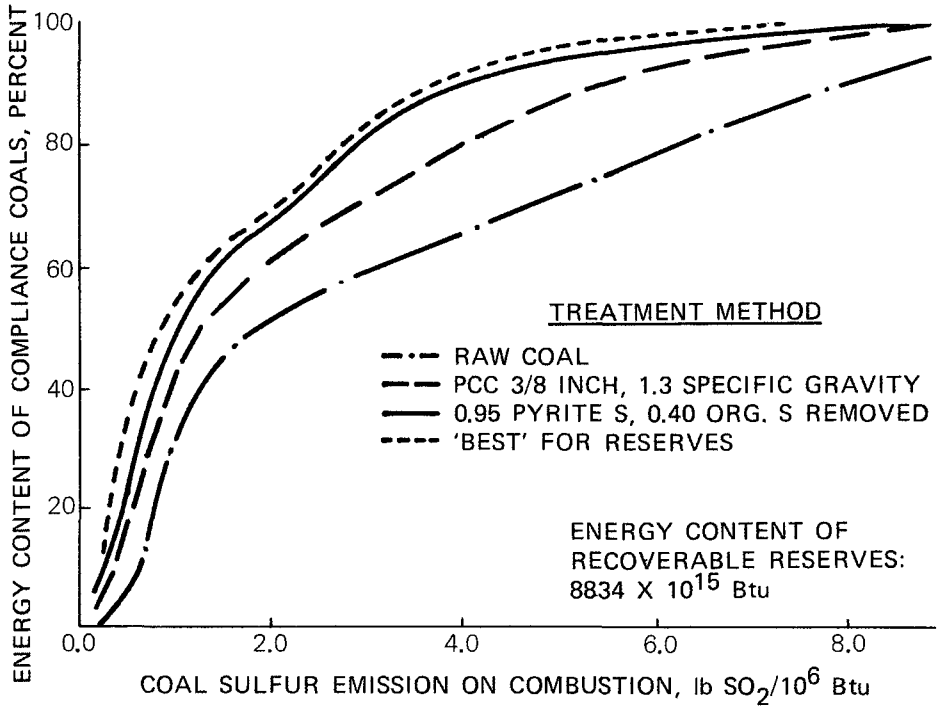


FIGURE 2—*Estimated cleaning potential of United States coals*

HIGHER FEDERAL STANDARDS

Figure 2 presents similar data on the cleaning potential of U.S. coals. While figures 1 and 2 indicate that physical and chemical coal cleaning can be used to provide coals capable of meeting a variety of emission limits, new federal standards requiring sulfur reductions above about 50 percent would preclude the use of physical cleaning as a sole method of complying with SO_2 emission standards in the boilers where applicable. Sulfur reduction requirements of 80 percent or greater would eliminate the use of chemical coal cleaning as an effective technology for compliance with these standards.

The demand for physical or chemical coal cleaning will depend upon the relative amounts of coals capable of meeting various sulfur emission standards and the relative costs of other SO_2 emission control techniques. In 1975, approximately 467 million tons of coal were consumed, primarily in utility, industrial, and commercial boilers (7). Under the National Energy Plan (NEP), coal consumption for these uses and non-boiler industrial applications is expected to exceed 1057 million tons in 1985.

1985 COAL CONSUMPTION

In 1975, virtually all coal firing was subject only to state emission regulations for existing boilers. Table 4 presents estimates of the 1985 coal consumption by boiler category and the emissions levels with which each boiler category must comply. Even considering that few coals could be desulfurized to levels below 1.2 lbs $SO_2/10^6$ Btu, physically cleaned coals (if a high sulfur removal is not required) could provide complying fuels to meet 79 percent of the projected steam-coal demand in 1985. These projections are, of course, highly dependent upon impending energy legislation and new emission standards to be promulgated by EPA.

Pollution control cost comparisons are complex. Factors unique to a given application and site often determine which pollution control option is the most cost effective. Simplified cost comparisons can be made by evaluating the ranges of annualized costs for coal cleaning and FGD.

TABLE 4
Estimated coal energy consumption by emission regulation (million tons)*

Boiler Category	1975	Projected 1985 Consumption by Emission Interval (lb $SO_2/10^6$BTU) <1.2	1.2 to <2.0	2.0 to <4.0	≤4.0	Total
Utility(†) (§)	404	204(‡)	403	113	59	779
Industrial and Commercial(‡) (§)	63	14	203	52	9	278
Total	467	218	606	165	68	1057

(*) Total 1985 consumption corresponding to NEP.
(†) One-third of all new utility boilers constructed after 1975 are assumed to comply with revised NSPS of 0.5 to 0.8 lb $SO_2/10^6$Btu. Two-thirds of all new utility boilers constructed after 1975 are assumed to comply with current NSPS of 1.2 lb $SO_2/10^6$Btu.
(‡) All new industrial and commercial boilers are assumed to comply with emission standards of 1.5 to 2.0 lb $SO_2/10^6$Btu.
(§) The distribution of use for all categories of existing boilers is assumed to comply as follows: <1.2 lb $SO_2/10^6$Btu, 20 percent; 1.2 to <2.0 lb $SO_2/10^6$Btu, 35 percent; 2.0 to <4.0 lb $SO_2/10^6$Btu, 30 percent; ≤4.0 lb $SO_2/10^6$Btu, 15 percent.

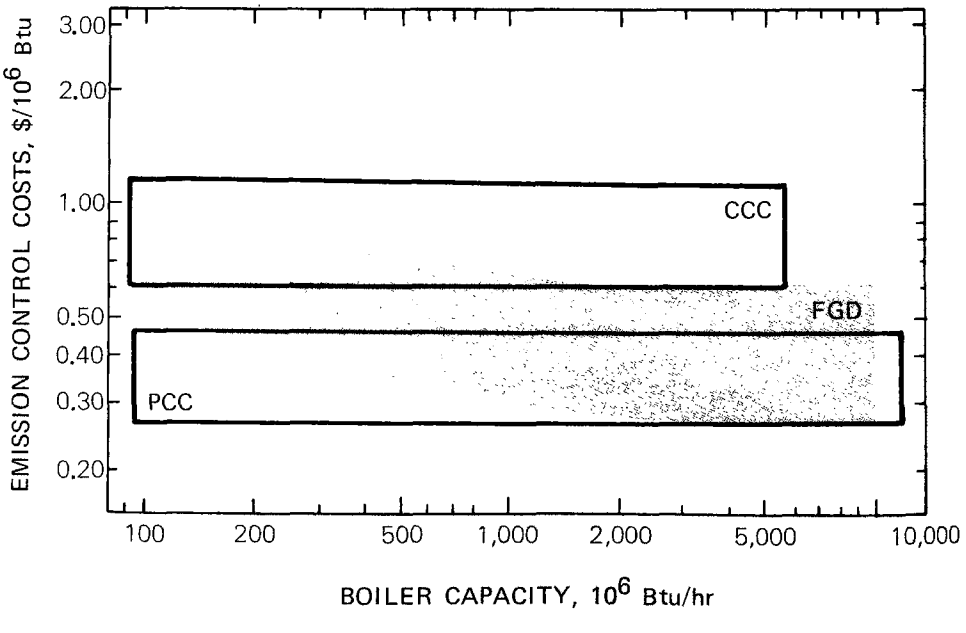


FIGURE 3–*Annualized SO_2 and particulate control costs*

SULFUR REMOVAL ABOVE 90 PERCENT

Utility and industrial FGD systems now in use have demonstrated sulfur removal efficiencies in excess of 90 percent (8, 9, 10). FGD costs are sensitive to the type of FGD system, boiler capacity, boiler capacity factor, and level of desulfurization required. Annualized FGD costs increase with decreasing boiler capacity, decreasing boiler capacity factor, and increasing sulfur removal.

Annualized coal-cleaning costs are sensitive to plant capacity, plant complexity, and coal-replacement costs. Coal-replacement costs are defined as the cost of coal energy which must be discarded with the plant residue (carbon and mineral matter). Plant complexity increases with the number of different process operations involved.

CONTROL COSTS

Figure 3 presents estimates of annualized SO_2 and particulate control costs for PCC, CCC, and FGD. (Particulate control costs of $\$0.10/10^6$ Btu are included so that the costs of coal cleaning can be compared with the costs of FGD which contain costs for particulate control.) An analysis of the cost ranges in figure 3 and the desulfurization potential of physical and chemical cleaning indicates that:

- Where technically feasible, cost savings from the use of PCC can be realized for utility and industrial boilers, especially small boilers with low capacity factors.
- PCC probably cannot be used to meet revised NSPS standards for utility boilers, unless it is used in combination with FGD.
- Chemical coal cleaning does not appear to be cost competitive with FGD in large base-loaded utility boilers. Chemical coal cleaning can possibly be used in a cost effective manner in small industrial boilers with low capacity factors.
- The most probable use of chemical coal cleaning is in combination with PCC to provide lower sulfur levels than available from PCC.

In some cases, under current state and federal standards, the SO_2 control costs from using FGD in combination with PCC may be less than those for using FGD alone (11). Studies comparing the costs of a combination of PCC and FGD with those of FGD in meeting an 80 to 90 percent sulfur removal standard have not been completed,

CRUSHING AND GRAVIMETRIC SEPARATION

The DOE Coal Preparation and Analysis Group at Bruceton, Pennsylvania, is continuing laboratory experiments to determine the effect of crushing and gravimetric separation on the liberation and removal of pyritic sulfur from U.S. coals. These coals are collected from the principal coal beds of the United States. Information generated from this study is necessary to assess the impact that physical coal cleaning might have on the level of SO_2 emissions from stationary combustion sources.

SULFUR REDUCTION POTENTIAL

In 1976, a report of investigations was published on the sulfur reduction potential of 455 coal samples from 6 major U.S. coal regions (6). Since then, an additional 220 samples have been collected from the Western and Appalachian Region States. During the past year washability analyses were completed on 31 raw coal channel samples collected from Maryland, Ohio, and Pennsylvania. In addition, four Arkansas and seven Texas lignite samples were collected and tested.

The data show that, on the average, the lignite samples contained 15.9 percent ash, 0.23 percent pyritic sulfur, and 1.09 percent total sulfur on a moisture-free basis. The average moisture content was 30.9 percent and the average heating value was 10,377 Btu/lb. Only the two Arkansas samples, which contained less than 0.7 percent organic sulfur, could be upgraded to meet the current new source performance standard of 1.2 lb $SO_2/10^6$ Btu. All but one of the Texas lignite samples contained more than 1 percent total sulfur; however, since most of this was organic sulfur, none of the Texas samples could be upgraded to meet current NSPS.

TECHNOLOGY ASSESSMENT

A major 3-year project to assess technology for the physical and chemical desulfurization of coal was begun in January 1977. This project is being conducted by Versar, Inc, with the assistance of the Denver Equipment Division of the Joy Manufacturing Company. The principal activity on the project is the development of data on the performance of commercial coal cleaning equipment in separating fine coal and pyrite. Other project activities will include an evaluation of fine coal dewatering and drying, chemical coal cleaning processes, coal preparation requirements for synthetic fuel conversion processes, and pollution control technology used for coal cleaning.

FINE COAL

Performance and cost data relating to the beneficiation of fine coal in commercial equipment has been assembled. Insufficient fine coal performance data were found to exist for dense media cyclones, hydrocyclones, and flotation cells. A mobile laboratory has been constructed and is undergoing shakedown tests at a coal preparation plant. Tests are planned at a number of commercial plants to obtain additional performance data on fine coal cleaning.

An evaluation study of current chemical coal cleaning processes has been completed (2). Reviews were conducted of 31 different processes; of these, 11 of the most promising were selected for comparative evaluations. Estimated annual operating costs for the 11 processes, including the cost of coal ($25/ton), ranged from $38.50 to $65.72/ton. A process information summary of the 11 chemical coal cleaning processes evaluated is presented in table 5.

Literature studies on coal drying, fine coal dewatering, and coal pre-preparation requirements for synthetic fuel conversion processes are nearing completion.

HOMER CITY COAL CLEANING

An advanced coal cleaning pilot plant is currently under construction near the Homer City Generating Station Power Complex, Homer City, Pennsylvania (figure 4).

TABLE 5
Process information summary of major chemical coal cleaning processes

Process & Sponsor	Method	Type Sulfur Removed	Stage of Development	Problems	Annual Operating Cost $/Mg Clean Coal ($/ton) including Cost of Coal (*)
"Magnex," Hazen Research Inc., Golden Colorado	Dry pulverized coal treated with Fe $(CO)_5$ causes pyrite to become magnetic. Magnetic materials removed magnetically	Up to 90% Pyritic	Bench & 91 kg/day (200 lb/day) pilot plant operated	Disposal of S-containing solid residues, continuous recycle of CO to produce Fe (CO_5) requires demonstration	44.8 (40.7)
"Syracuse" Syracuse Research Corp., Syracuse, N.Y.	Coal is comminuted by exposure to NH_3 vapor; conventional physical cleaning separates coal/ash	50-70% Pyritic	Bench scale	Disposal of sulfur containing residues	43.4 (39.5)
"Meyers," TRW, Inc., Redondo Beach, Ca.	Oxidative leaching using $Fe_2 (SO_4)_3$ + oxygen in water	90-95% Pyritic	8 metric ton/day for reaction system. Lab or bench scale for other process steps.	Disposal of acidic $FeSO_4$ & CaSO; sulfur extraction step 4 requires demonstration	47.9 (43.4)
"LOL" Kennecott Copper Co. Ledgemont, Ma.	Oxidative leaching using O_2 and water & moderate temp. and pressure	90-95% Pyritic	Bench scale	Disposal of gypsum sludge, acid corrosion of reactors	50.6 (45.3)
"ERDA" (PERC) Bruceton, Pa.	Air oxidation & water leaching @ high temperature and pressure	95% Pyritic; up to 40% Organic	Bench scale 11 kg/day (25 lb/day) continuous unit under construction	Gypsum sludge disposal; acid corrosion at high temperatures	56.9 (51.6)

(*) Raw coal cost is included at $27.6/metric ton ($25/ton)

continued on page 236

FIGURE 4—*Back view of coal-cleaning pilot plant (Homer City), showing both slurry tanks*

TABLE 5 (continued)

Process and Sponsor	Method	Type Sulfur Removed	Stage of Development	Problems	Annual Operating Cost $/Mg Clean Coal ($/ton) including Cost of Coal (*)
"GE" General Electric Co., Valley Forge, Pa.	Microwave treatment of coal permeated with NaOH solution converts sulfur forms to soluble sulfides	75% Total S	Bench scale	Process conditions not established. Caustic regeneration process not established	44.3 (40.2)
"Battelle" Battelle Memorial Institute Columbus, Oh.	Mixed alkali leaching	95% Pyritic; 25-50% Organic	9 kg/hr (20 lb/hr) mini pilot plant and bench scale	Closed loop regeneration process unproven. Residual sodium in coal	62.0 (56.1)
"JPL" Jet Propulsion Laboratory Pasadena, Ca.	Chlorinolysis in organic solvent	90% Pyritic; up to 70% Organic	Lab scale but proceeding to bench and mini pilot plant	Enviromental problems; conversion of HCl to Cl_2 not established	50.3 (45.9)
"IGT" Institute of Gas Technology hy Chicago, Il.	Oxidative pretreatment followed by hydrodesulfurization at 800°C	95% Pyritic; up tp 85% Organic	Lab and bench	Low Btu yield (55%). Change of coal matrix	72.4 (65.7)
"KVB" KVB, Inc. Tustin, Cal.	Sulfur is oxidized in NO_2-containing atmosphere, sulfates are washed out	95% Pyritic; to 40% Organic	Laboratory	Waste & possibly heavy metals disposal. Possible explosion hazard via dry oxidation	53.8 (48.8)
"ARCO" Atlantic Richfield Company Harvey, Il.	Not given	95% Pyritic; some Organic	Continuous 0.45 kg/hr (1 lb/hr) bench scale unit	Unknown	51-64 (46-58) Estimated

(*) Raw coal cost is included at $27.6/metric ton ($25/ton).

TABLE 6
Homer City plant product specifications

	Medium-sulfur Coal	Low-sulfur Coal	Refuse
Weight distribution, percent	56.2	24.7	19.1
Energy distribution, percent*	61.6	32.9	5.5
Energy content, Btu/lb (dry basis)	12,549	15,200	3,367
Ash content, percent	17.75	2.84	69.69
Sulfur content, percent	2.24	0.88	6.15
Emission factor, lb $SO_2/10^6$ Btu	3.57	1.16	36.54

* Overall plant Btu recovery is 94.5 percent which includes 1 percent credit for thermal drying loss.

TABLE 7
Phase 1 plant acceptance test results (moisture-free basis)

	Ash %	Total Sulfur, %	Btu %	lb $SO_2/10^6$ Btu
Feed coal	20.05	2.33	12,239	3.82
Clean coal	13.05	1.51	13,527	2.24
Refuse	76.85	5.37	2,646	40.81
Average Btu recovery, percent – 97.80				
Average yield, percent – 85.50				
Average sulfur removal, percent – 41.36 (lb $SO_2/10^6$ Btu Basis)				

The coal preparation facility is jointly owned by Pennsylvania Electric Company (a subsidiary of General Public Utilities Corporation) and New York State Electric and Gas Corporation. The facility will process 5.2 million tons of ROM coal per year, with a design capability of 1,200 tons per hour. The plant has four distinct process circuits: 1) coarse coal, 2) medium coal, 3) fine coal, and 4) fine coal scavaging. Unique design features of the Homer City plant include:

UNIQUE DESIGN FEATURES

- Selective crushing to maximize the amount of 1/4 inch by 100 mesh coal.
- Use of small diameter (14 inches) heavy media cyclones to process the 9 x 100 mesh size fractions.
- Computerized control of the dense media at a low specific gravity (1.3).

The major purpose of the plant is to clean coals for compliance with SO_2 sulfur emission standards. As shown in table 6, the plant is expected to produce medium and low sulfur coals. The medium sulfur coal will be used in the two existing 600 MW generating units to meet a Pennsylvania emission standard of 4.0 lb $SO_2/10^6$ Btu. The low sulfur coal will be used in a new 650 MW unit to meet Federal NSPS of 1.2 lb $SO_2/10^6$ Btu.

3-YEAR PROJECT AT HOMER CITY

EPA, PENELEC, EPRI, and DOE are cooperatively supporting a 3-year test project at the Homer City complex. Objectives of the project are to:

- Determine the variability of sulfur and other pollutants in coal fed to the cleaning plant.
- Determine the performance of equipment used for the separation of coal and pyrite.
- Determine the capability of plant process controls to maintain the coal product streams within sulfur, ash, and Btu specifications.
- Characterize pollutant streams emitted from the preparation and power plants.
- Determine if a need exists for the development of improved pollution control technology.
- Evaluate the effects of using clean coal on the performance of the boilers and electrostatic precipitators at the power plant.
- Evaluate the effectiveness of planned residue disposal techniques.
- Determine the fate of potentially hazardous minor and trace pollutants contained within the coal used at the preparation and power plants.
- Determine capital and operating costs of the preparation and power plants; i.e., the costs of using, physical coal cleaning to meet SO_2 emission standards.

The preparation plant is scheduled for construction in two phases. The phase 1 plant, completed in October 1977 was capable of cleaning coal to 4.0 lb $SO_2/10^6$ Btu. The phase 1 plant, shut down during the United Mine Workers strike, was not scheduled to begin operation until this spring in order to expedite construction of the phase 2 plant-cleaning circuits. The complete plant is scheduled to begin operations in the fall of 1978.

ACCEPTANCE TESTS

Acceptance tests on the phase 1 plant were completed last fall. Operation of the equipment and plant was near design conditions. The average sulfur content of the clean coal over the 3-day acceptance test period was 2.24 lb $SO_2/10^6$ Btu. Table 7 summarizes acceptance test results.

A number of tests are now being conducted to establish electrostatic precipitator and boiler performance characteristics while the power plant boilers are burning uncleaned coal. Preparation plant performance tests and power plant operating evaluations are scheduled to begin late this year.

DENSE MEDIA PILOT PLANT

A dense-media cyclone pilot plant test program is being conducted by DOE at Bruceton, Pennsylvania. This project is being conducted with the support and cooperation of the owners of the Homer City power complex, EPA, and the Electric Power Research Institute. The objective of the test program is to detail and optimize the performance of dense-media cyclones for fine coal cleaning at lower than normal specific gravities of separation. This program was initiated during the past year. The cyclone pilot plant has been designed and constructed, and all necessary equipment has been installed. Several shakedown tests were recently run to check plant operation and to establish procedures for sample collection, processing, and analysis. A 12-month test program is planned to evaluate the effects of several variables on the performance of the dense media cyclone: media to coal ratio, inlet pressure, orifice size, magnetite grade, media viscosity, media additives, and magnetite size distribution. The results of these pilot plant tests are to be used to evaluate the performance of the dense media circuits in the Homer City coal cleaning plant.

FROTH FLOTATION

Froth flotation is commercially used to separate coal and mineral matter. Froth flotation is a physical/chemical process for the separation of solids, based upon the selective adhesion of water to some particles and the selective adhesion of air to other particles. Separation of coal from mineral matter occurs as finely disseminated bubbles are dispersed throughout a coal-water slurry. The coal particles in the slurry adhere to the air bubbles and are transported to the surface of the pulp; i.e., the coal/air/water mixture. These bubbles and their attached coal particles, commonly referred to as froth, are then removed as a froth overflow; the mineral matter remains in suspension and is removed with the water underflow.

COAL/PYRITE FLOTATION

The process of bubble adhesion can be modified by the use of certain chemical reagents. These reagents enhance the selective adhesion of air or water to certain particles. Reagents are also used to stabilize the froth, thus allowing time for removal of the floated particles. Unfortunately, the surface properties of some coal and pyrite particles are not sufficiently dissimilar to permit efficient separation. In some cases, multiple stages of flotation and the proper combinations of reagents result in a separation (12, 13). In other cases, the coal does not appear to be amenable to coal/pyrite separation by flotation. The DOE coal/pyrite flotation process, developed specifically for coal/pyrite separation, consists of a first stage coal flotation step to remove coarse, free pyrite and other refuse. The clean coal froth concentrate is then repulped and treated with a coal depressant, a pyrite collector, and a frother to selectively float the remaining pyrite in the second state.

The installation of a two-stage coal/pyrite flotation circuit in the Lancashire No. 25 preparation plant under a cooperative agreement between Barnes and Tucker Company and the DOE was completed in late September 1977. A 1-year test program was started after termination of the UMW strike.

ADSORPTION/DESORPTION REACTIONS

A study of adsorption/desorption reactions in the desulfurization of coal by the DOE two-stage flotation process (12) has been completed by the University of Utah (14). This research has provided information concerning the method of adsorption of various organic depressants on coal. It has shown that this adsorption is physical rather than chemical, and the depressant cannot be removed by repeated washing.

Laboratory flotation tests demonstrated that the first stage coal flotation response is sensitive to the residual concentration of the second stage coal depressant (Aero Depressant 633) in the recycled water. However, it was shown that repeated contact with fresh coal removes much of the residual depressant from the water, suggesting that the contact of recirculated water with fresh coal and refuse in a preparation plant might remove most of the residual depressant.

The other portion of this research concerning the second stage pyrite collector (potassium amyl xanthate) indicated that the adsorption of xanthate by pyrite involves a chemisorption reaction which, in essence, goes to completion. Also, it was found that coal/pyrite flotation response with amyl xanthate differs significantly from that of ore/pyrite. The pyrite collector consumption is about an order of magnitude greater for coal/pyrite than for ore/pyrite. The reason for the high amyl xanthate requirement for coal/pyrite flotation appears to be related to surface heterogeneities in the marcasite component of the coal/pyrite, particularly clay inclusions, which contribute significantly to its hydrophilic character.

HIGH-GRADIENT MAGNETIC SEPARATION

High-gradient magnetic separation (HGMS) is a new technique which provides a practical means for separating small, weakly magnetic particles on a large scale. This technology, utilized commercially in the purification of kaolin clay, was investigated by General Electric Company with the objective of establishing the technical feasibility for removing a substantial fraction of the inorganic sulfur from dry coal powders.

As a result of tests to evaluate the feasibility of HGMS, it was concluded that (15):

- Dry magnetic separation by HGMS is feasible if the coal fines are first removed. Gravity feed techniques must be employed since the mixing effects of pneumatic transported mixtures counteract the magnetic separation effects.
- Multiple passes may be desirable to increase coal recovery (only single passes were made in this work).
- Pyrite removal by HGMS from oxidized and freshly mined coals is substantially the same.

DEWATERING OF COAL

Fine coal handled or cleaned in slurry form is dewatered to render it suitable for conveying and blending, to decrease its transportation cost, and to increase its effective calorific value. The removal of water from coal finer than 28 mesh is difficult and expensive. Vacuum filters are relatively economical for dewatering coal in the minus 28 mesh size range, but the product usually contains over 20 percent moisture. As a result, thermal drying is often required to reduce the moisture content of the filter cake to acceptable levels. However, thermal driers are costly and a source of air pollution.

USE OF SURFACTANTS

Under a Department of Energy (DOE) contract, Syracuse University is studying the use of surfactants to enhance the dewatering of fine coal (16). (Surfactants are chemicals used to reduce the surface tension of water.) Previous research by DOE has shown that the addition of surfactants to coal slurries prior to vacuum filtration can reduce the final moisture content of the dried coal filter cake. Results of the Syracuse investigation indicate that surface tension is not a unique criterion for predicting the dewatering behavior of surfactant solutions in the reduction in filter cake moisture content. Changes in surface energies at the solid/liquid and solid/air interfaces may also be important. Test data show, for example, that it takes the adsorption of six layers of a non-ionic surfactant at a surface tension of 30.92 dynes per cm to slightly surpass the final water content of coal achieved with the adsorption of a monolayer of an anionic surfactant at a surface tension of 40.66 dynes per cm. Test data also seem to indicate that excessive quantities of surfactants may result in the formation of micelles (organic molecular aggregates) which entrap water and adhere to the surface of coal particles. This would result in increased water retention in the filter cake.

The successful use of surfactants as dewatering promoters in coal preparation plants will therefore depend on the careful control of surfactant concentration in the vacuum filter feed.

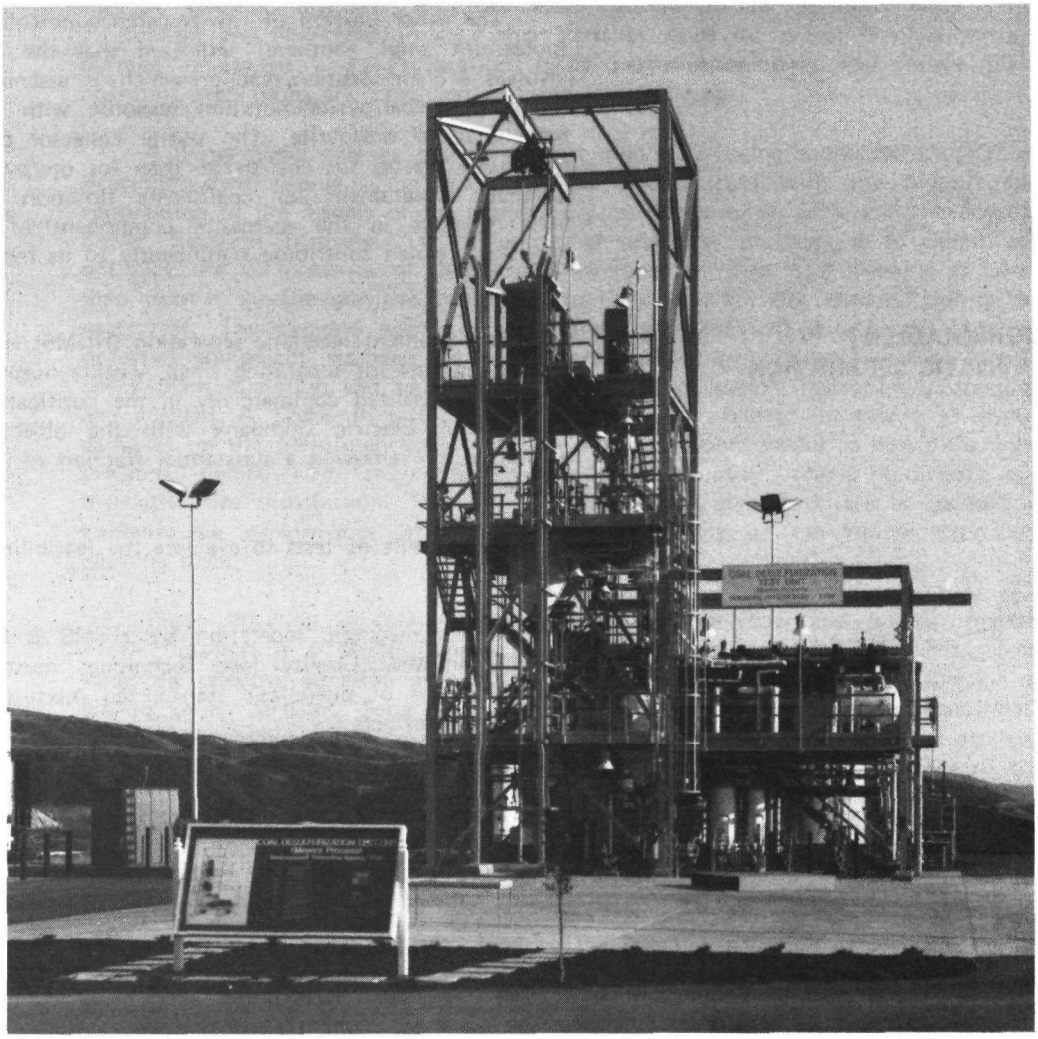


FIGURE 5—*Reactor test unit at Capistrano, California*

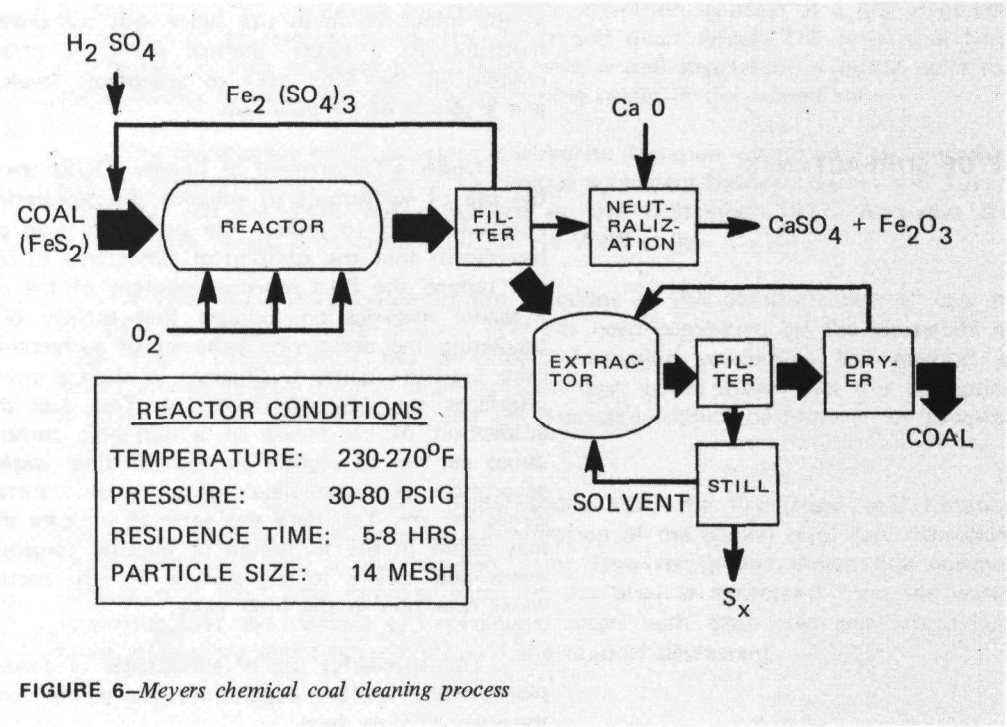


FIGURE 6—*Meyers chemical coal cleaning process*

AQUEOUS FERRIC SALT LEACHING

In previous years EPA supported bench and laboratory scale development work on coal desulfurization by aqueous ferric salt leaching (17, 18). This process developed by TRW is capable of removing 90 to 95 percent of the pyritic sulfur from U.S. coals. Construction of a 1/3-ton per hour reactor test unit (RTU) capable of pilot scale testing has been completed at Capistrano, California. More than 254 hours of RTU test operations have been completed and 49,700 lbs of coal have been processed. Figure 5 is a picture of the Reactor Test Unit (RTU).

The test reactor was shut down in February 1978 because of metal corrosion in the primary reactor. Replacement of the reactor vessel and resumption of testing depend on a possible transfer of the project to DOE. Meanwhile, bench scale tests are continuing to evaluate a process modification called Gravichem.

MEYERS CHEMICAL COAL CLEANING

Figure 6 is a schematic of the Meyers chemical coal cleaning process. Coal is mixed with an aqueous solution of ferric sulfate, previously derived from the coal, to form a slurry. The slurry temperature is raised to 100°-130°C where the ferric sulfate oxidizes the pyritic sulfur content of the coal to form elemental sulfur and iron sulfate. At the same time, oxygen or air is introduced to regenerate the reacted ferric sulfate. Iron sulfate dissolves into the leach solution while the elemental sulfur is removed in a second extraction. The coal is dried and solvent recovered. The products of the process are iron sulfate, which may be limed to give a dry gypsum and iron oxide material, and elemental sulfur. Trace elements from the coal are rejected from the leach solution with the stabilized gypsum/iron oxide solid. Elemental sulfur is the most desirable product which can be obtained in the process of controlling SO_2 pollution since it may be easily stored without additional pollution or may be marketed. The gypsum/iron oxide product is a storable solid product.

The RTU incorporates equipment to evaluate the key process steps of coal/leach solution slurry formation, coal leaching, leachant regeneration, and coal/leachant filtration (separation). Checkout and shakedown of the RTU was completed at the end of September 1977. Initial performance tests were made on Appalachian coal donated by the American Electric Power Service Corporation (AEP) from its Martinka mine. Operation of the plant through January of 1978 demonstrated that the RTU could be run continuously in three-shift operations. The input coal, containing 1 percent inorganic sulfur, was continuously and reliably reduced to a pyritic sulfur level of 0.16 percent (19). Although there was no measurable coal loss, calculations indicate an overall process energy efficiency of 93 to 96 percent, including process heat and electrical energy requirements. The average heating value of the processed coal was increased by 350 Btu/lb. RTU coal product, after bench-scale extraction of residual sulfate and elemental sulfur, was reduced to a total sulfur content of 0.68-0.75 percent (1.0-1.2 lb $SO_2/10^6$ Btu).

Leach rates in the RTU were improved over bench-scale values by an average factor of 5 due mainly to favorable coal segregation in the primary reactor (19).

LEACH SOLUTION

The leach solution/coal/oxygen environment caused corrosion in the primary reactor/regenerator system indicating that upgrading of the 316L material of construction is needed to support further testing. Extensive evaluations using erosion/corrosion coupons indicated that fiber reinforced plastics, elastomers, and 316L stainless steel are suitable for leach solution/coal service at temperatures up to 90°C. Titanium, Hastelloy, or rubber-lined brick over mild steel are needed for reactor/regenerator service conditions at temperatures up to 130°C (19).

GRAVITY SEPARATION

Supporting bench-scale experimentation showed that the iron sulfate/sulfuric acid leach solution can be used as a homogeneous dense media to efficiently gravity-separate fine coal at specific gravities of 1.2 to 1.35. Beneficial process cost improvements are obtained, based on using this gravity-separation effect. A significant portion of the input coal which floats in the leach solution is almost pyrite free and may bypass the reactor, elemental sulfur extraction, and dryer portions of the Meyers Process. This revised technology is termed the Gravichem Process (figure 7). When applied, at bench-scale, to a Tennessee Valley Authority (Interior Basin) coal containing 12 percent ash and 7 lb of $SO_2/10^6$ Btu, two products are obtained: a 4-percent ash float coal containing 3 lb $SO_2/10^6$ Btu and

an 11 to 12 percent ash sink coal containing 4 lb $SO_2/10^6$ Btu after treatment by the Meyers Process (19). Both of these products meet state SO_2 emission standards for this coal.

MICROWAVE DESULFURIZATION

Laboratory experiments by the General Electric Company have demonstrated the technical feasibility of coal desulfurization by microwave energy (20). Pyrite is preferentially excited by the microwave energy producing volatile or water soluble sulfur compounds which may be easily removed from the coal. Also, microwave irradiation of mixtures of coal, water, and NaOH appears to convert both pyritic and organic sulfur to water soluble sulfides.

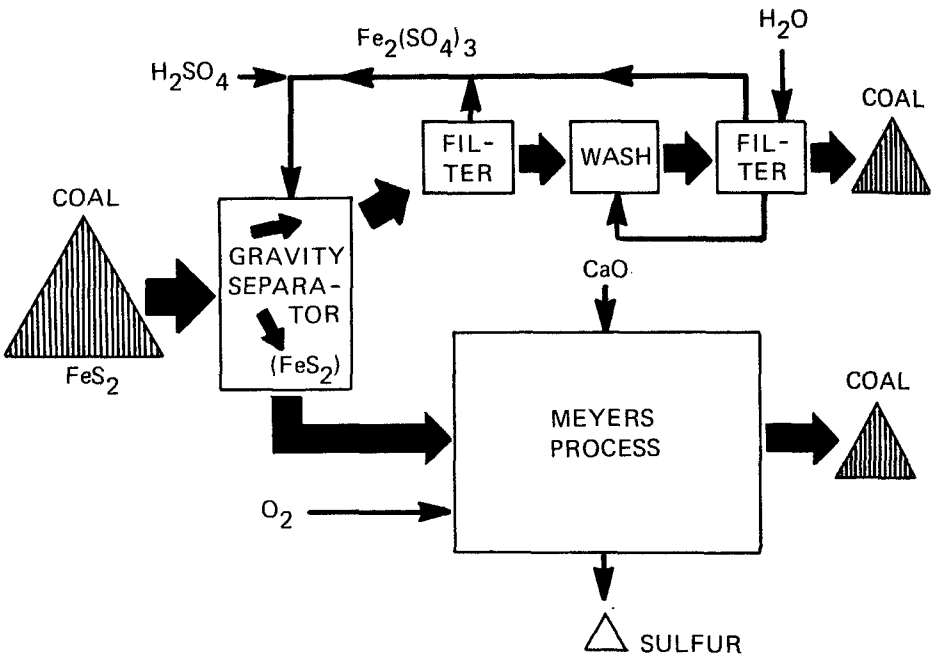


FIGURE 7—*Gravichem process*

TREATMENT CONDITIONS NOT SEVERE

Treatment conditions are not severe. Exposure times of less than 1 minute at atmospheric pressure are adequate. Pyrites and sodium hydroxide (with small amounts of water) absorb microwave energy much more efficiently than coal itself. It is postulated that sulfur reactions occur due to selective activation of FeS_2, NaOH, and H_2O. The action of these compounds produces localized high temperature and high pressure conditions which accelerate sulfur reactions before the coal reaches decomposition (volatilization) temperatures. Present cost estimates suggest that microwave desulfurization may be economically competitive with other chemical desulfurization processes. Laboratory experiments are continuing under sponsorship of EPA and DOE.

BATTELLE HYDROTHERMAL

Battelle's Hydrothermal process is capable of removing 95 percent of the pyritic sulfur and up to 40 percent of the organic sulfur from a variety of U.S. coals. A large fraction of the process costs result from unit operations which occur after the reaction step converts the pyritic and organic sulfur to water soluble sulfides. These unit operations include the separation of liquids and solids, the regeneration of spent leachant, and the dewatering/drying of the product coal.

EPA-supported laboratory experiments to evaluate methods for reducing the costs of these unit operations indicate that (21):

- Spent leachant and reacted coal should be separated under oxygen free conditions to prevent oxidation of sodium sulfide to sodium sulfate. The latter is water soluble and cannot be precipitated from the spent leachant in subsequent steps.

- Iron carbonate is probably the most cost effective reactant for regeneration of the spent leachant.

- Serial washing and vacuum filtration to wash residual leachant from the coal, followed by use of screen bowl centrifuges, appear to be the most effective coal washing and dewatering procedure.

Battelle anticipates that incorporation of these process changes will reduce costs to the range estimated for competitive chemical coal cleaning processes.

ENVIRONMENTAL ASSESSMENT

Overall objectives of the environmental assessment activities have been to characterize coal contaminants and to identify the fate of these contaminants during coal processing and coal use. Initial studies have focused on sulfur and potentially hazardous accessory elements (minor and trace elements) contained in coal. Recent studies have been concerned with a wider range of pollutants—those which may be considered hazardous or toxic under the provisions of the Water Pollution Control Act (priority pollutants), the Resource Conservation and Recovery Act (hazardous wastes), the 1977 Clean Air Act Amendments (hazardous air pollutants), or the Toxic Substance Control Act. The basic intent of the environmental assessment activities is to identify pollutants which pose health or ecological threats and devise cost effective strategies for dealing with the pollutants.

A 3-year project to assess the environmental impacts of coal preparation, coal transportation, and coal storage is being conducted for IERL-RTP by Battelle's Columbus Laboratories. Major project activities are to include:

- The development of a technology overview containing a description of all current coal cleaning processes and their associated pollution control problems.

- The development and performance of an environmental test program to obtain improved data on pollutants from commercial coal cleaning plants.

- The development of criteria to be used in assessing the potential health and ecological impacts of pollutants from coal cleaning processes.

- The performance of studies to determine the relative environmental impacts of coal cleaning, FGD, and other SO_2 emission control methods.

PHYSICAL AND CHEMICAL TOXICITY CHARACTERIZED

Studies to develop criteria for assessing the relative environmental hazards associated with pollutants resulting from coal preparation, coal transportation, and coal storage are nearing completion. The approach has been to characterize the physical and chemical toxicity of pollutant or effluent streams sampled at their respective sources. This differs from the approach taken in environmental impact assessments—the characterization of air, water, and biological quality in the facility under study. The source assessment criteria incorporates methodologies being developed by IERL-RTP and adapts them to coal cleaning processes (22).

The fundamental criterion for evaluating the importance of any pollutant is the relationship between its concentration and the maximum concentration which presents no hazard to man or environmental biota. In evaluating the relative hazard of various pollutant concentrations, it is convenient to define three important concentration levels: Minimum Acute Toxicity Effluents (MATEs), Estimated Permissible Concentrations (EPCs), and Elimination of Discharge (EOD).

MATE, EPC, AND EOD DEFINED

MATE is defined as that pollutant concentration in undiluted emission streams that would not adversely affect those persons or ecological systems that are exposed to the streams for short periods of time. EPCs are concentration levels of dispersed emission streams which will not cause the receiving medium (air or water) to exceed safe continuous exposure concentrations. EOD is defined as that concentration of pollutants in emission streams which will not cause a pollutant concentration to exceed natural background levels.

Using these concepts and existing health and ecological effects data, Multimedia Environmental Goals (MEG's) have been developed to aid in assessing the degree of hazard associated with pollutants in energy process emission streams.

COAL PREPARATION POLLUTANT LIST

Existing health and effects data have been used to generate MEG's for approximately 650 known pollutants associated with energy processes (23). Using this information and existing data on coal contaminants, pollutants from coal preparation, and pollution from coal waste disposal, a list of about 75 priority coal preparation pollutants has been selected (24). This list includes 49 elements and 23 chemical substances or aggregated pollutant parameters. A shorter abbreviated list of pollutants, being used to evaluate chemical and physical transport models as well as estimated emissions and permissible concentrations, includes arsenic, beryllium, cadmium, iron, mercury, lead, manganese, selenium, sulfate sulfur, sulfur dioxide, nitrate nitrogen, and nitrogen oxides.

COAL CLEANING TEST SITES

Concurrent with the development of source assessment criteria, studies are in progress to select coal cleaning plant sites for environmental testing. The classification of coal cleaning facilities into various site categories has been based on four criteria: the acid neutralization potential of the soil surrounding the facility, the pyritic sulfur content of the run-of-mine coal, the average annual precipitation, and the coal cleaning process technology. By taking combinations of the extremes (high and low) for each variable and eliminating combinations which do not occur, 10 possible site categories were obtained.

An initial sorting of the more than 400 known coal cleaning plants, using information available in the literature, produced lists of facilities which correspond to each of the 10 site categories. For categories which included a large number of cleaning plants, three secondary constraints were imposed that eliminated plants considered undesirable because of field sampling problems. This shortened list includes 46 facilities. Site visits are planned to those listed facilities to obtain information which, although not available in the literature, will be required before final selection of sampling sites.

MASTER TEST PLAN

The master test plan is being developed to ensure a comprehensive test program and to facilitate the planning and preparation of the site-specific field test plans at the coal cleaning facilities designated as test sites. The master test plan will identify the potential pollution sources associated with a generalized coal cleaning plant and will suggest the media likely to be impacted by the effluents from these sources. Test objectives related to each pollution source will be defined to simplify the process of selecting sampling locations and measurements that are critical to those objectives. The phased approach to environmental testing under development by IERL-RTP is also presented.

The common elements relating to water and air quality parameters to be measured at each test site are:

- Process wastewater sampling—upstream and downstream from pollution control devices.
- Surface runoff and leachate sampling.
- Ground water sampling.
- ROM and final product coal sampling.
- Refuse disposal sampling.
- Air pollution emissions from thermal dryers, coal piles, and the refuse disposal area.

HUMAN HEALTH EFFECTS ASSAYS

Included in the common element portion of the master test plan is a general discussion of the importance of performing ecological and human health effects assays and a short description of tests that should be performed on each type of sample. This test plan is now undergoing final revision.

Between December 1976 and April 1977, a series of environmental tests were conducted at the Homer City Generating Station near Homer City, Pennsylvania. The intent of this monitoring was to evaluate the air, water, and biological quality

in the vicinity of an advanced coal cleaning plant which was then under construction. These studies were conducted prior to operation of the cleaning plant as a reference point for furture, and more comprehensive, environmental testing planned during operation of the plant. The results of these tests are currently being evaluated.

COAL CONTAMINANTS

Three distinct programs are directed to the identification and characterization of contaminants in coal. Specifically, the research attempts to demonstrate the occurrence, association, and distribution of trace element and mineral phases in the coal seam.

One portion of this research, led by the Illinois State Geological Survey, concentrates on coals of the Illinois Basin, This work has three principal goals: 1) to determine the mode of occurrence and distribution of trace elements and minerals in coal seams; 2) to study the mineralogy and genesis of sulfide minerals in coal, and 3) to evaluate the potential for removal of minerals from coal by various preparation techniques.

ORGANIC AFFINITIES

The most significant contribution recently was the publication of *Trace Elements in Coal: Occurrence and Distribution* (1) which summarizes the results of the last 6 years of EPA supported activity. The report succeeded in demonstrating various levels of organic affinities for some of the trace elements in coals. Ge, Be, B, and Sb all have high affinities for organic matter, with Ge being highest. Zn, Cd, Mn, As, Mo, and Fe have a tendency to reside with the inorganics, with Zn and As being most consistent. Elements including Co, Ni, Cu, Cr and Se have intermediate organic affinities, suggesting that these metals are present in coals as organometallic compounds, chelated species, or as adsorbed cations.

A second area of investigation by the U.S. Geological Survey is underway in Reston, Virginia. This project has dual objectives. One is to determine the geologic factors which affect or control the physical cleanability of coal and to develop geologic models which can be used to help maximize efficiency and minimize environmental impact from coal mining, cleaning, and burning. The second objective is to provide the necessary chemical, physical and mineralogical data on the Nation's coal resources to permit evaluation of the environmental impact resulting from coal preparation and utilization.

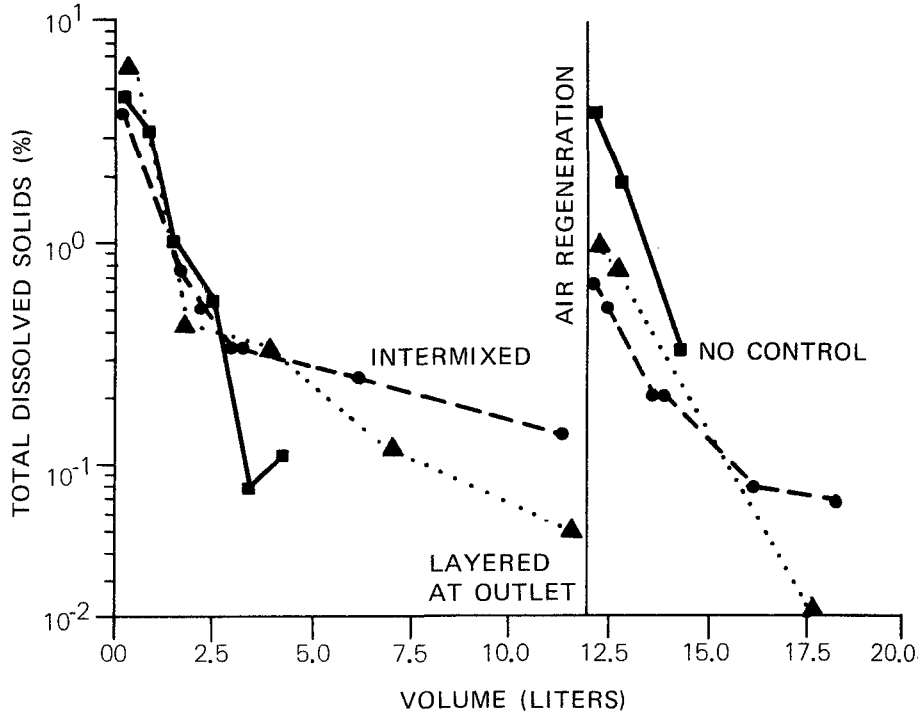
CONCLUSION FROM FREEPORT SEAM

The annual report for the first objective of this study is nearing completion; however, several preliminary conclusions can be drawn on the Upper Freeport coal seam which the report will address. Despite the complex nature of this seam, stratigraphic analysis suggests that facies (geologic zones) in the coal can be mapped throughout the study area. Therefore, those aspects of coal quality which are a function of facies can also be mapped. Mineralogic determinations suggest that quartz, pyrite, kaolinite, illite, and calcite are the most abundant species with marcasite, siderite, sphalerite, and chalcopyrite occurring occasionally. Data on trace elements of environmental concern suggest that arsenic is associated with the iron disulfides, cadmium appears with zinc in sphalerite, and selenium is associated with lead as a lead selenide.

The third study in this area, being conducted at the Los Alamos Scientific Laboratory (LASL), deals with the evaluation of the contaminant potential of coal preparation wastes. The research has three distinct phases: 1) to characterize the minerals, trace elements, and their association in coal preparation wastes, 2) to study the effects of weathering and leaching on trace elements in coal wastes, and 3) to identify and evaluate techniques for controlling or preventing trace element contamination from coal waste materials. Phases 1 and 2 have been completed. The results are available in two EPA publications (3,25). A second annual progress report is in preparation. The results of the LASL work are discussed later in this paper in relation to *Pollution Control Technology*.

TRACE ELEMENTS

DOE recently completed a study showing the trace element content of various coal specific gravity fractions for 10 U.S. coals (26). Most of the trace elements of interest were concentrated in the heavier specific gravity fractions of the coal, indicating that they are associated with mineral matter. Removal of the high density



TOTAL DISSOLVED SOLIDS VS LEACHATE VOLUME FOR COLUMN LEACHING STUDY OF COARSE LIMESTONE/REFUSE MIXTURES (-3/8 in).

FIGURE 8—*Control of trace element leaching*

fractions of coal should result in trace element reductions, ranging (for some elements) up to 88 percent.

FATE OF COAL TRACE ELEMENTS

In a related, but greatly expanded effort, the Bituminous Coal Research Inc. is evaluating the fate of coal trace elements during mining, transportation and preparation. These studies encompass the collection and analysis of 20 run-of-the-mine (ROM) samples which are representative of U.S. coals. To date, two 1,000 pound run-of-mine samples have been collected. The first was a blend of Upper and Lower Freeport bed coals from the Rochester & Pittsburgh Coal Company, Indiana, Pennsylvania. The second was Illinois No. 6 bed coal from the Old Ben Coal Company, Benton, Illinois. Each sample was crushed and divided into three size fractions: 1-1/4 inch x 1/4 inch, 1/4 inch 30 mesh, and 30 mesh x 0. Each size fraction was subdivided into three specific gravity fractions (1.34, 1.55, and 1.80). Each size and specific gravity fraction has been analyzed for As, Be, Cd, Cr, Cu, F, Pb, Mn, Hg, Ni, Se, V, and Zn. Analyses are now being performed to determine the relative organic or inorganic affinity of each element.

POLLUTION CONTROL TECHNOLOGY

The subprogram to develop coal cleaning pollution control is in a formative phase. A wide variety of techniques exist for controlling conventional pollutants (total suspended solids, total particulate emissions, pH,). However, as coal cleaning processes evolve and as pollution control regulations become more specific and stringent, modifications and improvements must be made in pollution control techniques. The subprogram for development of pollution control technology, therefore, addresses current and projected pollution control needs.

The Los Alamos Scientific Laboratory (LASL) is conducting studies to assess the potential for environmental pollution from trace or minor elements that are discharged or emitted from coal preparation wastes and stored coals, and to identify suitable environmental control measures.

Initial studies were concerned with the assessment of the identities, structure, and chemistry of the trace elements and minerals in samples of high sulfur, coal preparation wastes (3). In accordance with this aim, extensive quantitative analyses were made of the elemental and mineral compositions of more than 60 refuse samples collected from three coal cleaning plants in the Illinois Basin (25). These waste materials were found to be composed mainly of clay minerals (illite, kaolinite, and mixed-layer varieties), pyrite, marcasite, and quartz. Smaller amounts of calcite and gypsum were also identified in some of the refuse samples. The elements present in greatest abundance (Si, Al, Fe, Na, K, Ca, and Mg) are components of the major mineral species. Potentially toxic trace elements found in environmentally significant quantities included Mn, Co, Ni, Cu, Zn, As, Cu, Se, Cd, and Pb.

The structural relationships and associations among the trace elements and major minerals in the refuse samples were investigated by statistical correlation of chemical and physical data and by direct observation of refuse structure with electron and ion microprobes. It was found that the mineral associations of many of the trace elements that have been identified as being highly leachable from the refuse samples (and, therefore, of environmental concern) were associated with the refuse clay fractions rather than the major pyritic fractions.

STATIC AND DYNAMIC TESTS

In studies completed this year, static and dynamic tests were conducted to determine the trace element leachabilities of the various waste samples. Generally, the trace elements leached in the highest quantities (Fe, Al, Ca, Mg, and Na) are constituents of the major refuse minerals. Several other elements, while not present in the refuse in large amounts, were nonetheless found to be easily removed by leaching. This group included Co, Ni, Zn, Cd, and Mn. The highest degree of trace element leachability was exhibited by waste samples that produced the most acidic leachates. Trace element leaching was also found to be a function of refuse particle size (relative surface area), temperature, and access to air.

TOXIC ELEMENTS

Based on results of the mineralogy studies, elemental studies and the laboratory leaching experiments, F, Al, Mn, Fe, Co, Ni, Cu, Zn, and Cd were selected as the elements of most concern in the Illinois Basin preparation plant wastes. These elements are often toxic in aqueous systems or soils or are present in the refuse materials in a highly leachable state.

Following completion of the leaching studies, experiments were started to assess potential technologies to (a) prevent the release (leaching) of trace elements from coal preparation wastes, or (b) remove the dissolved trace elements from acidic leachates.

CONTROL METHODS

Tests were conducted to evaluate the degree of trace element control that could be exerted by adding neutralizing agents to high sulfur refuse materials prior to disposal to reduce leachate acidity and trace element dissolution (27). Column leaching experiments that utilized mixtures of crushed limestone and refuse were conducted to test the effectiveness of this control method. Limestone was combined with the refuse to simulate three different geometric arrangements in refuse dumps: limestone placed on top of the refuse, limestone placed beneath the refuse, and limestone intermixed with the refuse.

Adding coarse limestone to the acid refuse material was only partly successful in controlling leachate acidity (27). The pH values of the leachates from most of the refuse/limestone combinations were higher throughout the leaching tests than were those for the refuse alone; however, even in the best instances, neutralization by the *in situ* limestone was not sufficient to prevent the dissolution of refuse solids (figure 8). As expected from the leaching studies, the release of some trace elements was found to be dependent upon the degree of acidity control. Elements, such as Al, K, V, and Cr (which were quite sensitive to leachate pH) tended to be released in lesser quantities from the refuse limestone systems than from pure refuse. There was little apparent effect of the limestone additions on the leachate concentrations of Fe, Mn, Co, Cu, and Zn.

ALKALINE NEUTRALIZATION

Other studies focused on potential control technologies to reduce the content of undesirable trace elements extant in the aqueous drainages associated with refuse

disposals. Tests were conducted to evaluate the degree to which trace element solubilities are affected by treatment with neutralizing agents, such as lime, limestone, and lye (sodium hydroxide). These experiments indicated that alkaline neutralization is an effective means for controlling the trace element concentrations in refuse waste water. The pH and iron contents of the treated solutions were within acceptable limits, based on the 1977 EPA effluent limitation guidelines. Mn, however, was a borderline case that sometimes exceeded acceptable concentration limits in the leachates. Lye was generally more effective than limestone or lime in reducing the trace element content of the drainage samples.

CONTROL OF BLACK WATER

Black water (process waste water) from coal preparation plants consists of mixtures of fine coal, clay minerals, quartz, calcite, pyrite, and other mineral particles dispersed in water. The effluents must be effectively treated regardless of whether the water is to be reused or discharged. Pennsylvania State University has completed a systematic investigation to characterize the solids in black water in coal preparation plants (28).

Tests were conducted with samples collected from preparation plants throughout the United States. It was found that the mineral composition of black water is largely determined by the nature of the adjacent roof and floor which are introduced into the run-of-mine coal by overbreak during mining. The contribution of coal associated mineral matter to the overall composition of black water was minor in the sample evaluated.

POLYMERIC FLOCCULANTS

Studies of the interaction of polymeric flocculants with coal and clay particles revealed that these reagents are adsorbed more strongly on coal than on clay minerals. The results have some important implications in the flocculation of black water systems in which coal and clays are present simultaneously. For example, the addition of sufficient polymer to give adequate flocculation of the clay minerals could lead to considerable overdosage and consequent redispersion of the fine coal particles. In addition, the very strong adsorption on the coal would give rise to excessive reagent consumption.

STABILIZATION OF WASTES

Reject ponds are becoming increasingly impractical because of safety, environmental, and land-use considerations. An alternative approach to the slurry disposal of the fine wastes is the treatment of these wastes to create stable solids—a process termed stabilization.

Under contract to DOE, Dravo Lime Company is conducting a study to characterize the engineering, physical, and chemical properties that affect stabilization of fine wastes from coal preparation plants. The requirements and conditions for stabilizing these wastes with and without stabilizing agents are being determined.

Nine samples were collected from preparation plants in Pennsylvania, West Virginia, Virginia, Illinois, and Indiana. All samples were subjected to laboratory analyses for index properties—permeability, consolidation, penetration, and direct shear; and stabilization characteristics—variations of additive type (Calcilox, lime, portland cement), dosage, waste solids level, temperature, and time. The data are currently being analyzed and final report is to be issued in several months. If additional research is warranted, a second phase involving on-site testing with a mobile laboratory will be carried out.

CONCLUSIONS

The past year has been one of transition. Potential applications of coal cleaning, and hence R&D goals, have been greatly affected by new environmental legislation and impending energy legislation. Studies are now in progress to identify the technical capability and costs of various coal cleaning technologies for removing sulfur and other contaminants from coal. Progress has been made in the development of physical cleaning techniques for improved pyrite removal and coal energy recovery.

Progress continues in the development of chemical coal cleaning processes, but impending environmental standards result in uncertainties concerning future market applications.

Methodologies have been developed for the environmental assessment of coal preparation processes, and tests are scheduled to begin shortly. The conditions under which trace elements are leached from coal preparation wastes have been identified, and preliminary studies have identified the effectiveness of several pollution control techniques.

CONVERSION FACTORS

ton = 0.907 metric tons
lbm = 0.436 kg
Btu = 1055.6 joule
Btu/lb = 2326 joule/kg
in. = 2.54 cm
$^{\circ}C = 5/9 \times (^{\circ}F - 32)$
lb./in. = 0.07 kg/cm^2

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FLUE GAS DESULFURIZATION OF COMBUSTION EXHAUST GASES

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Fossil fuels, primarily coal, burned to produce electric power and generate steam for various industrial uses contain up to about 5% sulfur. In the combustion process almost all of this sulfur is converted to sulfur dioxide (SO_2); thus, in the case of a 5% sulfur coal, 100 grams of SO_2 would be released for each kilogram of coal burned. In the U.S. about 80% of all sulfur oxide emissions are from combustion of fossil fuels.

SMALL CONCENTRATIONS DAMAGE

Sulfur dioxide is considered by many to be harmful to human health and damaging to materials and vegetation at extremely small concentrations (parts per million) in the atmosphere. The National Air Pollution Control Administration, a predecessor of the U.S. Environmental Protection Agency (EPA), fulfilling its responsibility under the law, published an air quality criteria document for sulfur oxides in 1969. Subsequently, ambient air quality regulations and new source performance standards were established to control sulfur dioxide.

In order to support the regulations, EPA has fostered the development and demonstration of various control technologies for sulfur dioxide since the early 1970's. This research and development work has included laboratory, pilot plant, prototype and full scale utility demonstration of the technology under various in-house and contractor-conducted programs.

LEADING SOLUTION

Currently, flue gas desulfurization (FGD) is considered to be the leading technically viable and economic near-term solution to control of sulfur oxide emissions from combustion of high-sulfur coal. Generally, the high-sulfur coal deposits are located in the industrialized, highly populated, eastern and midwestern sections of the country where the consumption of coal is the highest. Most of the low-sulfur coal is located in the west. Transportation of low-sulfur coal from west to east in most cases turns out to be uneconomical.

In the past, poor reliability or dependability has been the prime criticism of FGD. During the past half decade, however, dependability of utility systems has improved markedly. Another criticism of FGD has been its high cost. Although the cost issue has been the subject of much controversy in the past, with the present data base, this issue can be put into more reasonable perspective. The cost of generation of electricity is probably increased by 10% to 20% if an FGD system is used for pollution control.

FGD IN THE UTILITY INDUSTRY

Use of FGD in the utility industry is projected to increase dramatically. Based on currently known planned units, a 5-fold increase is projected in the next 8 years.

If we assume more stringent regulations will apply to the utility industry (revised new source performance standards) we might expect an order of magnitude increase in the same period.

THE PROBLEM

Based on recent EPA estimates, about 26 to 30 million metric tons per year of sulfur oxides are emitted to the atmosphere in the United States by various combustion and other industrial processes. This is equivalent to emission of about 140 liters of SO_2 for every man, woman and child in the country each day!

The majority of sulfur oxide emissions come from a relatively small variety of sources. About 80% of all emissions are from stationary source fuel combustion and about two-thirds of all emissions are from the electric utility industry. The remaining 20% of emissions are mainly from a few industrial processes: metals smelting and refining, petroleum refining, minerals products processing, and chemicals manufacturing. In 1976 almost 60% of these industrial emissions came from the metals industries with the remainder being divided somewhat evenly among the other three mentioned areas.

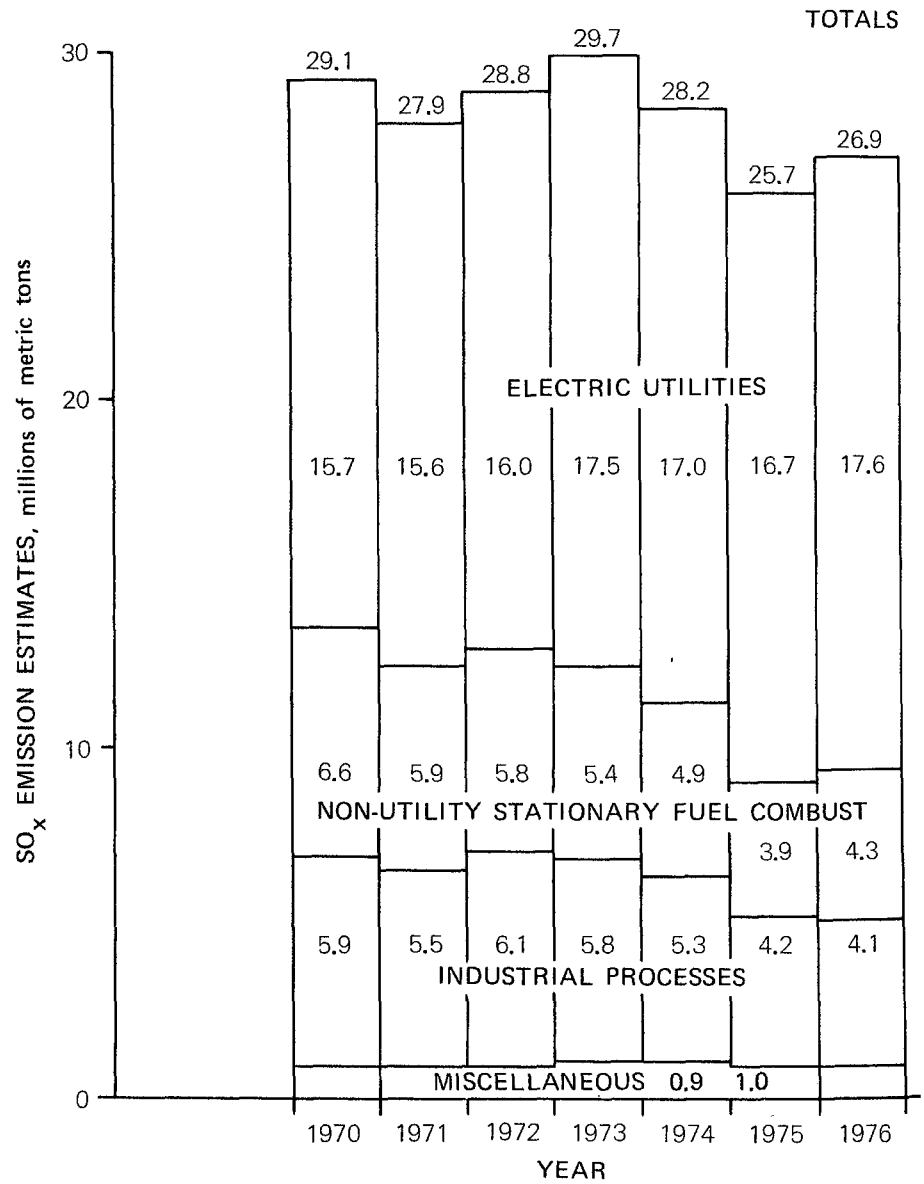

FIGURE 1–*Nationwide SO_x emission estimates, 1970 - 1976*
Source: (EPA, 1977)

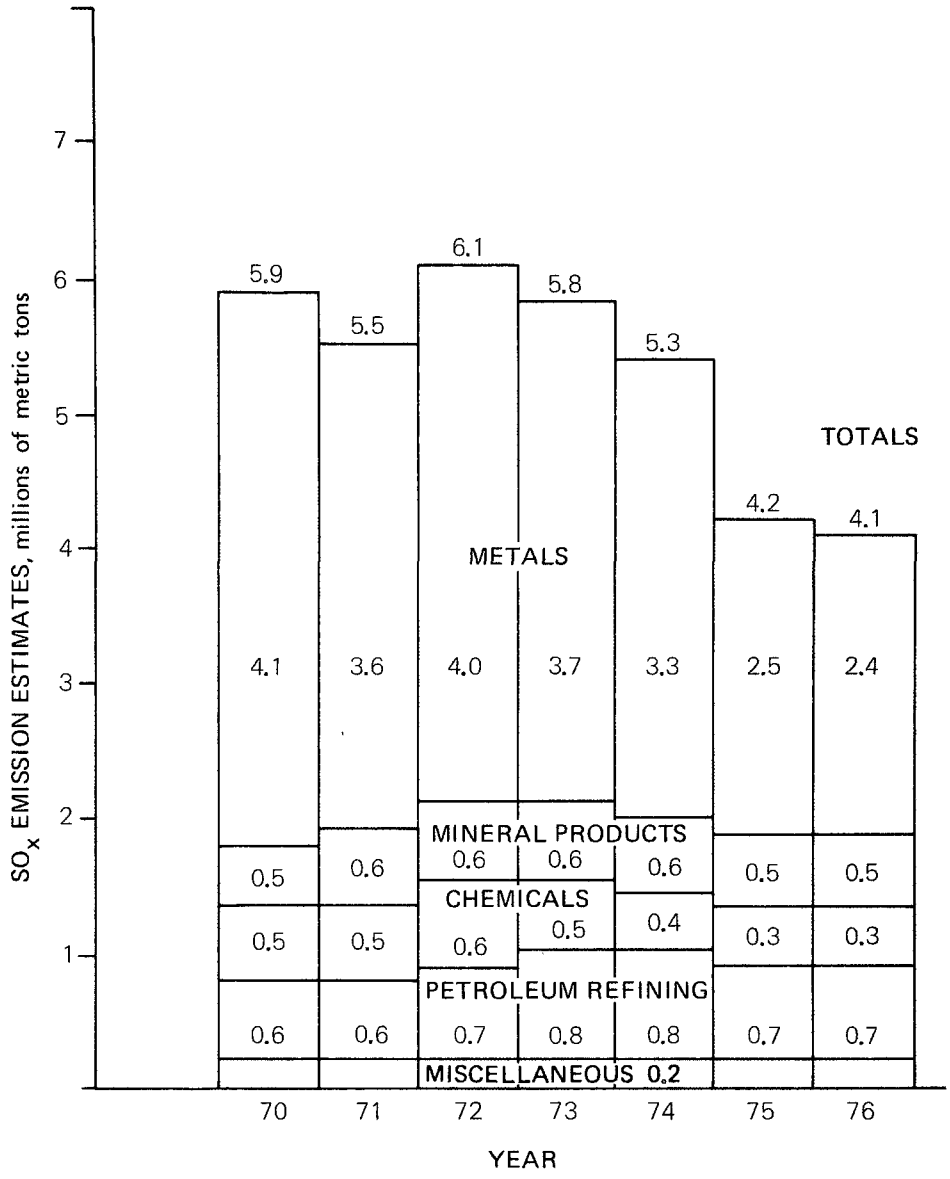

FIGURE 2–*SO_X emissions from industrial processes, 1970 - 1976*
Source: (EPA, 1977)

DATA SHOW DOWNTREND

These national and industrial process SO_X emissions are presented graphically in figures 1 and 2, respectively. Figure 2 is a breakdown of the total industrial process emissions shown in figure 1. The data indicate that our national emissions of sulfur oxides are being stabilized and even show a downtrend. Apparently, the downtrend is due mainly to lower emissions from the industrial process sources which show a reduction of one-third between 1972 and 1976, mainly due to metals smelting and refining.

It is obvious from these data that adequate control of sulfur oxides in our atmosphere will depend on control of sulfur oxide emissions in combustion exhaust gases. With our Nation's commitment to use our coal reserves for energy production, this fact is even further emphasized.

REGULATION

Sulfur dioxide is federally controlled under the Clean Air Act (amended August 1977) in two basic ways: by emission limitations and by promulgated ambient air quality standards. The states and municipalities may enact (and some have enacted) legislation and/or regulation which is more stringent than the federal laws and regulations.

LIMITATIONS

Emission limitations on sulfur dioxide are imposed on new fossil fuel-fired steam generators by regulations promulgated on December 23, 1971. These regulations apply to steam generators with a heat input of more than 73 MW (250 million Btu/hr) and for which construction or modification was initiated after August 17, 1971 (the date of proposal of the standards). The regulations limit emissions to 520 ng/J (1.2 lb/million Btu) heat input for solid fuels (e.g., coal) and 340 ng/J (0.8 lb/million Btu) heat input for liquid fuels (e.g., oil).

As an example, this limitation requires removal of more than 70% of the sulfur dioxide emitted when burning a coal containing 3% sulfur and having a heating value of 28,000 J/g (12,000 Btu/lb). These limitations apply to almost all utility boilers and some large industrial boilers.

The EPA is currently considering revision of these new source performance standards (NSPS) to be more stringent for the larger boilers (over 73 MW input). Regulation of emissions from the smaller boilers is also being considered. Current thinking is that NSPS should require 85% to 90% SO_2 removal with credit given for precombustion processes for sulfur removal from fuel. The 520 ng/J (1.2 lb/million Btu) limitation would still be a ceiling, applicable to extremely high sulfur coals; however, if emissions from a source burning low sulfur coal were below 90 ng/J (0.2 lb/million Btu), no further reduction would be required even if the 85% to 90% reduction were not being attained. To temper these limitations somewhat, an allowance of 3 days per month during which SO_2 removal could drop to as low as 75% is also being considered.

FALL-BACK POSITION

It is interesting to note that in the early 1970's the NSPS requirements were thought to be stringent and considered to be the limiting maximum requirement in the law. With several legal precedents on enforcement, the NSPS are now considered a limiting minimum requirement in the law. With aspects of environmental law including Prevention of Significant Deterioration, use of Best Available Control Technology, and Lowest Achievable Emission Rate, the NSPS are now considered a fall-back position in enforcement of the law.

As mandated by the Clean Air Act, EPA's administrator has promulgated primary and secondary national ambient air quality standards (NAAQS) for SO_2. Primary standards are designed to protect the public health, while secondary standards are meant to protect the public welfare. These standards are given in table 1.

While the NSPS directly limit emissions from certain new sources, the NAAQS indirectly control emissions from all sources.

STATE IMPLEMENTATION PLANS

To meet the primary standards, the Clean Air Act amendments require each state to adopt (and submit to the administrator) a State Implementation Plan (SIP) to provide for implementation, maintenance, and enforcement of the primary standard as soon as practicable, but not later than 3 years from the date of approval of the SIP. Requirements of the SIP to implement, maintain, and enforce

TABLE 1
National ambient air quality standards for SO_2

	Primary	Secondary
Annual Mean	80 $\mu g/m^3$ (0.03 ppm)	–
Maximum 24–hour Concentration*	365 $\mu g/m^3$ (0.14 ppm)	–
Maximum 3–hour Concentration*	–	1,300 μ/m^3 (0.5 ppm)

*Not to be exceeded more than once a year

the secondary standard must specify "a reasonable time at which such secondary standard will be attained." The Clean Air Act amendments of 1977 require review of the criteria documents and NAAQS for sulfur oxides before 1980.

To control SO_x emissions from combustion sources, we can (1) use fuels containing less sulfur, (2) remove sulfur from the fuel before combustion (coal cleaning and fuel processing), (3) remove sulfur during combustion (fluid bed combustion), (4) remove sulfur from the flue gases after combustion (FGD), or (5) any combination of the above.

LOW SULFUR FUELS

In line with a reasonable and forward looking national energy policy, we cannot rely to any great extent on naturally occurring low-sulfur oil and natural gas as a means of controlling SO_x emissions from stationary combustion sources. Generally, low-sulfur coal deposits are located in the western part of the U.S. In the highly industrialized and populated east and midwest, where much of the coal will be burned, predominantly high-sulfur coal is mined. Transportation of low-sulfur coal from west to east is usually not economical even when compared with using FGD with high-sulfur coal.

In 1975 and 1976 nearly 100% of the new fossil fuel fired electrical generating capacity ordered by U.S. utilities was coal-fired. In 1977, 100% of the ordered generating capacity was coal-fired (Richards, 1978).

Use of low sulfur coal may be a reasonable option for some existing facilities now burning coal; however, with potential requirements of revised federal NSPS requiring 90% sulfur removal, use of low sulfur coal, alone, at new coal burning facilities may not be acceptable. It has been estimated (Ponder et al., 1976) that even with the present NSPS, low-sulfur coal production in 1980 will supply less than 44% of the utility industry's coal demand.

COAL CLEANING

Techniques for removing sulfur from coal prior to combustion include physical or chemical coal cleaning and the generation of clean synthetic fuels. The former deals with removal of inorganic sulfur-containing matter (e.g., pyrite and sulfate) that is physically associated with the coal. The latter deals with sulfur that is chemically bound to the organic structure of the coal.

Physical coal cleaning, based on the difference in specific gravities or surface properties of the inorganic matter and the remainder of the coal, has been in use for years. From 20% to 80% of the pyritic sulfur can be removed, depending on the coal and techniques used. It has been estimated (Ponder, et al., 1976) that less than 13.5% of our coal reserves can be physically cleaned to meet present NSPS. Obviously, in complying with more stringent NSPS, physical coal must be used with FGD or in combination with other controls.

PHYSICAL COAL CLEANING

Currently, 50% of the domestically consumed coal is physically cleaned to remove mineral matter and mining residue. A portion of the metallurgical grade coals is also cleaned to remove sulfur. Cleaning operations for steam coals have not previously been designed and operated to remove sulfur for compliance with SO_2 emission regulations. The first U.S. steam coal preparation plant, designed to remove sulfur for compliance with state and federal SO_2 emission regulations, has just begun operation at Homer City, Pennsylvania. Two other sulfur removing plants are being planned by the Tennessee Valley Authority (TVA). None of these steam coal plants incorporate the most advanced physical preparation techniques now used in the metallurgical and mineral industries.

CHEMICAL COAL CLEANING

Chemical coal cleaning processes vary substantially because of the different chemical reactions which can be used to remove sulfur and other contaminants from coal. Chemical coal cleaning processes usually entail grinding the coal to small particles and treating these particles with chemical agents at elevated temperatures and pressures. The coal's sulfur is converted to elemental sulfur or sulfur compounds which can be physically removed from the coal structure. Some chemical leaching processes, such as the TRW-Meyers Process, remove only pyritic sulfur. Other less advanced processes, such as that under development by the Department of Energy (DOE), are capable of removing organic and pyritic sulfur.

Chemical coal cleaning processes are currently under development at the bench and pilot scales. Optimistically, several chemical processes could be ready for commercial demonstration in 3 to 5 years.

FLUID BED

These processes, atmospheric and pressurized, remove sulfur from coal during combustion by burning the coal in a fluidized bed of limestone or dolomite. The sulfur in the coal reacts with the bed reagent to form dry calcium sulfate. A portion of the fluid bed is continuously withdrawn to remove the sulfur compounds either by direct disposal or by regeneration of the spent bed material. These processes are currently at the pilot/prototype development stage and may reach commercialization by 1985-1990. This technology will be suitable for new large combustion processes and is projected to be less costly than FGD. One process advantage over the nonregenerable wet scrubbing FGD processes is that these processes produce a dry solid waste product rather than a sludge. A process disadvantage is that fluid bed combustors require a much higher consumption of limestone for the same amount of sulfur removal than does a wet limestone FGD system. Consequently, the cost may in fact be higher than that for FGD.

FLUE GAS DESULFURIZATION

Flue gas desulfurization is the removal of sulfur oxides from combustion exhaust gases in most cases by chemical reaction with an absorbent in water slurry or solution in an absorption tower. The tower is known as a scrubber, thus the common terminology, wet scrubbing. Basically, a scrubber is a device in which gas/liquid contact occurs. Certain other FGD processes under development remove the sulfur oxides by dry adsorption.

Well over 50 FGD processes have been invented; many have undergone testing in small scale laboratory or pilot-plant operations. But relatively few have served to date for SO_2 control of full scale utility and industrial boilers in this country. On the other hand, considering our commitment to coal and the potentially more stringent pollution control regulations, increased use of FGD may well be the only near-term available course of action.

PROCESSES IN CURRENT USE

There are currently six types of FGD processes in use for control of SO_2 emissions from full scale utility systems. These are summarized in table 2 by process type, number of systems, controlled generating capacity, and percentage of the total for each type.

TABLE 2
Operating utility FGD systems

Process	No. of Units	Controlled Generating Capacity, MW	Capacity, % of Total
Limestone Slurry Scrubbing	11	5233	50
Lime Slurry Scrubbing	10	3517	33
Lime/Alkaline Fly Ash Scrubbing	3	1170	11
Soda Ash Solution Scrubbing	3	375	4
Magnesium Oxide Scrubbing	1	120	1
Wellman–Lord/Allied Chemical	1	115	1
Totals	29	10530	100

Source: (Laseke, 1978)

TABLE 3
Operating nonutility FGD systems

Process	No. of Units	Controlled Capacity ft^3/min., actual*	MW Equivalent Controlled	Capacity, % of Total
Soluble Alkali Scrubbing, Throwaway (Na, NH_3, alkaline waste)	27	4,360,000	1362	83
Dual Alkali	5	542,000	169	10
Lime Slurry	1	280,000	88	5
Limestone Slurry	1	73,000†	23	2
Totals	34	5,255,000	1642	100

*3200 acfm (actual cubic feet/min) = 1 MW

†Estimated to conform with other figures in the table

Source: (Tuttle et al., 1978)

The mix of FGD systems currently applied at nonutility stationary-source combustion systems is summarized in table 3.

SALABLE AND THROWAWAY

The various FGD processes may be divided into two categories: regenerable and nonregenerable (perhaps more properly into salable product and throwaway processes). The regenerable or salable product processes produce sulfur or a by-product containing sulfur which may be sold to partially offset the cost of operation of the FGD system. The potential products are elemental sulfur, sulfuric acid, liquid SO_2, and possibly gypsum if there is a market for the sale of it. (However, if impure gypsum is produced and is disposed of as solid waste, the system would be classified as throwaway.) Throwaway or nonregenerable systems produce a liquid, solid, or sludge waste product containing the sulfur removed from the flue gases. Of the systems appearing in tables 2 and 3, only the magnesium oxide and Wellman-Lord/Allied Chemical are salable product processes.

THROWAWAY FAVORED

Based on current controlled capacity, 98% of the operating utility processes and 100% of the nonutility processes are throwaway systems. The throwaway processes are heavily favored in current application due to more favorable economics, simplicity, and prior experience with previous applications relative to the salable product processes.

It is also interesting to note that, while only 4% of the utility systems (the soda ash systems) produce a sizeable liquid waste stream, 83% of the nonutility applications (soluble alkali, throwaway) produce such a stream. In general, disposal of large volumes of liquid wastes containing soluble solids is environmentally unacceptable. Also, the cost of soluble alkali reagents is higher than calcium based alkali. In most cases a permit for such operations must be secured from the appropriate regulatory authority. Since utility systems are generally larger than nonutility systems, discharge permits for such operation may be less likely obtainable and reagent cost considerations thus become more significant. Most soluble throwaway systems either treat the soluble waste stream to reduce chemical oxygen demand (COD) and then feed the waste through some municipal wastewater process, or simply evaporate the liquid. As we aim toward zero discharge, however, these once-through soluble scrubbing systems will become less prevalent.

Brief descriptions of most of the significant U.S. operating systems are given below.

SLURRY SCRUBBING

In concept, lime or limestone slurry scrubbing processes are very simple. In practice, however, the chemistry and system design for a full-scale operation can be more complex than seems evident at first glance.

These systems use a slurry of lime or limestone in water to absorb SO_2 from power plant flue gas in a gas/liquid scrubber. The slurry generally ranges from 5% to 15% solids. Various types of scrubbers or gas/liquid contact devices are employed commercially: spray towers, grid towers, plate towers, venturis, marble-bed scrubbers (packed beds of glass spheres) and turbulent-contact absorbers (lightweight hollow plastic spheres—ping-pong balls—held between restraining grids in a countercurrent scrubbing tower). These scrubbers usually operate with a liquid-to-gas (L/G) ratio of 6 to 15 1/normal m^3 (40 to 100 gal./1,000 actual ft^3).

LIMESTONE SLURRY

A schematic of the 10 MW prototype limestone system at the TVA/EPA test facility at TVA's Shawnee steam plant, figure 3, shows a turbulent-contact absorber with an open-chevron mist eliminator. Flue gas flows up through the tower and contacts slurry which sprays down over the packing, countercurrent to the gas stream. The gas/liquid counterflow keeps the spheres in turbulent motion, which improves gas/liquid contact.

The overall absorption reaction taking place in the scrubber and the hold-tanks for a limestone slurry system produces hydrated calcium sulfite:

$$CaCO_3 + SO_2 + 1/2\ H_2O \rightarrow CaSO_3 \cdot 1/2\ H_2O + CO_2 \quad (1)$$

LIME SLURRY

With a lime slurry system, the overall reaction is similar but yields no CO_2:

$$CaO + SO_2 + 1/2\ H_2O \rightarrow CaSO_3 \cdot 1/2\ H_2O \quad (2)$$

(The actual reactant in Equation 2 is $Ca(OH)_2$, since CaO is slaked in the slurrying process.)

In practice, some of the absorbed SO_2 is oxidized by oxygen which is also absorbed from the flue gas. This shows up in the slurry as either gypsum ($CaSO_4 \cdot 2\ H_2O$) or as a calcium sulfite/sulfate mixed crystal [$Ca(SO_3)_x(SO_4)_y \cdot z\ H_2O$]. Slurry is recycled around the scrubber to obtain the high liquid-to-gas ratios required. A bleed stream is taken from the scrubber liquid circuit to remove the calcium-sulfur compounds formed. This is accomplished by thickening, filtration, ponding, and various combinations of these operations. The calcium-sulfur compounds are solids to be disposed; the liquor separated is usually recycled to the system.

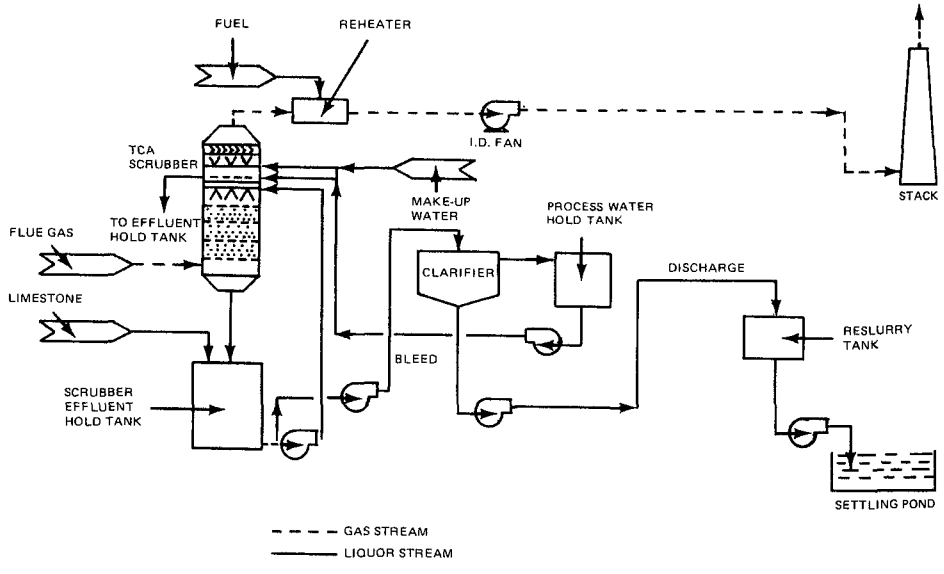

FIGURE 3—*Schematic of wet limestone scrubbing system*

Lime and limestone slurry scrubbing systems can be engineered for almost any desired level of SO_2 removal. Commercial utility systems are generally designed for 80% to 90% removal; however, some systems have at times achieved more than 99% removal. The higher removal rate is not incrementally very costly: investment savings realized in designing for 80% rather than 90% SO_2 removal amount to only about 3.2% to 4.5% (Slack and Hollinden, 1975).

ALKALINE FLY ASH SCRUBBING

Western U.S. low-sulfur coals appear particularly suitable to SO_2 control by scrubbing the waste gases with a slurry of the alkaline fly ash which results from the combustion process. There are two ways to add the alkaline ash to the system: (1) collecting the fly ash in an electrostatic precipitator upstream of the scrubber and then slurrying the dry fly ash with water so that it can be pumped into the scrubber circuit, and (2) scrubbing the fly ash directly from the flue gas by the circulating slurry of fly ash and water.

Most western coals have a low sulfur content (less than 1.0%). They also usually have a low heating value and consequently require close control to hold their combustion emissions within current federal limits for NSPS defined as mass emissions per unit heat input. While typical eastern bituminous coals have heating values of about 28,000 J/g (12,000 Btu/lb), lignite coals may have heating values as low as 16,000 J/g (6,800 Btu/lb). The bituminous coal could contain as much as 0.7% sulfur and still meet the NSPS limitation of 520 ng/J, without controls; but the lignite would have to have no more than about 0.4% sulfur due to its lower heating value.

Generally, the coals best suited to this method are the western lignites and subbituminous coals. Certain of these coals (e.g., those from North Dakota, Montana and Wyoming) contain up to 20% ash; and the ash contains up to 40% alkaline constituents including oxides of calcium, magnesium, sodium and potassium, some of which are offset by acidic constituents (Ness et al., 1977). With potentially more stringent NSPS, this process may, however, have to be used with supplemental lime or limestone to meet standards.

SODA ASH SCRUBBING

This method of controlling SO_2 involves scrubbing the flue gas with a solution of sodium carbonate and bicarbonate, to produce a mixture of sodium sulfite and sulfate by these reactions:

$$Na_2CO_3 + SO_2 \rightarrow Na_2SO_3 + CO_2 \quad (3)$$

$$2\ NaHCC_3 + SO_2 + H_2O \rightarrow Na_2SO_3 + 2\ H_2O + 2\ CO_2 \quad (4)$$

$$Na_2SO_3 + 1/2\ O_2 \rightarrow Na_2SO_4 \quad (5)$$

The sodium carbonate does not have to be pure. Nevada Power Company uses trona salt, a naturally-occurring mineral containing 60% $NaHCO_3$, 20% NaCL, 10% sulfates, and 10% insolubles.

This process has definite limitations in large-scale utility applications, since it requires a relatively cheap source of sodium carbonate or bicarbonate and an ability to dispose of large volumes of waste salt solution. Nevada Power is located near trona deposits—in an area where natural evaporation rates far exceed rainfall and where land is relatively abundant. The company processes its liquid waste in solar evaporation ponds and deposits the crystallized waste salts back at the mine.

MAGNESIUM OXIDE SCRUBBING

The magnesium oxide process is a regenerable or salable product process. It does not produce waste material—SO_2 removed from the flue gas is concentrated and used to make marketable H_2SO_4 or elemental sulfur.

Employing a slurry of MgO—or $Mg(OH)_2$—to absorb SO_2 from flue gas in a scrubber, this process yields magnesium sulfite and sulfate. When dried and calcined, the mixed sulfite/sulfate produces a concentrated stream (10% to 15%) of SO_2 and regenerates MgO for recycle to the scrubber. Carbon added to the calcining step reduces any $MgSO_4$ to MgO and SO_2.

In commercial applications, the scrubbing and drying steps would normally take place at the power plant. The regeneration and H_2SO_4 production steps might be performed at a conventional sulfuric acid plant. Alternatively, a central processing plant could produce sulfur from mixed magnesium sulfite/sulfate brought in from several desulfurization locations.

WELLMAN-LORD SYSTEM

The Wellman-Lord process (sold by Davy Powergas, Inc) is also a regenerable or salable product system. When coupled with other processing steps, it can make salable liquid SO_2, H_2SO_4, or elemental sulfur.

The W-L process employs a solution of Na_2SO_3 to absorb SO_2 from waste gases in a scrubber or absorber, converting the sulfite to bisulfite:

$$Na_2SO_3 + SO_2 + H_2O \rightarrow 2\ NaHSO_3 \quad (6)$$

Thermal decomposition of the bisulfite in an evaporative crystallizer regenerates sodium sulfite for reuse as the absorbent:

$$2\ NaHSO_3 \xrightarrow{\Delta} Na_2SO_3 + SO_2 + H_2O \quad (7)$$

The evaporative crystallizer produces a mixture of steam and SO_2 and a slurry containing sodium sulfite/sulfate plus some undecomposed $NaHSO_3$ in solution. As water condenses from the steam/SO_2 mixture, it leaves a wet SO_2-enriched gas stream to undergo further processing for recovery of salable sulfur values.

SOLUBLE ALKALI SCRUBBING

Most industrial boilers use a soluble alkali scrubbing process—basically as described for soda ash scrubbing, and using sodium carbonate, bicarbonate, hydroxide, or ammonia based alkali—which converts sulfur in the flue gas to sulfite/bisulfite and sulfate in solution.

For spent scrubbing liquors, disposal practices include consume in pulp/paper manufacturing, discharge to evaporation ponds, treat (mainly by air oxidation) and discharge to city sewer system, and treat and discharge to rivers.

Some sodium-alkali users are considering regeneration of scrubber liquor by treating the spent liquor with calcium hydroxide. This would actually give them dual alkali systems with the attendant advantage of eliminating a liquid-waste stream.

DUAL ALKALI

Table 3 shows that dual alkali systems have become the second most prevalent type of SO_2 control for industrial boilers. They may become the first choice as more sodium alkali systems are converted to dual alkali in the face of new regulations that may limit disposal of liquid wastes containing large amounts of dissolved salts.

Dual alkali processes, like lime/limestone slurry scrubbing, are throwaway systems. In the operation as a whole, lime is consumed to produce a wet solid waste (mainly calcium sulfite/sulfate) just as in lime slurry scrubbing. In addition, however, dual alkali systems require a small amount of sodium alkali makeup.

BISULFITE FORMED

A solution of sodium sulfite/bisulfite and sulfate in a scrubber will absorb SO_2 from the flue gas or other waste gas. Only the sulfite is active in absorbing SO_2, forming bisulfite as in the Wellman-Lord system:

$$\text{Absorption: } SO_3^{=} + SO_2 + H_2O \rightarrow 2\ HSO_3^{-} \quad (8)$$

The bisulfite-rich liquor, treated with lime in a reaction tank, regenerates active alkali for recycle to the scrubber:

$$\text{Regeneration: } 2\ HSO_3^{-} + Ca(OH)_2 \rightarrow SO_3^{=} + CaSO_3 + 2\ H_2O \quad (9)$$

$$SO_4^{=} + Ca(OH)_2 \rightarrow 2\ OH^{-} + CaSO_4 \quad (10)$$

The sulfate and sulfite precipitate as a hydrated mixed crystal, or as a gypsum phase ($CaSO_4 \cdot 2\ H_2O$) plus a hydrated mixed crystal, depending upon the

concentration of dissolved species. Also, depending upon solution concentrations, the mixed crystal is predominantly calcium sulfite, with up to about 25% calcium sulfate co-precipitated. Sulfite/bisulfite oxidation by oxygen in the flue gas produces sulfate in the system.

AUTHORITY PROVIDED

The 1970 and 1977 Amendments to the Clean Air Act provide the authority for EPA's current research, development, and demonstration program in the FGD area. EPA's FGD RD&D program is conducted by the Industrial Environmental Research Laboratory at Research Triangle Park, N.C. (IERL-RTP). The primary purpose of this program has been to improve, develop, and demonstrate reliable, cost-effective and environmentally acceptable FGD processes for reducing SO_x emissions from both existing and new stationary combustion sources.

EPA has been aided in this effort by at least two other federal organizations, the Tennessee Valley Authority (TVA) and the U.S. Bureau of Mines (USBM). For example, EPA's key program in the nonregenerable area is the lime/limestone prototype test program at TVA's Shawnee Steam Plant (near Paducah, Kentucky), and a major regenerable process (citrate) demonstration unit is being built at a St. Joe Minerals plant based on pilot palnt work by USBM.

FGD DEVELOPMENT—HIGH PRIORITY

In the federal energy/environment research and development program, FGD technology development has been given a high priority. Studies by EPA indicate that FGD is competitive in cost with advanced control methods, such as chemical coal cleaning and fluidized bed combustion; therefore, FGD should play an important role in controlling emissions at least until the end of the twentieth century.

This technology has progressed rapidly in part due to financial aid passing through the Federal interagency program. Several FGD studies, pilot plants, prototypes, and demonstration-scale facilities have been funded by EPA. Progress has been achieved in FGD development by the private sector; however the overall pace of development was increased by the initiation of the federal interagency effort.

Some of the more significant current federal FGD programs are summarized below.

An important part of the lime/limestone development effort involves the operation of a prototype scrubbing test facility, the TVA Shawnee Steam Plant. This versatile facility allows comprehensive testing of two 10 MW scrubber types under a variety of operating conditions. Bechtel Corporation of San Francisco designed the test facility and directs the test program. TVA constructed and operates the facility.

The major concerns of the utility industry to date regarding lime/limestone scrubbing have centered on scaling and plugging potential, the large quantities of waste sludge generated, and the high costs (capital and operating) of scrubbing. It is toward these areas of concern that the Shawnee program has been directed.

MAJOR OBJECTIVES

Major objectives of the original 2-year test program were (1) to characterize fully the effect of important process variables on SO_2 and particulate matter removal, (2) to develop and verify mathematical models to allow scaleup to full-scale scrubber facilities, (3) to study the technical and economic feasibility of lime/limestone scrubbing, and (4) to demonstrate long-term reliability. Later the Shawnee program was extended and the scope was expanded to investigate promising equipment and process variations to (1) minimize costs, energy requirements, and quantity (and improve the quality) of the sludge produced, (2) maximize SO_2 removal efficiency, (3) develop a design/economic study computer program, and (4) improve system control and operating reliability, especially in the mist eliminator area. Of particular interest were studies of forced oxidation, increased alkali utilization, and MgO or other additives to increase SO_2 removal efficiency and to force subsaturated gypsum operation. Subsaturated operation was first established in the EPA pilot FGD scrubber and later tested at Shawnee. The main advantage of subsaturated operation is reduced scaling in scrubber systems.

The Shawnee program has made major contributions toward improvement of lime and limestone scrubbing technology. The most significant results to date include

(1) demonstration that conventional lime/limestone systems can be operated reliably on a 10 MW level (two separate reliability problems have been identified—scaling and accumulation of soft mud-type solids—and methods to control each have been demonstrated), (2) mud-type solids deposition was shown to be a strong function of alkali utilization and at high utilization (greater than about 85%) these solids are much more easily removed, (3) equipment or process variations were demonstrated which individually improved alkali utilization, reduced costs, reduced sludge volumes, improved SO_2 removal efficiency, and favorably influenced the system chemistry, and (4) development of useful industrial tools, such as the design/economic study computer program and the computerized Shawnee data base. (Williams, 1977)

PILOT FGD SCRUBBER PROGRAM

The FGD pilot plant operated by Acurex at IERL-RTP consists of two scrubbers having a flue gas capacity of about 0.1 MW. They have been in operation since 1972 to provide in-house experimental support for EPA's larger, prototype scrubber test facility at the Shawnee Steam Plant. The IERL-RTP scurbbers have 1% of the capacity of the Shawnee prototypes and are 1/1000 the size of a small full-scale utility system. In addition to supporting Shawnee, the pilot plant also provides IERL-RTP with the capacity to independently evaluate new concepts in lime/limestone scrubbing technology. Many of the new concepts tested at Shawnee were first conceptualized and developed in the IERL-RTP pilot plant.

Currently, plans to modify the pilot plant, to allow testing of dual alkali systems, are being formulated. The pilot plant will be designed to test dual alkali systems with either lime or limestone regeneration. This allows the in-house pilot plant to support EPA's development and demonstration efforts in dual alkali technology as it has supported the lime/limestone program in the past.

INDUSTRIAL BOILER FGD SYSTEM

EPA has sponsored an 18-month test program at a lime/limestone industrial boiler FGD system installed to control SO_2 and particle emissions from seven small coal-fired heating boilers (approximately 23 MW equivalent, total) at the Rickenbacker Air Force Base near Columbus, Ohio. The FGD system was installed under contract between the Air Force and Research Cottrell, the U.S. licensee for the A. B. Bahco lime/limestone scrubbing process. This process was developed by A. B. Bahco, a Swedish company, and is reported to be particularly well suited for industrial boiler applications in that it is manufactured in standard sizes in the range of 5-50 MW equivalent and is adaptable to a high degree of automation. The application of the Bahco scrubber at Rickenbacker was the first such installation in the U.S. and the first anywhere on a coal-fired industrial boiler.

Although numerous mechanical problems have been encountered since startup in March 1976, the operation has improved to the extent that 95% availability has been demonstrated for approximately one-half year. There were no problems with scale formation or plugging with either lime or limestone and the system easily met or exceeded all emission and operating cost guarantees. A final report on this program is currently being prepared for general publication.

LIME SCRUBBING TEST PROGRAM

In the spring of 1976 a test program was initiated at the Paddy's Run plant of LG&E. Some of the objectives of the program were to compare carbide lime with ordinary commercial lime in the operation of a full scale system, to test the gypsum subsaturated mode of operation with both absorbents, and to investigate the effects of magnesium oxide and chloride addition to the system. Scrubber testing took place between the fall of 1976 and the summer of 1977, with Radian conducting the system analysis and evaluation.

It was found that, whereas subsaturated operation was achieved with carbide lime, similar operation with commercial lime did not give the same result. A major finding of the program was that carbide lime contained trace quantities of an oxidation inhibitor (suspected to be thiosulfate) which promoted subsaturated operation. Subsaturated operation was eventually achieved at LG&E with commercial lime with the addition of magnesium oxide in small quantities.

Final reports on both the LG&E scrubber testing and carbide lime characterization studies are being prepared for general publication.

DUAL ALKALI DEMONSTRATION

In September 1976, EPA contracted with LG&E for cost-shared, full-scale coal-fired utility demonstration of the dual alkali process at the 280 MW Cane Run No. 6 boiler. The demonstration project consists of four phases: (1) design and cost estimation, (2) engineering design, construction, and mechanical testing, (3) startup and performance testing, and (4) 1 year of operation and long-term testing. Construction is expected to be complete by the end of 1978, and testing will begin in early 1979.

The FGD system was designed by Combustion Equipment Associates and Arthur D. Little, Inc. and is currently being constructed by LG&E. In June 1977 a contract was established with Bechtel National, Inc. in San Francisco to design and conduct a test program to evaluate the system installed at LG&E.

A report on the Phase 1 preliminary design and cost estimate for the system was published in January 1978 (Van Ness et al., 1978). In addition to the design and cost estimate for the LG&E system, it also gives cost projections for similar hypothetical systems in the 500 and 1000 MW range. The report projects the LG&E system costs at less than $60/kW capital cost and less than 3 mills/kWhr annualized operating costs in 1976 dollars.

WELLMAN-LORD/ALLIED CHEMICAL SYSTEM

EPA and Northern Indiana Public Service Company (NIPSCO) have jointly funded the design and construction of an FGD demonstration plant using the W-L SO_2 recovery process and the Allied Chemical SO_2 reduction process to convert recovered SO_2 to elemental sulfur. The operational costs for the system will be paid by NIPSCO, and a comprehensive test and evaluation program, conducted by TRW Corporation, will be funded by EPA. The demonstration system has been retrofitted to the 115 MW, coal-fired unit 11 at the D. H. Mitchell Station in Gary, Indiana.

The demonstration program consists of three phases: Phase I, the development of a process design, major equipment specification, and a detailed cost estimate, was completed in December 1972. Phase II, the final design and construction, was completed by Davy Powergas, Inc. in August 1976.

Between August 1976 and August 1977 various problems involving both the boiler and the FGD system (primarily the boiler) delayed the acceptance tests, which eventually were conducted during the first half of September 1977. During the acceptance tests, system performance exceeded all performance criteria tested, including SO_2 removal (91% attained, 90% required), particle emissions, utility costs, sodium barbonate consumption, and sulfur product purity. The system is currently undergoing Phase III, long-term testing.

AQUEOUS CARBONATE DEMONSTRATION

EPA and Empire State Electric Energy Research Corporation (ESEERCO), a research orgainzation sponsored by New York's eight major power suppliers, have contracted to fund jointly the design and construction of a demonstration of Atomic International's sulfur-producing aqueous carbonate process. The demonstration is being retrofitted to a 100 MW boiler at Niagara Mohawk Power Company's coal-fired Huntley Station in Tonawanda, New York.

The demonstration will be in four phases. Phase I, the design and cost estimate, was completed in May 1977. Phase II, construction, is expected to begin by the end of 1978. Phase III, acceptance testing, and Phase IV, demonstration testing, will follow.

CITRATE DEMONSTRATION

EPA and USBM have entered into a cooperative agreement to pool funds and technical talents to demonstrate the citrate process, a regenerable sulfur producing process, which has been developed through pilot scale by USBM. A concurrent development program, carried out by an industrial consortium headed by Pfizer Chemical Company, also led to a pilot operation of the process. Based on the results of these two pilot programs, EPA and USBM have initiated the demonstration of this technology on a 50 MW coal-fired boiler at St. Joe Minerals Corporation in Monaca, Pennsylvania.

The demonstration will be in four phases. Phase I, the design and cost estimate, was completed in November 1976. Phase II, detailed design, procurement,

and construction, began in March 1977 and is scheduled to be completed in October 1978. Acceptance testing, Phase III, should be accomplished by the end of 1978, at which time a 1-year test and evaluation program, Phase IV, will be initiated.

OTHER FEDERALLY FUNDED PROJECTS

In addition to the current pilot and demonstration programs, previously discussed, other federally funded activities in the FGD area include the Shawnee TVA/EPA 150 MW dry limestone process demonstration, the 150 MW magnesium oxide process demonstration at Boston Edison, the Cat-Ox process demonstration at Illinois Power, the laboratory/pilot-plant/prototype development program conducted by A. D. Little (prototype at Scholz Plant of Gulf Power), the TVA pilot plant work at the Colbert Steam Plant, the General Motors industrial boiler FGD test program, and the Key West limestone scrubbing test program. These programs are now completed; some are considered successful, others are not.

In addition to the many development/demonstration projects, the federal programs also include several engineering and survey projects with the general purpose of developing information on FGD and associated areas for use by the government, the equipment and system developers, and the ultimate users of the technology. These projects, generally classified as FGD support studies and technology transfer activities, tend to complement each other. Included here are the TVA/EPA By-product Marketing Studies, the Reductant Gas Process Study, a reheat assessment study, sludge fixation and disposal studies, the TVA/EPA Comparative Economics of SO_2 Control Processes, and the EPA Surveys of Utility and Industrial Boiler FGD Systems, conducted by PEDCo Environmental.

CURRENT FGD STATUS

Application of FGD for control of fossil-fuel fired utility and industrial boilers has increased dramatically during the 1970's in response to the Clean Air Act and its amendments and the rapidly escalating price of fuel oil. The operating, under construction, and currently planned full-scale FGD systems are summarized in table 4.

It is interesting to note that about half of the tabulated utility units are in the planned category, while only about 7% of the total industrial boiler systems are in this category. This probably indicates that it is more difficult to accurately determine future plans for these smaller industrial boiler systems than for utility systems.

A recent report (Ando and Laseke, 1977) estimates that in Japan there were about 500 FGD plants, equivalent to about 28,000 MW in total capacity in operation at the end of 1977. About half of the gas processed was reported to be from utility boilers and the other half from industrial boilers and other sources.

TABLE 4
Summary of U.S. FGD systems

Status	Utility		Industrial Boiler		
	No. of Units	Capacity MW	No. of Units	Capacity 10^3 acfm†	MW, Equivalent
Operational	31*	10,550*	34	5,232	1,635
Under Construction	38	15,664	5	1,636	511
Planned	62	29,465	3	788	247
Totals	131	55,679	42	7,656	2,393

*Includes two utility prototype systems

†3200 acfm (actual cubic feet/min) = 1 MW

Sources: (Laseke, 1978; Tuttle et al., 1978)

MAIN CONCERNS

The main concerns about use of FGD are its dependability and costs. As with any other new technology, operating problems have become evident due both to design and manner of operation. As experience in design and operation has been gained, dependability of the systems has improved. Costs of FGD are considered high by some; however, it is obvious that cost is a relative parameter. It is estimated that the cost of operation of an FGD system at an electric utility plant may raise the cost of electric power generated by 10% to 20%. Whether this is reasonable and worthwhile can only be measured against the health benefits to our population.

Since initial operation of FGD systems, many of the problems that have been encountered have been eliminated or greatly alleviated. These include chemical scaling or deposition of solids on the scrubber internals, physical deposition of solids or plugging, corrosion and/or erosion of the scrubber components, and waste disposal. Scaling and plugging have been particularly troublesome in the scrubber mist eliminators. Corrosion/erosion and scaling have been primary problems, attacking in-line steam tube reheaters.

Control of process chemistry has been the major tool in eliminating scaling problems. In lime/limestone systems, gypsum scaling is a major concern. By maintaining the system liquors at a low level of supersaturation or actually subsaturated with respect to gypsum (see discussion of the Shawnee and LG&E programs), scaling is generally controlled.

EROSION AND CORROSION

Erosion and corrosion are generally reduced by intelligent selection of materials of construction. Due to the acidic conditions present in certain areas of the system, carbon steel is not well suited. Many scrubber manufacturers specify various stainless steel alloys or are lining their vessels with rubber, polyester, epoxy and other polymer materials. In addition it has been found that fly ash collected in wet scrubbing systems contributes to erosion/corrosion of the systems; therefore collection of fly ash upstream of the SO_2 scrubber will also alleviate this problem.

In addition to solving scrubber operating problems directly, vendors and users frequently specify a certain amount of equipment redundancy or spare capacity as a method of dealing with problems. Thus if a problem occurs, the operator can shut down the troublesome component, and continue operating on the standby component. This concept can be applied to small individual components such as instruments or pumps or to entire subsystems such as scrubber modules. For example, a 500-MW scrubber system designed with one-third redundancy might consist of four equal 167-MW scrubber modules.

INDICES OF DEPENDABILITY

Many parameters can be defined and calculated as indices of a system's dependability and each is probably suited to a slightly different viewpoint. Four such indices are discussed in the EPA Utility FGD Survey reports (Laseke, 1978) and are defined below:

$$\text{Availability} = \frac{\text{Hours the FGD system is available for operation}}{\text{Hours in the period}}$$

$$\text{Operability} = \frac{\text{Hours the FGD system was operated}}{\text{Boiler operating hours in the period}}$$

$$\text{Reliability} = \frac{\text{Hours the FGD system operated}}{\text{Hours it was called upon to operate}}$$

$$\text{Utilization} = \frac{\text{Hours the FGD system was operated}}{\text{Hours in the period}}$$

AVAILABILITY IMPROVED

The dependability of FGD systems for which data were available is plotted as a function of startup date in figure 4. There is considerable scatter in the data; however, a correlation coefficient for the least-squares linear plot indicates that the plot is statistically significant (Laseke and Devitt, 1977). The graph indicates a general trend of improved dependability of FGD systems as experience is gained. Specific data points indicate that availability or operability (either is plotted as data

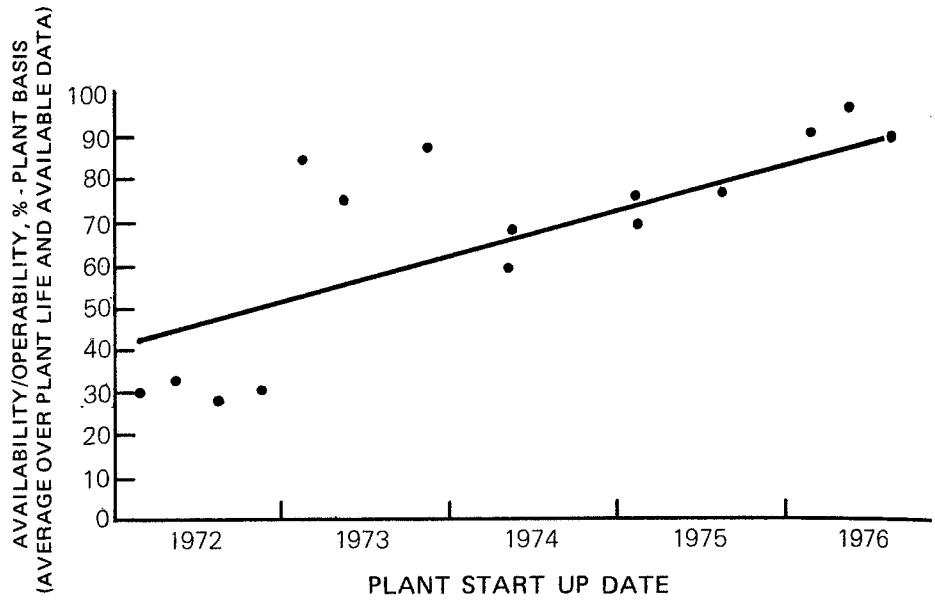

FIGURE 4—*Cumulative FGD system dependability (expressed in terms of operability or availability factors) versus plant startup date*

Source: (Laseke and Devitt, 1977)

are available) improved from about 30% in 1972 to about 90% for some of the units started up in 1976.

COSTS

So many factors affect the costs of installing (capital cost) and operating (annualized operating cost) FGD systems that it is difficult to arrive at a single accepted set of figures. Some of the factors affecting capital costs are type of system, design efficiency, materials of construction, process variation, extent of redundancy, site specific requirements, new or retrofit, size of system, and method of disposal of wastes. Likewise, some factors affecting annualized operating costs are interest charges on the capital cost of the system, fuel sulfur content, removal efficiency, cost of labor, cost of reagents, by-product credit, hours of operation of the boiler, and life expectancy of the system.

In the electric utility industry, capital costs are expressed in cost per unit of plant capacity ($/kW) and annualized operating costs are expresssed in cost per unit of energy output (mills/kWhr), so that plants can be compared on the same basis. The annualized operating cost can be viewed as the additional cost of production of a kilowatt-hour of energy attributable to the FGD system. It includes capital cost by amortizing the initial investment for the FGD plant over the expected life of the plant and allocating a portion of this cost to each unit of energy output.

Two basic approaches may be taken in an attempt to project FGD costs: (1) use actual costs for systems already operating, and (2) use engineering design and cost estimating techniques (based to some extent on experience) to arrive at generalized costs based on given sets of conditions.

The EPA Utility FGD Survey (Laseke, 1978) reports costs for 20 operating utility systems (one system was dropped as unreasonably low in cost). These costs are reported as submitted by the utilities and thus are not on a common basis (e.g., some operating costs do not include amortization of capital; others may include system modification costs). In addition, the reported costs are generally given for the years in which the plants were constructed, and thus do not take into account rising construction costs. A summary of these reported costs by system type, with ranges and averages, is given in table 5.

TABLE 5
Reported costs of operating utility FGD systems

System Type (Number Reported)	Size, MW* Range	Size, MW* Avg	Capital Cost, $/kW Range	Capital Cost, $/kW Avg	Operating Cost, mills/kWhr Range	Operating Cost, mills/kWhr Avg
Limestone (7)	115-1420	559	23-102	60.9	0.3-2.2	1.21
Lime (7)	64-1650	468	38-151	82.5	2.0-5.9	4.78
Fly Ash Alkali (2)	450-720	585	71-84	77.5	0.26	0.26
Soda Ash (1)	250	250	44	44	—	—
Wellman Lord/Allied (1)	115	115	129	129	8.1	8.1
MgO† (1)	108	108	137	137	4.7	4.7

*Separate FGD systems located at the same plant are reported combined.

†Figures for size and capital cost are adjusted. The operating MgO system reported is controlling 108 MW of flue gas from a 316 MW boiler. The remainder of the flue gas is scrubbed for particulate matter only.

TABLE 6
TVA projected capital and annualized operating costs*

System Type	Size, MW	Capital Cost, $/kW	Annualized Operating Cost, Mills/kWhr
Limestone	200	88.4	4.20
	500	68.4	3.41
	1000	51.4	2.74
Lime	200	79.9	4.54
	500	61.1	3.65
	1000	44.9	2.94
MgO	200	95.6	5.03
	500	71.7	4.02
	1000	53.0	3.26
Wellman Lord/Allied	200	112.0	6.60
	500	84.8	5.37
	1000	64.2	4.46

*Basis:

1. New coal-fired power plant, 3.5% S coal, midwest plant location.
2. Average cost basis 1977. Construction 1975-1978.
3. Minimum process storage and only pumps spared.
4. Working capital is included in total investment.
5. For throwaway systems, sludge disposal in on-site clay lined pond.
6. 30-year plant life, 7000 hr/year operation.
7. Byproduct credit and sludge fixation costs excluded.
8. 90% SO_2 removal.

COSTS COMPARISON

Generalized costs for most of the FGD systems now in use have been projected by TVA (McGlamery et al., 1976), using a given set of assumptions. Several of these projected costs are given in table 6 for comparison with reported actual costs; however, due to the many factors that affect costs and the non-common basis, perfect agreement should not be expected. Nevertheless, the average reported capital cost for operating limestone systems (559 MW average capacity) is only 11% lower than the TVA generalized cost for a 500 MW unit. The annualized cost, however, is off by a factor of about 3, possibly due to the fact that some of the reported systems do not include amortization of capital and working capital which may account for more than half of the annualized cost. For the lime systems, the average reported actual cost (468 MW average capacity) is 35% higher than the TVA estimate for a generalized 500 MW lime system, and the average reported annualized operating cost is 31% higher than the generalized cost. It should be noted that the TVA costs are all for new systems, while the reported actual costs average new and retrofit systems.

FGD COST INCREASES

Based on a cost for generation of electric power of 3¢ per kWhr and the TVA projected annualized operating costs for new 500 MW FGD plants in 1978, the percentage increases in cost for generation of electric power attributable to FGD are 11% for a limestone system, 12% for a lime system, 13% for a magnesium oxide system and 18% for a Wellman-Lord/Allied Chemical system.

In the past, fuel consumption has grown at a high rate in the United States. Production of electricity for example was growing at about 7% annually (or doubling every 10 years) before the Arab oil embargo in 1973. Since then, there has been a reduction in the growth of fuel consumption somewhat due to conservation and improved efficiency.

According to an energy use projection model proposed by Data Resources, Inc., the national energy consumption for the year 2000 will be about double what it was for 1975. Data from this model are shown in table 7. (Gilleland, 1978)

CONSERVATIVE ESTIMATE

This could very well be a conservative estimate, in that it is based on a Gross National Product increase of 3.7%/yr and only a 3%/yr energy consumption increase between 1975 and 2000. It is interesting to note that the increase in electricity generation in this model is 5.3%/yr compared with the 7%/yr in the past. This gives the result that, while energy consumption in the economy may double in the next quarter century, electricity production may almost quadruple. Assuming a continued push toward the use of coal to supply our energy requirements, it is logical to also assume that utilities will play a major role in increasing coal usage. The Federal Power Commission projects an electric utility growth rate of 5.56% through 1995. It also estimates that 50.3% of the generating capacity in 1995 would be fossil-fuel fired (Patel and Gibbs, 1978). Assuming a negligible number of oil and natural gas generating units in 1995, and given the fact that about 45% of our present

TABLE 7
United States consumption of energy by sector in 10^{15} Btu*

Consuming Sector	Year 1975	Year 2000	Average Annual Increase, %
Residential and Commercial†	13.8	15.6	0.5
Industrial†	18.4	28.4	1.8
Transportation†	18.5	28.3	1.7
Electricity Generation	20.7	75.3	5.3
Totals	71.4	147.6	3.0

*1 Btu = 252 cal = 1054.8 J

†Direct consumption of fuels

Sources: (1977 *National Energy Outlook,* Federal Energy Administration; *Economic Growth in the Future,* Edison Electric Institute)

generating capacity is coal-fired, it can be concluded that coal-fired power plants will produce about the same or a somewhat greater proportion of our electric power by the end of the century. All of this indicates a growing need for FGD.

Based on the EPA Utility FGD Survey (Laseke, 1978), taking into account specific known FGD systems in operation now, currently under construction, and those in various stages of planning, we can project about 56,000 MW of generating capacity being controlled by FGD systems by 1986. (See table 4.) As previously mentioned, there was at the end of 1977 about 10,000 MW of FGD controlled utility generating capacity.

NON-UTILITY BOILER APPLICATION

It is more difficult to project the non-utility boiler FGD applications since plans for construction are not announced as far in advance. In addition, many industrial boilers in operation and planned are too small to be covered by present federal and state NSPS.

With utility boilers, however, assuming an annual growth rate of 5.5% for coal-fired boilers through 1990 and further assuming that with revised NSPS (1978 revision), all new coal fired boilers will be controlled by FGD after 1983, the projected applications of FGD are 87,000 MW of control by 1985 and about 176,000 MW by 1995.

In October/November 1973, national public hearings on power plant compliance with sulfur oxide air pollution regulations were held in Washington, D.C. As a result of those hearings, EPA concluded there would be a need for 66,000 MW of power plant FGD control by the end of 1975, 73,000 MW by the end of 1977, and 90,000 MW by the end of 1980 (EPA, 1974) in order to meet NSPS and the other requirements of State Implementation Plans to achieve NAAQS. These figures assumed use of some low-sulfur coal and some redistribution of low-sulfur coal supplies.

POWER PLANT FGD CONTROL

Figure 5 shows a plot of the growth of utility FGD application between 1968 and 1977, together with projections for known currently planned FGD applications and projected application of FGD, assuming all coal-fired boilers would be controlled after 1983. Also shown in figure 5 is the projected need for FGD expressed in the 1973 national public hearings. The plot shows that we now fall short of the 1973 projected requirements and will probably continue falling short unless application of FGD increases dramatically as is the case in the projection, assuming that all new coal-fired power plants be controlled by FGD after 1983. This projection would be reasonable with revised new source performance standards requiring 85%-90% SO_2 removal.

The projected increase in the use of high sulfur coal in the coming years will be accompanied by a corresponding increase in the emissions of sulfur oxides. Because of the limitations of the low sulfur coal and coal cleaning options, application of FGD technology is playing a critical control role since it provides the leading near-term option presently available for quickly reducing sulfur oxide emissions in compliance with the Clean Air Act Amendments.

ATTRACTIVE ALTERNATIVES

Several important emerging technologies including fluidized bed combustion will offer attractive alternatives to the use of FGD but will probably not make significant commercial impact prior to 1985.

The Federal Interagency FGD program in conjunction with the private sector has been instrumental in furthering the development, demonstration, and application of FGD technology. Utility application of FGD systems presently includes over 55,000 MW of capacity either in operation, under construction, or planned. Although some technical problems still persist at certain installations, the general dependability of FGD systems has steadily improved during the past several years as the technology has matured.

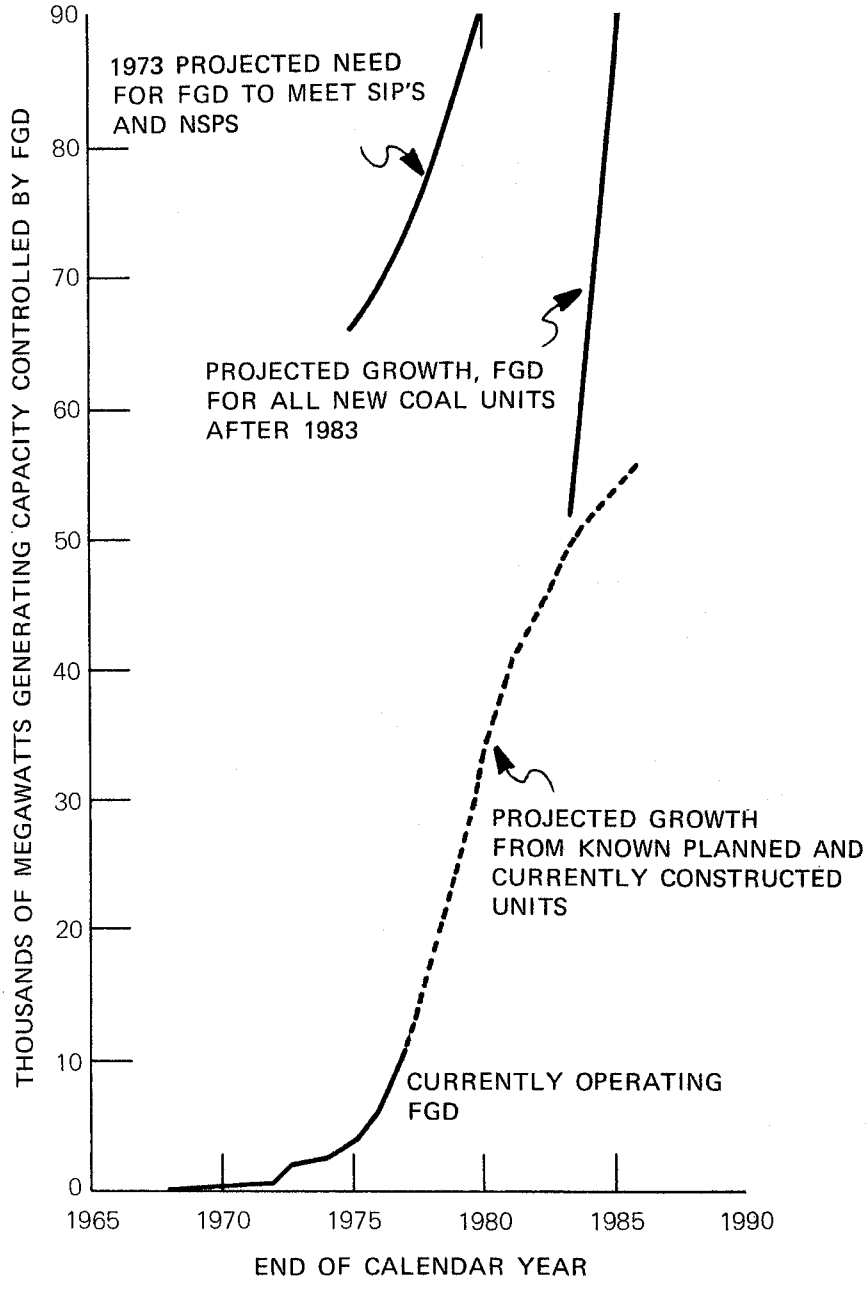

FIGURE 5—*Utility FGD, present application, projected growth, and need*

Sources: (Laseke, 1978 and EPA, 1974)

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DISPOSAL OF POWER PLANT WASTES

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SOLID WASTE GENERATION

Modern fossil-fueled, steam-electric generating plants present the full spectrum of potential environmental problems—pollution of air and water and the generation of large quantities of solid waste. Essentially all of the solid wastes, excluding bottom ash, are generated by the use of air pollution control devices—mechanical collectors (e.g., cyclones), electrostatic precipitators, baghouses, and scrubbers—to control emissions of fly ash and sulfur dioxide (SO_2). Although there are other wastes, such as those from water treatment systems, the quantities of these are small compared with the large amounts of ash and SO_2 scrubber waste produced.

COAL ASH PRODUCTION

Coal ash production by electric utilities is expected to reach 65 million metric tons/yr, including over 45 million metric tons/yr of fly ash, by 1980(1). U.S. electric utility commitments to SO_2 scrubbers, or flue gas desulfurization (FGD) systems, currently total over 55,000 MW of electrical generating capacity(2). Assuming that all of these plants will burn a typical high sulfur eastern coal and use a limestone scrubbing FGD system, approximately 29 million metric tons/yr (dry) of FGD waste, exclusive of fly ash, will be produced by the mid-1980's, when all of these plants are onstream.

Extensive utilization of coal ash is both technically and economically feasible. For example, fly ash can be admixed with portland cement clinker to as high as a 1:5 ratio (ash:clinker). With portland cement production in the U.S. currently around the 80 million ton/yr mark, this means that approximately one-third of the 1980 fly ash production *could be used* for this single application. However, current utilization of fly ash for all applications is just over 13 percent of production, according to the National Ash Association(3).

GYPSUM PRODUCTION

In Japan, over a million metric tons of gypsum were produced, primarily for use in wallboard and portland cement, by FGD processes in 1975(4). TVA has recently completed a study for EPA which indicates that approximately two-thirds of the gypsum requirements for the portland cement industry in the U.S. could be supplied by FGD systems *in a competitive market*(5). However, this use would consume only about 10 percent of the FGD waste expected to be produced in the mid-1980's. On the other hand, a shift to grass-roots wallboard plants near power plants (instead of near natural gypsum delivery points) could increase this low

percentage substantially. The wallboard industry currently consumes about 11 million metric tons of gypsum annually, almost 4 times the portland cement industry's annual consumption(5).

In any event, because of the *current* lack of market demand for most of the coal ash and FGD wastes, most electric utilities find that disposal of these wastes is the most attractive choice. However, once the decision is made in favor of disposal, the environmental and economic effects of the various disposal options have to be addressed.

COAL ASH DISPOSAL

Disposal of coal ash, either in ponds or landfills, has been practiced for many years. Ash ponds at power plants overflow to watercourses in numerous locations. Until recently, such practice was not of major environmental concern, very likely because the major chemical constituents of fly ash (i.e., those comprising the greatest percentage by weight) have a very low solubility. However, both existing and pending regulations on plant discharges and disposal of wastes on the land have caused a trend towards (1) dry ash handling and disposal in a landfill, (2) co-disposal of ash with FGD waste (either in a zero-discharge pond, with recycle of water to the plant, or as part of a FGD waste treatment process), or (3) a zero-discharge pond, with recycle of water to the plant.

Because of these concerns, considerable research and development was undertaken by governmental and private organizations. Results of these efforts are a greater understanding of the nature of FGD wastes, and a trend toward more environmentally acceptable and cost-effective methods for disposal, either 1) in ponds which are lined with clay or other low permeability material (to reduce the potential for water pollution) or 2) in a landfill, usually after chemical treatment of the waste to improve its physical stability and reduce its permeability.

Initially, FGD waste was disposed of in ponds, usually along with fly ash from the plant. However, since FGD systems have been in the limelight since early in the period of U.S. environmental awareness, very early in their commercial history there was concern about disposal of wastes from these systems because (1) the large amount of occluded water in the wastes or sludges made them physically unstable, (2) the quite variable physical and chemical properties of the wastes caused them to be an unknown material, and (3) the soluble and slightly soluble chemical constituents in the wastes caused them to be potential sources of water pollution.

COAL MINE RECLAMATION

Other methods of coal ash and FGD waste disposal are currently being considered, including the return of these wastes for use in coal mine reclamation. At least two plants, in North Dakota and Texas, are already disposing of the wastes in this manner. Disposal in the ocean, possibly by construction of an artificial reef of treated blocks of FGD waste and fly ash, is also being studied; the environmental acceptability of this method has not yet been demonstrated.

Federal legislation which applies to the handling and disposal of coal ash and FGD waste in ponds, landfills, coal mines, and the ocean is shown in table 1. The two most significant legislative acts (i.e., acts which have the greatest impact on disposal of these wastes) are 1) the Federal Water Pollution Control Act (FWPCA) Amendments of 1972 and 2) the Resource Conservation and Recovery Act (RCRA) of 1976.

FWPCA REQUIREMENTS

The FWPCA established a program whereby all discharges to navigable waters require a permit, issued by EPA or a state delegated the authority by EPA. The Act also required industries to use the best practicable control technology currently available (BPCTCA) to control pollutant discharges by July 1, 1977 and requires application of best available technology economically achievable (BATEA) by July 1, 1983.* EPA has established national effluent guidelines (based on BPCTCA and

*The FWPCA Amendments of 1977 made the effective date for BATEA a variable, depending on the chemical(s) being controlled.

TABLE 1
Federal regulatory framework for disposal of coal ash and FGD waste

Possible Environmental Impact	Legislation	Administrator
Surface Water Contamination	• Federal Water Pollution Control Act Amendments of 1972	• Environmental Protection Agency
Groundwater Contamination	• Resource Conservation and Recovery Act of 1976	• Environmental Protection Agency
	• Safe Drinking Water Act of 1974	• Environmental Protection Agency
Waste Stability/ Consolidation	• Dam Safety Act of 1972	• Army Corps of Engineers
	• Surface Mining Control and Reclamation Act of 1977	• Office of Surface Mining Reclamation and Enforcement
	• Occupational Safety and Health Act of 1970	• Occupational Safety and Health Administration
	• Federal Coal Mine Health and Safety Act of 1969	• Mining Enforcement Safety Administration
Fugitive Air Emissions	• Clean Air Act	• Environmental Protection Agency
	• Hazardous Materials Transportation Act of 1975	• Department of Transportation
	• Federal Coal Mine Health and Safety Act of 1969	• Mining Enforcement Safety Administration
	• Occupational Safety and Health Act of 1970	• Occupational Safety and Health Administration
Contamination of Marine Environment	• Marine Protection Research and Sanctuaries Act of 1972	• Environmental Protection Agency

BATEA) for existing power plants, as well as New Source Performance Standards (NSPS) for plants for which construction was initiated after the regulations were proposed.

EFFLUENT GUIDELINES

A summary of effluent guidelines and standards for steam-electric power plant ash ponds is given in table 2. The discharge requirements for total suspended solids (TSS) from fly ash ponds in many cases require control of lightweight cenospheres (floaters). In addition, a number of existing plants have to treat ash pond overflow to meet the pH requirement because most fly ashes are alkaline. (In some cases pH in an ash pond discharge can be 10 or above.) Reducing the pH by adding acid not only may be expensive, but also could result in an increase in certain trace metal concentrations. (Bottom ash ponds, on the other hand, typically have a relatively neutral pH, lower trace metals, and solids which settle more easily than fly ash.)

TABLE 2
Effluent guidelines and standards for power plant ash ponds

Discharge Stream	Controlled Parameter	BPCTCA†		BATEA†		NSPS†	
All Plant Discharges	pH	6.0-9.0		6.0-9.0		6.0-9.0	
	Polychlorinated biphenyls (PCBs)	zero		zero		zero	
		30-day average	daily maximum	30-day average	daily maximum	30-day average	daily maximum
Bottom Ash Transport Water	total suspended solids (TSS)	30	100	30÷12.5‡	100÷12.5	30÷20	100÷20
	oil and grease	15	20	15÷12.5	20÷12.5	15÷20	20÷20
Fly Ash Transport Water	TSS	30	100	30	100	zero	zero
	oil and grease	15	20	15	20	zero	zero

†All quantities except pH are in units of mg/1.

‡÷12.5 or ÷20 indicates the required degree of recycle (or number of cycles) of water;
÷12.5 means 8% blowdown allowed, while ÷20 means 5% blowdown allowed.

ACHIEVING ZERO DISCHARGE

Achieving zero discharge requires either complete recycle of water used to sluice fly ash to the pond or dry fly ash collection and disposal in a landfill. Dry collection and landfill disposal of fly ash is current practice. However, few fly ash ponds are operated with complete recycle of sluice water; possible operational problems caused by an increase in soluble constituents in the sluice water, for the most part, have been examined only theoretically.

Note that no guidelines or standards have been promulgated specifically for FGD systems (although the limitations for low volume waste streams are currently being applied). In general, it is assumed that there will be no direct discharge from these systems. However, because of operational problems which required extra water, some of the commercial FGD systems have required a discharge. Nevertheless, these systems were designed to operate closed-loop; i.e., with the only discharge of water being that associated with the FGD waste. In the more recent systems to come on line, this design feature is an operational fact.

MAJOR ENVIRONMENTAL CONCERN

With no direct discharge from FGD systems taking place, the major environmental concern associated with FGD waste disposal is the potential contamination of groundwater. This can also be said for an ash pond with no discharge, or disposal of ash in a landfill. The major federal legislation which addresses these potential problems in the RCRA.

Before enactment of the RCRA, there was no comprehensive federal authority to regulate disposal of wastes. This Act is designed to eliminate improper disposal of wastes by federally regulated disposal of hazardous waste§ and by state regulated (with federal assistance) disposal of nonhazardous solid waste. The Act defines a hazardous waste as a waste which poses a "substantial present or potential hazard to human health or the environment" if improperly managed.

§EPA may authorize state agencies to implement their own programs if they are deemed equivalent to EPA regulations for hazardous waste disposal.

CRADLE TO GRAVE CONTROL

The regulatory philosophy in the RCRA for hazardous waste is cradle to grave control. A manifest system will be used to track the movement of hazardous waste from the point of generation through transportation, treatment, and storage, to disposal, whether any of these steps are on- or off-site. Detailed requirements for hazardous waste disposal sites will be established by EPA. In addition, criteria and test methods to identify hazardous wastes will be established; a list of wastes known a priori to meet the criteria will be included in the regulations.

Although the RCRA called for promulgation of hazardous waste regulations by April 1978, they have been delayed. However, draft regulations have been prepared and are currently under review. The criteria for identifying hazardous wastes include characteristics such as flammability, corrosiveness, infectiousness, reactivity (e.g., strong oxidizing agents), radioactivity, and toxicity. The protocol for toxicity includes subjecting the waste to a toxicant extraction procedure (TEP), followed by a series of chemical or biological tests, including a test for bioaccumulation potential.

Currently, neither coal ash nor FGD waste has been declared a hazardous waste under the draft RCRA regulations. However, both fly ash and FGD waste are suspect because of the levels of certain trace elements in them. Nevertheless, testing (using the toxicity protocol) will be necessary before even a preliminary judgement can be made. It is clear, though, that, if any power plant waste is determined to be hazardous, it will be subject to a much more stringent set of regulations than nonhazardous waste.

STATE REGULATION

Nonhazardous solid waste will be regulated through individual state plans, the major point of which will likely be (according to RCRA) the elimination of open dumps; i.e., sanitary landfills must be used. Although protection of the environment must be a major consideration in the state plans, the implementation and enforcement of any regulation of disposal of nonhazardous wastes will be up to the state. The RCRA does not provide for federal enforcement of state regulations.

As shown previously, the FWPCA Amendments of 1972, the Safe Drinking Water Act of 1974, and the RCRA created the framework for the regulations which would eliminate or minimize chemical pollutant discharges into surface waters and groundwaters. Recognizing the need for better definition of approaches to meet the desire of this legislation, EPA in 1972 initiated a major program of research and development (R&D) in the area of FGD waste disposal. The primary objectives of this program were to better quantify any potential environmental problems associated with FGD waste disposal and to assess FGD waste disposal technologies. (Note that coal ash disposal alone was not investigated under this initial program. However, since FGD waste in most instances either contains fly ash—collected in the scrubber—or is mixed with ash prior to disposal, any thorough study of FGD waste—such as was conducted under this program—includes a study of fly ash. Because of this rather inseparable relationship between FGD waste and fly ash, the term flue gas cleaning [FGC] wastes was coined to cover both wastes. This term will be used in the remainder of this paper.)

WASTE AND WATER PROGRAM

In late 1974, plans were formulated to greatly expand EPA's FGC waste-related R&D efforts as part of the Energy/Environment R&D Program. These efforts included continuing improved quantification of potential environmental problems (of the 1972 program). They were also aimed at reducing costs, investigating a broader range of alternative waste disposal options, examining possible uses of the wastes. The Energy/Environment R&D Program involving disposal of power plant wastes is part of a larger program which involves control of waste and water pollution. The Waste and Water Program, as the larger program is known, is divided into three major areas:

- FGC Waste Disposal.
- FGC Waste Utilization.
- Water Utilization/Treatment.

Each of these program areas includes a number of projects; these are listed in table 3. The FGC Waste Disposal area of the Waste and Water Program consists of 17 projects, 5 of which are recently completed. The discussion which immediately follows describes some of the significant accomplishments of these projects.

FGC CHEMICAL CHARACTERISTICS

The chemical characteristics of FGC scrubber waste, to a large degree, have been quantified. FGC waste liquors have been shown to exceed drinking water standards for total dissolved solids (TDS), with high concentrations of calcium, sulfate, and chloride (and, in some cases, magnesium and sodium). In addition, concentrations of several trace metals have been noted in excess of drinking water standards. The chemical composition of FGC waste solids consists of calcium sulfite hemihydrate, calcium sulfate dihydrate (gypsum) and/or hemihydrate, and calcium carbonate, plus any fly ash collected in the scrubber. The percentage of each solid constituent is primarily a function of the alkaline additive (e.g., lime, limestone), the percent sulfur in the coal, and the manner in which the scrubber system is operated (e.g., whether forced oxidation is applied, whether fly ash is collected separately). Although fly ash has been shown to be a major contributor of trace elements to the

TABLE 3
Projects in the waste and water program

Project Title	Contractor/Agency
FGC WASTE DISPOSAL	
Assessment of Technology for Control of Waste and Water Pollution	Arthur D. Little, Inc.
§FGC Waste Characterization, Disposal Evaluation, and Transfer of FGC Waste Disposal Technology	The Aerospace Corporation
§-**Solid Waste Impact of Controlling SO_2 Emissions from Coal-Fired Steam Generators	The Aerospace Corporation
Lab and Field Evaluation of 1st and 2nd Generation FGC Waste Treatment Processes	U.S. Army Corps of Engineers (Waterways Experiment Station)
Ash Characterization and Disposal	Tennessee Valley Authority
§Studies of Attenuation of FGC Waste Leachate by Soils	U.S. Army Test and Evaluation Command (Dugway Proving Ground)
§Establishment of Data Base for FGC Waste Disposal Standards Development	Stearns, Conrad and Schmidt Consulting Engineers, Inc. (SCS Engineers)
Development of Toxics Speciation Model and Economic Development Document for FGC Waste Disposal	SCS Engineers
Shawnee FGC Waste Disposal Field Evaluation	Tennessee Valley Authority The Aerospace Corporation
Louisville Gas and Electric Evaluation of FGC Waste Disposal Options	Louisville Gas & Electric Co. (Subcontractor: Combustion Engineering, Inc.)
FGC Waste Leachate-Liner Compatibility Studies	U.S. Army Corps of Engineers (Waterways Experiment Station)
Lime/Limestone Wet Scrubbing Waste Characterization and Disposal Site Revegetation Studies	Tennessee Valley Authority

§Project Completed

**Direct Support of Regulation Development

continued

waste solids and liquor, separate collection of fly ash does not necessarily mean that concentrations of all these elements in the waste liquor will be insignificant (6).

PREFERENTIAL PARTITIONING

A compilation of existing data on coal ash, generated by TVA and others, was reported in early 1977 (7). This report showed that a number of potentially hazardous trace constituents tend to be concentrated in fly ash (as opposed to bottom ash). Further efforts are currently underway to better define this preferential partitioning of chemical constituents between fly ash and bottom ash, as well as the concentration of specific constituents as a function of particle size. This latter information would be especially significant in understanding the effect of the presence (or absence) of fly ash on FGD waste liquor composition.

FGC PHYSICAL PROPERTIES

The physical properties of FGC waste have been shown to vary considerably from system to system; chemical composition is related to, but does not adequately define, the size and type of the solid crystals. For example, in comparing the lime and limestone scrubber solids from the EPA/TVA Shawnee test facility, the

TABLE 3 (continued)

Project Title	Contractor/Agency
FGC WASTE DISPOSAL (Continued)	
§Development of EPA Pilot Plant Test Plan to Relate FGC Waste Properties to Scrubber Operating Variables	Radian Corporation
Dewatering Principles and Equipment Design Studies	Auburn University
Conceptual Design/Cost Study of Alternative Methods for Lime/Limestone Scrubbing Waste Disposal	Tennessee Valley Authority
Evaluation of FGC Waste Disposal in Mines and the Ocean	Arthur D. Little, Inc.
**Evaluation of Power Plant Wastes for Toxicity as Defined by RCRA	Radian Corporation Department of Energy (Oak Ridge National Laboratories)
FGC WASTE UTILIZATION	
§Gypsum By-Product Marketing Studies	Tennessee Valley Authority
Pilot Studies of a Process for Recovery of Sulfur and Calcium Carbonate From FGC Waste	Pullman-Kellogg
Fertilizer Production Using Lime/Limestone Scrubbing Wastes	Tennessee Valley Authority
§Use of FGC Waste in a Process for Alumina Extraction from Low-Grade Ores	TRW, Inc.
WATER UTILIZATION/TREATMENT	
Assess Power Plant Water Recycle/Reuse	Radian Corporation
Pilot Demonstration of Water Recycle/Reuse	Contractor Not Yet Selected
Characterization of Effluents from Coal-Fired Power Plants	Tennessee Valley Authority
§**Water Pollution Impact of Controlling SO_2 Emissions from Coal-Fired Steam Generators	Radian Corporation

§Project Completed

**Direct Support of Regulation Development

continued

limestone scrubber solids were found to be primarily individual platelets or rosette aggregates, while the lime scrubber solids were primarily spherical aggregates with somewhat better settling and dewatering properties. However, the chemical compositions of the solids from both scrubbers were quite similar to one another.

Regardless of the chemical composition, when FGC wastes are not adequately dewatered (or are allowed to rewet after dewatering), they tend to be physically unstable, or fluid, with little or no compressive strength. This physical instability of FGC wastes and the pollution potential of chemicals dissolved in the occluded water are the two major environmental concerns associated with disposal of these wastes.

PHYSICAL STABILITY

Several approaches for improving the physical stability of FGC wastes, as part of a disposal method, have been and continue to be studied. A basic feature of all approaches is the removal of sufficient water from the waste, either physically or chemically (or a combination of the two), to achieve physical stability. Occluded water is more easily removed physically if the solid particles are large enough to settle rapidly or provide a sufficiently porous structure for mechanical water removal (e.g., filtration). Difficulty in physical dewatering of FGC wastes is normally attributed to the small platelet crystalline structure of calcium sulfite. However,

TABLE 3 (concluded)

Project Title	Contractor/Agency
WATER UTILIZATION/TREATMENT (Continued)	
Treatment of Power Plant Wastes With Membrane Technology	Tennessee Valley Authority
Power Plant Cooling Tower Blowdown Recycle by Vertical Tube Evaporator With Interface Enhancement	University of California-Berkeley
§Treatment of Flue Gas Scrubber Waste Streams with Vapor Compression Cycle Evaporation	Resources Conservation Company
§Alternatives to Chlorination for Control of Condenser Tube Biofouling	Monsanto Research Corporation
**Environmental Impact of Alternatives for Control of Condenser Tube Biofouling	TRW, Inc.
§Bromine Chloride—An Alternative to Chlorine for Fouling Control in Condenser Cooling Systems	Martin Marietta Corporation
**Evaluation of Lime Precipitation for Treatment of Boiler Tube Cleaning Waste	Hittman Associates, Inc.
§**Assessment of Technology for Control of Toxic Effluents From the Electric Utility Industry	Radian Corporation
§** Field Testing/Lab Studies for Development of Effluent Standards for Electric Utility Industry	Radian Corporation
Effects of Pathogenic and Toxic Material Transported Via Cooling Device Drift	H_2M, Inc.
Assessment of Measurement Techniques for Hazardous Pollution From Thermal Cooling Systems	Lockheed Electronics Co. Northrop Corporation

§Project Completed

**Direct Support of Regulation Development

some forms of calcium sulfite crystals are more easily dewatered than others, suggesting the possibility of avoiding the less desirable forms by proper scrubber operation.

Currently, though, the relationship between scrubber operating parameters and the characteristics of the calcium sulfite crystals has not yet been defined adequately. However, certain qualitative observations, such as the comparison between lime and limestone scrubbers mentioned above, have already been made. For example, in limestone scrubbing systems, there appears to be an inverse relationship between sulfite crystal size and limestone additive stoichiometry (8). In addition, in tests with lime at Louisville Gas and Electric's Paddy's Run station, calcium sulfite crystals formed in a large (high retention time) tank were mostly individual platelets, while crystals formed in a small (low retention time) tank were primarily aggregates of platelets (9).

CRYSTAL NUCLEATION AND GROWTH

To better define the relationship between scrubber operation and calcium sulfite crystals, crystal nucleation and growth were studied. This study resulted in a computer model and a test plan for both completion of the model and defining the scrubber/crystal relationship (10). The tests will be conducted at the EPA-RTP pilot plant facilities later this year. Hopefully, the result of this testing will be the development of procedures for obtaining consistent, easily dewatered calcium sulfite solids.

A complementary approach to improving the quality of calcium sulfite solids would be to improve the performance of dewatering equipment. Laboratory pilot-scale testing using calcium sulfite waste from Louisville Gas and Electric has shown current commercial gravity settling devices (clarifiers, thickeners) to be far from optimum. A design approach has been developed whereby the clarification and thickening functions of the gravity settler have been separated into two pieces of equipment, each of which can be optimized for its function. The result is improved dewatering (thicker underflow) and satisfactory clarification (without using flocculants), with substantially smaller, less expensive equipment. Current plans are to demonstrate this design approach on a large pilot scale at TVA's Shawnee Steam Plant near Paducah, Kentucky. Testing should be underway by September or October 1978. A paper describing the laboratory pilot results will be presented later this month (11).

OXIDATION TECHNIQUES

One way to avoid the dewatering problems associated with calcium sulfite crystals in FGC waste is to use oxidation techniques to produce calcium sulfate or gypsum ($CaSO_4 \cdot 2H_2O$). Gypsum crystals are typically much larger and thicker than sulfite crystals; therefore they settle more quickly and trap less water upon settling. Oxidation of the calcium sulfite outside of the scrubber system, although feasible, is more expensive; oxidation within the scrubber loop is simpler and less expensive. This latter approach has been successfully tested at the laboratory and large field pilot level (12,13); commercial systems are now being offered by experienced suppliers.

Many utilities are currently choosing chemical treatment (sometimes called fixation) processes to physically stabilize their FGC waste. Field testing these processes under the EPA Waste and Water Program has shown that the treated waste exhibits significant structural improvement, at least a 50 percent reduction in major solubles (e.g., chloride) in the leachate, and an order of magnitude (or more) reduction in permeability (14). Another advantage of chemical treatment is that coal ash can be co-disposed of, along with the FGC waste. A coring rig on one of the treated waste disposal sites at TVA's Shawnee Steam Plant is shown in figure 1.

OTHER STABILIZATION/ DISPOSAL TECHNIQUES

Other stabilization/disposal techniques are being evaluated, such as the use of underdrainage and compacting of untreated FGC wastes, and the production/disposal of gypsum. A paper describing recent results of their evaluation is being presented later this month (15). In areas with appreciable rainfall, the underdrainage approach appears to require dividing the disposal area into several sections, i.e., over the life of the plant, the disposal would be accomplished one section at a time. For gypsum disposal in a pile, considerable maintenance may be required because of surface cracking from freeze-thaw cycles and/or erosion from rainfall (see figure 2) (15).

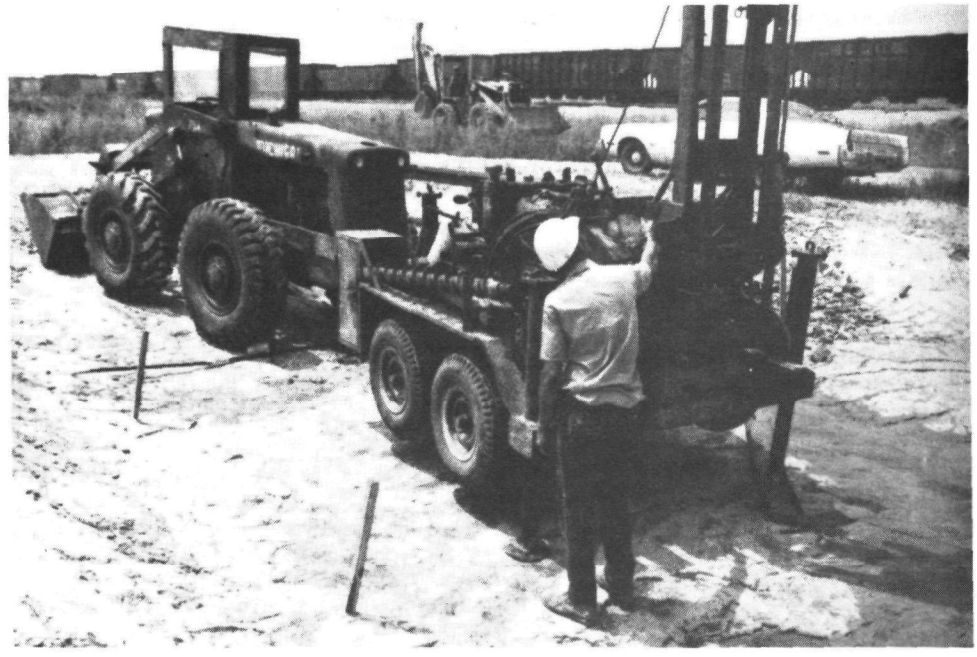

FIGURE 1—*Coring rig on FGC waste disposal test site at TVA's Shawnee steam plant*

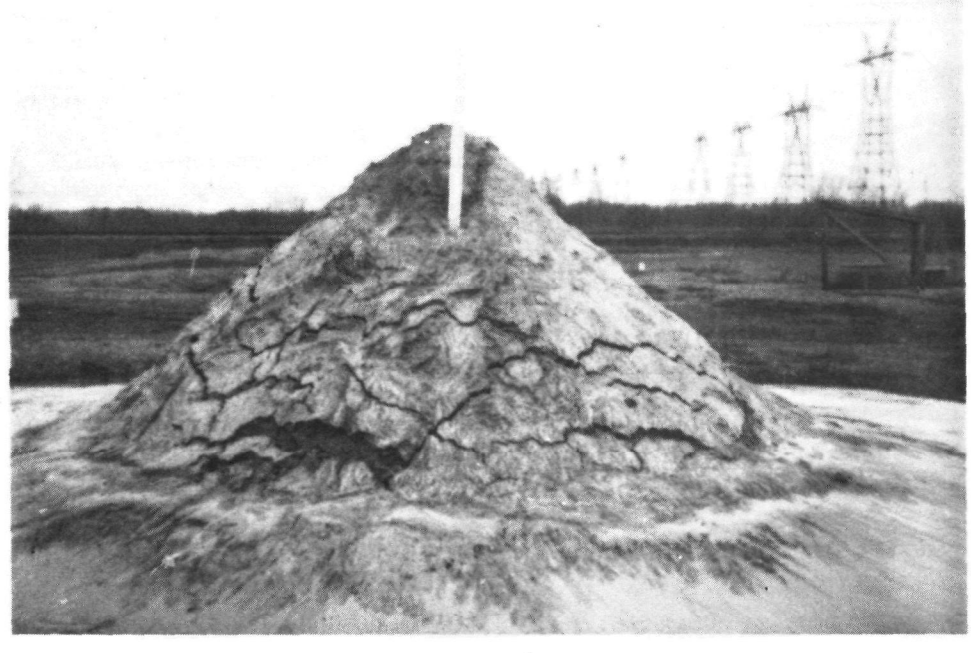

FIGURE 2—*FGC gypsum pile at Shawnee, showing freeze-thaw cracks and erosion*

COSTS

Along with the technical/environmental evaluation of alternative FGC waste disposal techniques, the costs of each technique have also been determined. Preliminary cost estimates (1977 $) for a typical high-sulfur coal-fired plant will be reported later this month; these show ponding costs of about $5-8 per metric ton (dry solids, including fly ash) and chemical treatment/landfill costs of about $10 per metric ton (same basis as ponding) (16). More detailed cost estimates (in 1980 $), also recently reported, show ponding costs of about $9 per metric ton and chemical treatment/landfill costs of about $14 per metric ton (16). (It should be noted that the $14 figure includes all dewatering equipment; the earlier $10 figure assumed the clarifier/thickener as part of the scrubber system. In addition, clarifiers were excluded in both ponding cost estimates.)

The $14 per metric ton cost converts to about 1.5 mills/kWhr revenue requirement; this compares to a total FGC system revenue requirement of about 5 mills/kWhr. Thus it is clear that the waste disposal costs are a major part of the FGC system costs and, further, that any significant savings in waste disposal costs will substantially reduce the total system costs.

OTHER EFFORTS

A number of the efforts described above (e.g., improving performance of dewatering equipment) are aimed at a reduction in disposal costs. Other efforts will be studied in the near future; e.g., using only the minimum quantity of fly ash required to chemically treat the FGC waste and marketing the excess, or using a combination of coal washing (for ash and sulfur removal) and FGC.

Another approach to reduce costs is to use disposal methods which avoid the need for a specially prepared disposal site (e.g., pond). Two methods currently under study are disposal in coal mines and in the oceans.

Coal-mine disposal of FGC waste has greatly interested engineers in the flue gas desulfurization industry for many years because of established means of transportation between the coal mine and the power plant and the need for material to fill the void left by mining of the coal. In addition, many plants may not have sufficient land area for on-site disposal. The same reasoning, of course, can be applied to coal ash alone. Preliminary technical/economic assessments conducted under the EPA Waste and Water Program indicated that active area surface mines are the most promising candidates for this disposal approach (17).

DISPOSAL IN AREA SURFACE MINE

FGC waste from the Milton R. Young Station of Minnkota Power Cooperative near Center, North Dakota, is currently being disposed of in an area surface mine near the plant. Ash from this plant has been disposed of in the mine for some time. A 2-year assessment of the environmental effects of this operation is being conducted by the University of North Dakota and the North Dakota State Geological Survey, under EPA sponsorship. Preliminary results of this effort are expected in late 1978. Successful demonstration of this disposal approach could make conversion to coal quite feasible even in areas where land for disposal is limited.

Preliminary costs of mine disposal were also determined; a wide range of from (in 1977 $) about $4 to about $10 per metric ton of dry solids, depending on treatment (if used) and transportation costs, were reported (17). More detailed costs of this disposal option are being prepared.

OCEAN DISPOSAL

Ocean disposal of FGC waste is also being assessed because many plants in the northeast may have difficulty switching to coal for lack of disposal sites; however, many of these plants do have access to the ocean. It was also recognized that the major soluble chemical constituents in FGC waste are found in relatively high concentrations in seawater. This assessment has identified several potential environmental problems, the major one of which is sulfite toxicity. It appears that these problems could be alleviated by either chemical treatment to a brick-like form (possibly creating an artificial reef) or oxidation to gypsum (followed by a widely dispersed disposal operation). Preliminary costs of this approach were estimated to be from (in 1977 $) about $4 to about $8 (treated) per metric ton of dry solids for disposal on the Continental Shelf; deep ocean disposal would be expected to add to these costs another $3 to $4 per metric ton (17). More detailed costs for this disposal method are being prepared. Pilot disposal simulation studies are underway to define the environmental effects of both untreated and treated FGC sludge disposal in the ocean.

As coal becomes the dominant fossil fuel for the generation of electric power, the environmental, technical, and economic problems associated with the handling and disposal of FGC wastes are anticipated to increase in prominence. A number of alternative solutions to these problems exist, but determining the viability of specific solutions requires consideration of factors that are specific to each plant situation. For example, an existing power plant with no FGD system may have to choose between the options of 1) recycling the fly ash sluice water, using side stream treatment for dissolved salts, or 2) converting to a dry ash handling system so that

WASTE DISPOSAL FOR SPECIFIC PLANTS

the ash can be used in a local cement plant. The options for specific plants will vary greatly, depending on things such as applicable regulations; land availability and cost; water availability, quality, and cost; geology of the plant site; coal characteristics (percent sulfur, ash, trace elements); and potential markets for wastes.

Obtaining the information required to identify available options and to allow rational choices to be made is the impetus behind the Energy/Environment R&D Program in power plant waste disposal. The results of these efforts, already described, when combined with existing commercial technology, form the bases upon which the regulations are established. These efforts are continuing; trends in the Energy/Environment Program as they relate to the regulatory programs, are discussed here. As previously mentioned, a report has been issued which summarizes and evaluates existing data on the characteristics of coal ash from studies made by the Tennessee Valley Authority (TVA) and others (9). TVA is currently characterizing fly ash as well as evaluating the effect of leachate from ash ponds at two of their plants. From the TVA efforts under the Energy/Environment Program, as well as from the efforts by the Electric Power Research Institute (EPRI) (18) and others, there is a considerable amount of data on coal ash. However, in order to fulfill the objectives of both the FWPCA and the RCRA, additional information is needed. Specifically,*the behavior of a variety of coal ashes should be studied in closed-cycle wet sluicing systems.* In addition, a variety of FGC wastes, including coal ashes alone, need to be tested according to the protocol proposed under the RCRA.

Results of testing under the RCRA could have a major effect on the Energy/Environment Program if a number of FGC wastes are determined to be hazardous; *additional testing of these wastes using the RCRA protocol would probably be required.* A hazardous tag on FGC wastes would also have a significant effect on the electric utility industry, as well as those industries which currently use these wastes for construction materials.

LONG-TERM DATA NEEDED

The effect which the RCRA will have on the various FGC waste disposal options which have been applied commercially and other options which continue to be studied is not yet clear. As described previously, the environmental effects of various approaches for FGC waste disposal (on land) have generally been evaluated by determining, as quantitatively as possible, the capability of a particular approach to minimize or eliminate groundwater and surface water pollution. For example, leachate generated by the waste in a specific situation was usually compared with drinking water or other water quality criteria; physical characteristics such as permeability were measured to determine the quantity of leachate which might be expected. On this basis, satisfactory disposal approaches would include lined ponds†† or well-managed landfills (of chemically treated waste). This general evaluation procedure has also been applied to the assessment of disposal in coal mines. All three of these methods—ponding, landfill, and mine disposal—are currently in commercial use; mine disposal of FGC waste has only taken place within the past year. *Long-term data on the environmental effects of these disposal operations are needed.*

ARTIFICAL REEF CONSTRUCTION

Another FGC waste disposal option currently being studied is ocean disposal. If proved to be environmentally acceptable, this option could be used by utilities in coastal states in which the availability of land for disposal sites is a major problem. A number of electric utilities in the Northeast have shown great interest in FGC waste disposal in the ocean. A variation of this option, currently proposed by the New York State Energy Research and Development Authority (NYSERDA), is artificial reef construction using large blocks of chemically treated FGC wastes. Ocean disposal has primarily been studied on a laboratory scale, although some small-scale field tests have been conducted by the State University of New York at Stony Brook. The effects on water chemistry as well as on marine life—through bioassay—are being evaluated. Current EPA ocean disposal regulations are being used as a benchmark in assessing test results. *A considerable amount of testing remains to be done.*

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††Typical ponding operations do not appear to be a desirable ultimate disposal method because of difficulties in pond reclamation and greater potential (than landfills) for groundwater contamination.

ESTIMATE OF COSTS

As environmentally acceptable FGC waste disposal options emerge, a reasonably accurate estimate of their costs must be determined; costs relative to alternative options are particularly significant. Costs of all the options just discussed have been, or are currently being, estimated. TVA is conducting detailed conceptual design/cost studies of a number of on-land disposal alternatives. As technological improvements occur, or as disposal options emerge which appear to be more economically attractive, *this cost data base will need to be expanded.* In addition, the effects of pending RCRA regulations will need to be determined.

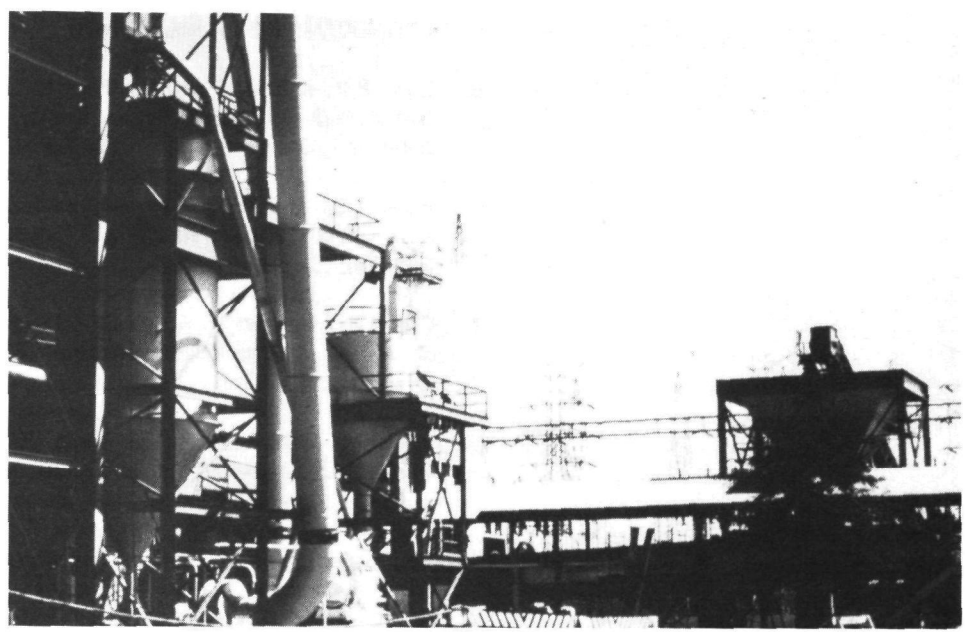
Improvements to FGC waste disposal technology to reduce costs so far have primarily concentrated on FGD scrubber system modifications to 1) improve alkali (e.g., limestone) feed utilization, and 2) reduce FGC waste volume by forced oxidation to calcium sulfate or gypsum. Studies are underway to evaluate both the environmental effects and the costs of gypsum disposal. Other cost reduction efforts have been directed at 1) defining FGD system operating parameters which will result in reasonably consistent, easily dewatered calcium sulfite solids, and 2) improving the performance of equipment for dewatering FGC wastes high in calcium sulfite. The first of *these efforts will require a better understanding of nucleation and growth of calcium sulfite crystals* in scrubber systems, a difficult task. The second effort is based on laboratory pilot studies which have shown the feasibility of major improvements over commercial designs, including a greater degree of dewatering at lower cost. However, *field pilot studies are required* before the concepts can be utilized commercially. One of the problems the field tests will address is the capability of the equipment to satisfactorily operate when variations occur in the waste properties.

CONCLUSIONS

A major effort in the Energy/Environment Program is underway to characterize solid wastes from power plants and to develop technology to minimize the potential adverse environmental impacts of these wastes. The program has achieved significant results in a number of areas.

Flue gas cleaning (FGC) wastes have been characterized physically and chemically; a variety of disposal options have been identified, including detailed costs associated with these options. Disposal of these wastes in coal mines is economically attractive and, therefore, is being investigated through lab and field tests. Methods for achieving major cost reductions in FGC waste disposal have also been identified and are making their way into the process supply market; these include oxidation to gypsum and improved dewatering equipment.

Results of these efforts are providing a technical data base for the regulation of the disposal of power plant wastes.



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CONTROL OF NITROGEN OXIDES FROM COMBUSTION

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ADVERSE EFFECT ON HUMANS

Nitrogen oxides (NO_X), principally nitric oxide (NO) and nitrogen dioxide (NO_2), are atmospheric pollutants having the greatest potential for adverse effects on human health and welfare. Human-activity originated emissions result in NO_X concentrations in urban atmospheres that are 10 to 100 times higher than those from natural sources in nonurban areas. Fuel combustion in equipment contributes about 99 percent of technology-associated NO_X emissions. For most equipment, about 95 percent of the NO_X is emitted as NO and 5 percent as NO_2. In the atmosphere, NO_X enters into complex photochemical reactions with hydrocarbons and sulfur oxides and results in the formation of undesirable secondary species, with a shift of residual NO to NO_2. The adverse effects of NO_2 and other pollutants on humans, animals, vegetation, and exposed materials were among the factors which led to passage of the Clean Air Act of 1970. With respect to NO_X, this Act empowered the EPA (1) to establish primary and secondary National Ambient Air Quality Standards (NAAQS) for NO_2, (2) to require a 90-percent reduction in NO_X emissions from light duty motor vehicles, (3) to establish New Source Performance Standards (NSPS) for stationary sources, (4) to set up mechanisms to ensure compliance and enforcement, and (5) to provide research, development, and demonstrations of new and improved, commercially viable methods for the prevention and control of pollution from the combustion of fuels. The Clean Air Act Amendments of 1977 require EPA (1) to revise the NAAQS for NO_2 to consider short term effects (not more than 3 hours), (2) to implement a revised level of automotive NO_X control, (3) to require NSPS based on use of the best technological continuous emission controls, and (4) to promulgate regulations for prevention of significant deterioration of air quality. The Amendments also require that any conversion of sources to coal firing be environmentally acceptable.

This section of the paper provides information on combustion generated NO_X which is necessary for a complete understanding of the EPA NO_X control program.

EMISSION SOURCES

In the United States in 1974, NO_X emissions from human activity were estimated to be about 23 metric tons per year. Of this amount, 46.1 percent was estimated to come from mobile sources, 50.4 percent from stationary combustion sources, and the remainder from miscellaneous sources. The stationary source NO_X can be further subdivided by the type of source and fuel burned to give a better picture of the complexity of the problem. Table 1 represents the major divisions, but each source can be further subdivided by equipment design.

Existing regulations for NO_X fall into three categories: (1) ambient air quality standards, (2) stationary new source performance standards, and (3) mobile source standards.

TABLE 1
Major sources of NO_x

Source	Percent of Stationary Source NO_x
Utility Boilers – Coal	31.0
Utility Boilers – Oil and Gas	17.5
Package Boilers – Coal	5.9
Package Boilers – Oil and Gas	14.5
Warm Air Furnaces – Oil and Gas	2.8
Engines	20.0
Miscellaneous Sources	8.3

AMBIENT AIR QUALITY STANDARDS

To provide a basis for ambient air quality standards, available information was compiled and analyzed by an advisory committee. The areas covered included not only atmospheric chemistry, but also effects on materials, plants, and humans. A major conclusion was that the ambient concentration of NO_2 should be used as the basis of the standards. This was based on two main points. First, NO is rapidly converted to NO_2 in the atmosphere and, second, toxicology studies of NO and NO_2 indicate that NO_2 is the more hazardous form at concentrations found in the atmosphere.

As required by the Clean Air Act of 1970, National Ambient Air Quality Standards (NAAQS) for NO_2 were set in 1971. The primary standard is based on a level required to protect the public health and the secondary, to protect the public welfare from any known or anticipated adverse effect associated with the presence of air pollutants in the ambient air. Both standards were set at 100 $\mu g/m^3$ for NO_2.

STATIONARY NSPS

The Clean Air Act of 1970 required the EPA Administrator to set standards for new sources. The only source category for which Federal New Source Performance Standards (NSPS) are in effect is steam generators with a thermal input greater than 73 MW (250 X 10^6 Btu/hr). The initial NSPS for this class of equipment burning gas, oil, and coal (except lignite) became effective in 1971. The lignite standard, which was promulgated in 1978, is based on firing method; however, cyclone-fired boilers are only allowed for high sodium fuels. The NSPS are summarized in table 2.

The basis of these regulations is combustion modification to reduce NO_x formation, and compliance is achieved with staged combustion and/or altered burner designs.

TABLE 2
New source performance standards for steam generators

Fuel	NSPS (NO_x as NO_2)	
	ng NO_x/J	lb $NO_x/10^6$ Btu
Coal (except lignite)	300	0.7
Lignite		
Pulverized Fired	260	0.6
Cyclone Fired	340	0.8
Oil	129	0.3
Gas	86	0.2

MOBILE SOURCE STANDARDS

Although the NO_x control strategy in the Clean Air Act of 1970 was predicated primarily on high level control standards for the automobile, the 1977 Amendments have eased the restrictions. The original standard of 0.24 mg/m (0.4 g/mile) for 1978 has been retained only as a research goal. This relaxation of the automotive standard places increased emphasis on control of stationary source NO_x emissions. From the current standard of 1.9 mg/m (3.2 g/mile), the standard is reduced to 1.2 mg/m (2.0 g/mile) through the 1980 model year, and to 0.6 mg/m (1.0 g/mile) for 1981 and later.

PENDING REGULATIONS

There are pending regulations based on the Clean Air Act Amendments and on establishment or revision of NSPS for stationary sources. Each major area is discussed briefly.

The Clean Air Act Amendments require that the EPA Administrator promulgate a short term NO_2 ambient air quality standard unless he finds that there is no significant evidence that such a standard is needed to protect public health. The Act also provides that the period of such a standard should be from 1 to 3 hours. A review of acute short term NO_2 effects and the prevalence of critical levels of NO_2 in the atmosphere is underway and will be used as the basis of a decision on the revision of the existing standard.

There are two areas under consideration for new or revised NSPS for steam generators. First, the available data are being reviewed to identify demonstrated technology for industrial boilers (less than 73 MW thermal, but greater than a not-yet-established lower limit). The draft review document proposed a standard of 260 ng/J (0.6 $lb/10^6$ Btu) for bituminous coal and 220 ng/J (0.5 $lb/10^6$ Btu) for lower grades of coal. Second, the data on NO_x control for steam generators greater than 73 MW thermal (utility and large industrial boilers) are being reviewed as the basis for a revision of the current NSPS.

NSPS for both gas turbine and reciprocating engines are also being prepared. The gas turbine standard has been proposed at 75 ppm (at 15 percent O_2) for nitrogen-free fuels, with a stepped approach for fuel nitrogen up to a maximum of 125 ppm (at 15 percent O_2) for fuels with over 0.5 percent nitrogen.

POLLUTANT FORMATION

The primary emphasis in EPA's NO_x control technology development program is on combustion modification to prevent pollutant formation. To optimize the control technology for any given fuel, it is necessary to understand the mechanisms by which NO_x is formed and destroyed during combustion. Two distinct sources of NO_x, identified by the terms thermal NO_x and fuel NO_x, are discussed below. In addition, it is necessary to ensure that control technology does not adversely affect other pollutants or system efficiency. A brief discussion of these factors is also given below.

THERMAL NO_x

The fixation of a small fraction of the molecular nitrogen in the combustion air results in the formation of thermal NO_x. Since the activation energies of several of the formation reactions are high, the rate of formation of thermal NO_x is strongly temperature dependent. Thermal NO_x is formed during the combustion of all fuels in the regions of peak temperature that occur in all diffusion flames.

FUEL NO_x

The oxidation of nitrogen compounds chemically bound in the fuel molecule produces fuel NO_x. Since significant amounts of nitrogen (0.1 to 2 percent by weight) are found in all heavy fuels (residual oil and coal), fuel NO_x is a major contributor to the total NO_x from these fuels. Based on small scale experiments, 50 to 90 percent of the total NO_x from residual oil and coal is fuel related, even though it is well established that only a fraction of the fuel nitrogen is converted to NO_x, with the balance forming molecular nitrogen. The main factor affecting the conversion to NO_x is oxygen availability. The reactions appear to be relatively insensitive to temperature.

In general, a well designed boiler that is properly maintained and operated produces low levels of carbonaceous pollutants (CO, HC, carbon particulate). Other pollutant emissions (SO_x and inorganic particulate) from these sources are less a function of operation than of fuel composition and, in some cases, firing mode. On

the other hand, stationary engines can emit significant amounts of CO and hydrocarbon. Since the combustion control techniques for NO_x require changes in the way fuel is burned, they also present the opportunity for optimizing the total combustion process to achieve low levels of other pollutants.

COMPLEX PROBLEM

Of all the fossil fuels currently used in the United States, coal is not only the most abundant, but also presents the most complex problem of combustion and emission control. In addition, there is no typical coal: properties of a given coal can vary within the same seam. In spite of the wide ranges of composition that affect both the way the fuel burns and the pollutant emissions, a general picture of the important pollutant formation mechanisms can be presented by discussing phenomena that occur for a single pulverized coal particle. For combustion in practical systems, pulverized coal is mixed with a fraction of the combustion air (called primary air) and introduced into the furnace through the fuel injector of the burner. The amount of primary air is determined by both the fuel properties and burner design; however, it is normally 10 to 30 percent of the theoretical air required for complete combustion. The actual stoichiometry under which any fuel particle reacts will depend on the fuel and air mixing history. The sequence of events occurring for a single coal particle is shown in figure 1, which indicates two combustion modes (volatile evolution and char burnout) as discussed below. Although every coal particle undergoes similar types of processes, the environment under which pollutant formation reactions occur is governed by the aggregate coal particle cloud reaction history.

VOLATILE EVOLUTION

As the coal particle is heated by radiation and convection, the volatile portion of the coal substance begins to evolve. The initial products contain carbon and hydrogen and probably represent side chains and cross linkages between the ring structures in the coal molecule. These initial volatiles react with the surrounding air and partially deplete the available oxygen. As the temperature increases and the ring structures begin to fragment, nitrogen containing intermediates (designated XN) are evolved and begin to react with oxygen to form NO_x. Subsequent reactions of XN with NO_x and other species produce molecular N_2. The amount of nitrogen evolved in the volatile fraction depends on the ultimate particle temperature; the fate of the XN compounds depends on the local stoichiometry around the particle. For fuel lean conditions, a substantial fraction will be converted to NO. For fuel rich

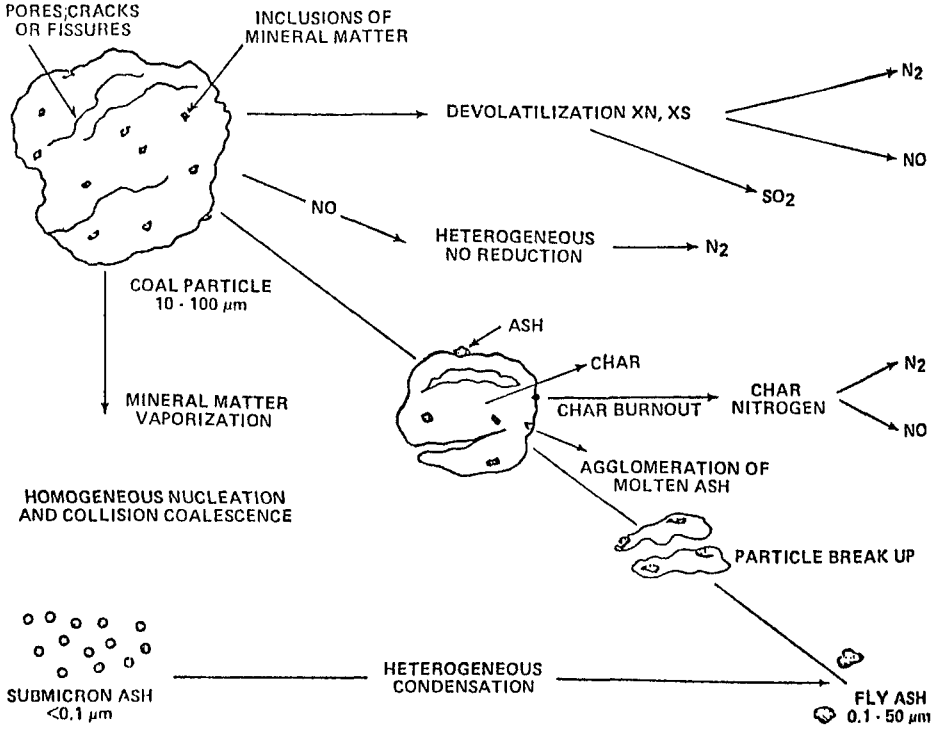


FIGURE 1—*Pollutant formation during pulverized coal combustion*

environments, the production of molecular nitrogen increases until an optimum stoichiometry is reached; then, for even richer stoichiometries, the residual nitrogen species (XN) are retained unreacted and burn in leaner secondary combustion zones. It also appears that some of the NO_x formed can be reduced to N_2 by heterogeneous reaction with coal particles or char. During this devolatilization process, inorganic and organic sulfur species are released as sulfur intermediates (designated XS). In general, the XS species are quantitatively converted to sulfur oxides (SO_2 or SO_3) at some point during the combustion process; however, these species may undergo different reactions or may influence other reactions in this devolatilization zone. Two examples may be cited. First a significant amount of the sulfur in some western coals can be retained in the ash, probably as a sulfate; however, this retention may be enhanced if the sulfur could be captured during devolatilization. Second, sulfur species can influence the conversion of nitrogen species (XN) to NO and other products; therefore, the history of sulfur intermediates relative to nitrogen intermediates (XN) is important in the devolatilization zone. Finally, a portion of the mineral matter from the coal is vaporized in the devolatilization zone and subsequently condenses and/or coalesces to form submicron particulate. The temperature and stoichiometry during devolatilization probably influences the potential for fine particulate formation.

CHAR BURNOUT

Following devolatilization, the residual coal matter (called char) is burned out. The composition of the char depends strongly on the conditions in the devolatilization zone; however, its major components are generally carbon and mineral matter with variable amounts of nitrogen and sulfur species. By the nature of coal combustion, char combustion occurs under predominantly fuel lean conditions. By design, carbon burnout is nearly complete, thereby maximizing energy efficiency and minimizing the carbonaceous particulate. The residual nitrogen species in the char form NO and N_2 during burnout in a mode of combustion which appears to promote N_2 formation. The sulfur species are either oxidized to SO_2 or retained with the mineral matter. The residual mineral matter forms particulate (flyash) in the 0.1 to 50 μm size range. Simultaneous with char burnout, residual gaseous species (CO, H_2, HC) must also be burned out. This mechanistic understanding of pollutant formation processes forms the basis for optimization of combustion techniques for emission control which are based on tailoring the air and fuel mixing history to minimize all objectionable species.

NO_x CONTROL TECHNIQUES

Several control techniques can be applied to stationary combustion. Combustion modification technology is the most cost effective and energy efficient for conventional combustion sources. For any technique the degree of control depends not only on the unit design but also on the fuel. Although NO_x reductions in excess of 80 percent relative to uncontrolled levels have been achieved by combustion modification, even greater control may be required. This may be obtained either by advanced combustion or by supplemental techniques such as ammonia injection and flue gas treatment. The various techniques are described briefly below.

DILUENT ADDITION

The most effective control of thermal NO_x is a reduction of the peak temperatures in the flame zone. One approach is the addition of an inert diluent to the fuel or air stream, thereby lowering the theoretical flame temperature at which combustion takes place. The two most common approaches are flue gas recirculation (i.e., the addition of relatively cool combustion gases recycled from the flue and mixed with the combustion air) and water injection (i.e., addition of water or steam to either the air or fuel stream). Of the two, water injection is the more effective on a mass basis due to the latent heat of vaporization effect; however, it imposes a stack heat loss that can be avoided with flue gas recirculation. These techniques are most effective for thermal NO_x and appear to have little effect on fuel NO_x. For example, 70 to 90 percent maximum reductions have been observed for natural gas and distillate oil in field and laboratory studies; for heavy oil the range is 20 to 50 percent and for coal, 10 to 30 percent. Flue gas recirculation alone or in conjunction with other techniques is used to achieve emission standards for gas and oil fired utility boilers. Its potential drawbacks are increased mechanical complexity and capital costs. Water injection is the state-of-the-art NO_x control technique for gas turbine engines.

STAGED COMBUSTION

Staged combustion is based on creation of a rich primary combustion zone in the furnace to reduce oxygen availability and peak temperature, followed by secondary air injection to achieve carbon burnout. The reduced oxygen availability reduces the conversion of fuel nitrogen to NO and the reduced peak temperature and subsequent heat removal prior to secondary air addition reduces thermal NO_x. One method of implementing this control is illustrated in figure 2. The air supplied to the burners is less than the amount necessary to completely combust the fuel, which produces a fuel-rich primary zone. Although the effectiveness of staged combustion increases significantly as the primary stoichiometry is decreased toward 75 percent of theoretical air, actual coal furnace primary zone stoichiometry is limited to 95 to 100 percent theoretical air by operational considerations (e.g.,

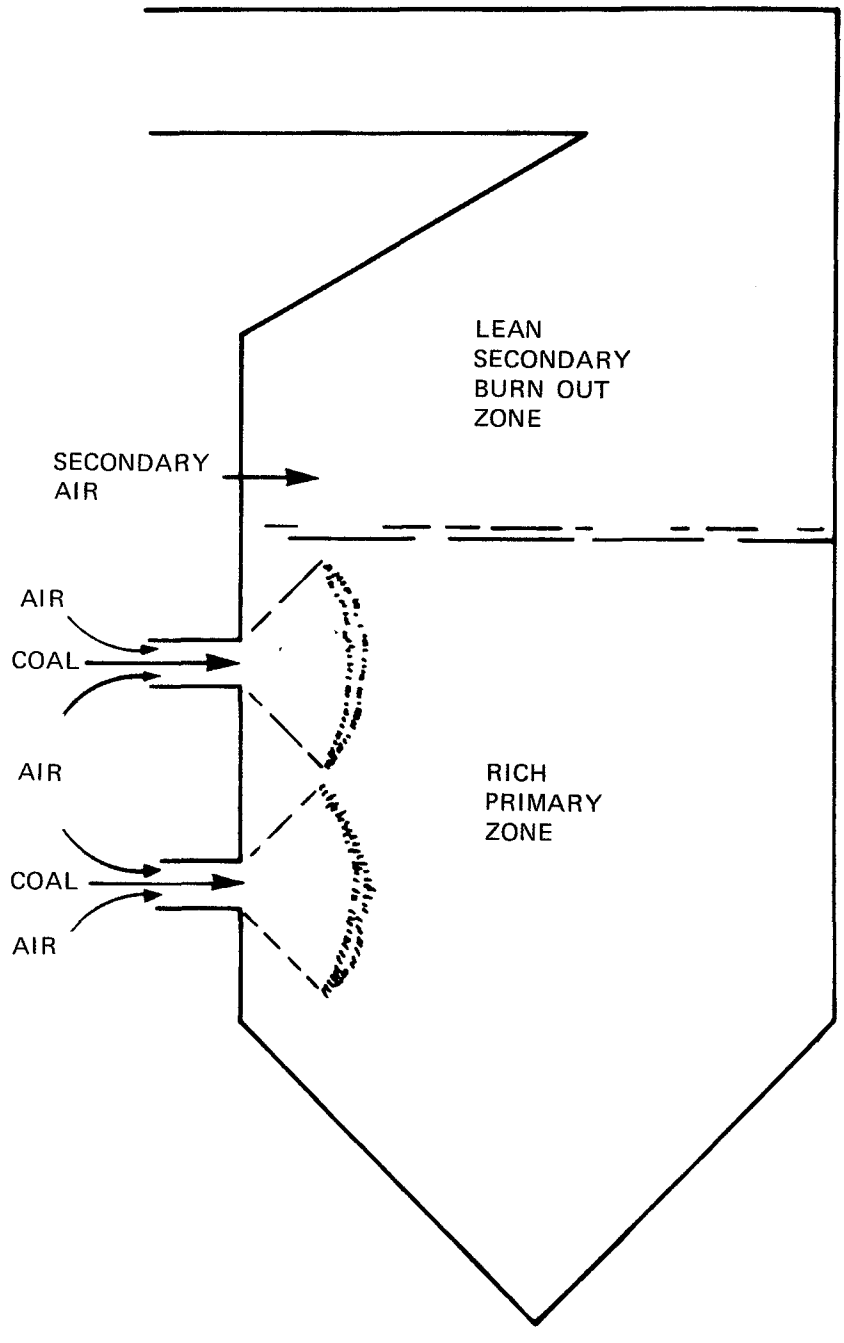


FIGURE 2–*Staged combustion*

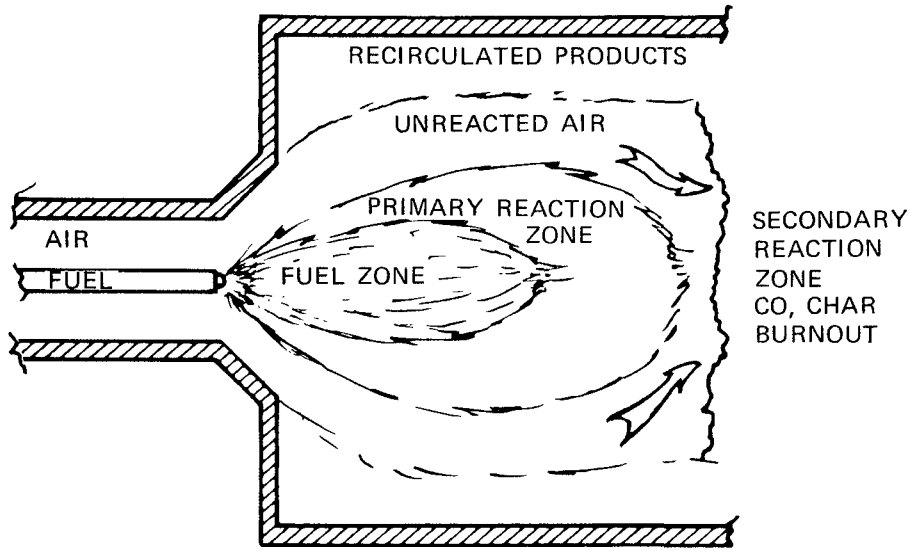


FIGURE 3–*Burner design*

slagging, corrosion). The secondary air is added above the top row of burners and an equal or greater secondary zone residence time is provided for carbon burnout. Although up to 90 percent reduction of NO_x has been observed in coal fired laboratory systems, the maximum practical reduction achieved on field operating boilers under actual or experimental conditions is 30 to 50 percent. Staged combustion is used in a number of configurations to achieve the NSPS for coal fired steam generators and is also employed to meet standards for oil and gas fired units.

BURNER DESIGN

Although diffusion flame burners of many designs have been used in fuel combustion for years, only recently has the modification of design approaches to achieve emission control received strong emphasis. The essential elements of any diffusion flame burner are a fuel supply and an air supply, generally represented in figure 3. Design variables used to achieve stable combustion and good fuel conversion efficiency include fuel distribution (controlled by injector design) and the rate of air mixing (controlled by throat velocity, use of swirl, and/or design of the flame holder). These same variables can control fuel and air mixing histories for emission control; however, the flame characteristics required may be significantly different than the conventional practice. As shown in figure 3, the fuel and air mix initially in a primary reaction zone which contains a wide range of stoichiometries, from very rich to very lean. This characteristic of diffusion flames appears to result in the partial conversion of fuel nitrogen to NO_x. The balance of the combustion air is mixed with the primary zone products farther downstream and combustion is completed. In addition, relatively cool combustion products recirculate within the combustion chamber and are entrained by the flame. This entrainment can provide a diluent effect which reduces peak temperature and, therefore, reduces thermal NO_x. Several pulverized coal burners designed to reduce NO_x have been tested by boiler manufacturers: reductions of 30 to 50 percent relative to uncontrolled levels have been achieved. Entrained combustion gas recirculation burners have achieved NO_x reductions in excess of 50 percent for clean fuels (natural gas and distillate oil). In addition, several studies of advanced burner designs for heavy oil and coal have shown the potential for 65 to 90 percent reduction relative to uncontrolled emissions. A modified burner design is currently used by one manufacturer to achieve the NSPS for coal fired utility boilers.

ADVANCED TECHNIQUES

Alternate combustion approaches do not employ classical diffusion flames and, therefore, may allow very low levels of NO_x. For example, catalytic combustion, which is still being studied on the laboratory scale, has shown the potential for NO_x emissions below 10 ppm for clean fuels. Further development is required to assess the full potential of this emerging technology in practical systems.

The ammonia injection technique involves the injection of ammonia (NH_3) into the boiler firebox above the combustion zone and the subsequent reduction of the NO_x to N_2 by homogeneous reaction. The process requires careful NH_3 to NO ratio control and injection at the proper temperature. Reductions of 90 percent have been achieved in the laboratory? and in excess of 60 percent, in field operating boilers. Due to reagent requirements, it is anticipated that this technique will be used to supplement combustion control techniques where very low NO_x levels are required.

Many processes for NO_x flue gases treatment have shown the potential for high removal efficiency. These processes, generally categorized as wet and dry, are discussed below:

DRY FGT PROCESSES

Selective catalytic reduction processes using ammonia as the reductant are the most developed and most promising flue gas treatment processes. Although there are many variations, anhydrous ammonia is usually injected into the flue gas after the boiler economizer, and the resultant mixture is passed over a catalyst. The ammonia selectively reduces the NO_x in the presence of the catalyst to molecular N_2 which then passes out of the NO_x removal system and into the boiler air heater. Selective catalytic reduction processes can remove 90 percent of the NO_x from the flue gas of a combustion source. In Japan, selective catalytic reduction processes have been successfully installed on commerical-scale gas- and oil-fired sources and are planned for coal-fired sources. A few dry processes can simultaneously remove 90 percent of the NO_x and SO_2 in combustion flue gas. One of the more promising processes uses copper oxide to absorb the SO_2. The resulting copper sulfate acts as a catalyst in the reduction of NO_x to N_2 with ammonia. A multiple reactor system is required to allow for continuous treatment of the flue gas and regeneration of the reactor saturated with copper sulfate. In the regeneration cycle, hydrogen is used to reduce the copper sulfate, and a concentrated SO_2 stream is produced which can be used to generate a salable byproduct.

WET FGT PROCESSES

The wet processes are less developed than the dry and have more inherent problems. The process chemistry is complex, and undesirable byproducts are often generated. However, wet processes have the potential for simultaneous removal of both NO_x and SO_2 in a more economical and energy efficient manner than the sequential installation of SO_2 and NO_x flue gas treatment processes. Therefore, wet NO_x/SO_2 processes are receiving considerable developmental attention. The processes can be subdivided into two general types: oxidation/absorption/reduction and absorption/reduction. The oxidation/absorption/reduction processes basically evolved from flue gas desulfurization systems. A gas phase oxidant, such as ozone or chlorine dioxide, is injected before the scrubbers to convert NO to the more soluble NO_2. The NO_2 is then absorbed into an aqueous solution with SO_2. The absorbed SO_2 forms a sulfite ion which reduces a portion of the absorbed nitrogen oxides to molecular nitrogen. The remaining NO_x are removed from the waste water as nitrate salts. The absorption/reduction processes were seemingly developed to avoid the use of a gas phase oxidant. A chelating compound (such as ferrous-EDTA), with an affinity for the relatively insoluble NO, is added to the scrubbing solution. The NO is absorbed into a complex with the ferrous ion, and the SO_2 is absorbed as the sulfite ion. The NO complex is reduced to molecular nitrogen by reaction with the sulfite ion. A regeneration step recovers the chelating compound and oxidizes the sulfite ion into sulfate which is removed as gypsum. The wet processes can remove 90 percent of the NO_x and SO_2 from combustion flue gas.

The uncertainties of key variables make the quantitative prediction of future trends very difficult; however, several factors appear to indicate the need for more stringent NO_x control capabilities in several areas. Some of these are discussed briefly.

INCREASED COAL USE

The National Energy Plan calls for a significant increase in coal utilization by industrial and utility sources. The actual increase depends on (1) coal production capability, (2) energy consumption growth rate, (3) nuclear energy expansion rate, (4) economics, and (5) environmental regulations. A first step is that virtually all new utility boilers are coal fired. The result on NO_x emissions from this source can be generally illustrated by the fact that the current NSPS for coal-fired utility boilers are 2.3 and 3.5 times those for oil- and gas-fired boilers, respectively. With the current NSPS for coal-fired utility boilers, one recent projection indicates that the increase in total NO_x emissions from 1972 to 2000 would be 30 and 80 percent for high and low nuclear scenarios, respectively. Progressively higher levels of emission controls through 1988 are required to significantly reduce the rate of increase. Therefore, major emphasis on emission controls for coal-fired industrial and utility boilers appears to be imperative.

ALTERNATE FUELS

Significant effort is underway in the United States to develop and commercialize processes for producing alternative gaseous, liquid, or solid fuels from coal or shale. Although most of these processes significantly reduce two of the objectionable components (sulfur and mineral matter) associated with coal, they do not eliminate chemically bound nitrogen. Typically, liquid fuels derived from coal and shale have nitrogen contents from 0.5 to over 2.0 percent by weight. Although this nitrogen can be at least partially removed by hydrotreating, it is potentially an expensive and energy intensive process. Similarly, low and medium Btu fuel gas produced from coal has the potential for containing up to 4000 ppm NH_3 and cleanup, particularly at high temperature, remains difficult. Evidence indicates that combustion modification should be equally or more effective for alternative fuels than for coal and heavy petroleum oil. Further development of the technology on the specific fuels is required.

Very low levels of NO_x may be required under several circumstances. First, the short-term NO_2 standard being considered may require stringent control in certain areas. The degree of control and the specific sources requiring control for any given location have not been established. It is also not obvious if large point sources or area sources will be the prime target of control. Second, regulations requiring the prevention of significant deterioration may require very low levels of NO_x in certain areas if development is to take place. Finally, certain local situations may require increased NO_x control capability. All of these factors provide impetus for establishing the optimum control achievable by (1) conventional combustion, (2) advanced combustion, and (3) postcombustion treatment.

NO_x CONTROL PROGRAM STATUS

The EPA's Industrial Environmental Research Laboratory at Research Triangle Park, N.C., is vigorously pursuing a program to develop and demonstrate NO_x control technology for a broad range of combustion sources burning a variety of fuels. Based on both experience and projections, major program emphasis is on coal combustion in industrial and utility boilers. Other source/fuel combinations are also covered, based on similar considerations. The program's technical approach is based on a balanced and coordinated mix of technology application, technology development, and fundamental research. In general, technology being readied for evaluation in field applications has been developed under EPA sponsorship. Optimization of the technology at the development stage has resulted from an empirical experimental approach and a complementary fundamental understanding of critical phenomena in the NO_x formation and destruction process. The major program areas are briefly described below, then a more detailed discussion of selected projects is presented.

MAJOR PROGRAM AREAS

Major projects of EPA's NO_x control technology program are grouped into four general classifications for convenience of discussion: (1) technology development and field evaluation for specific sources, (2) optimum technology development, (3) fundamental combustion research, and (4) environmental assessment and application testing. Due to the diversity of source/fuel combinations in the first classification, an individual discussion is provided below for each source category. Activities in the other three areas are discussed under more general headings.

Many, if not all, new utility and industrial boilers with a thermal input greater than 35 MW will be fired with pulverized coal. Since the equipment of this type has

the same general configuration (i.e., multiburner, wall- or tangentially-fired, field-erected watertube boiler), combustion modification approaches for NO_x control are also quite similar. Two major projects relate directly to this type of equipment: one for existing combustion technology; the other for application of an advanced low NO_x burner.

EVALUATION OF CORROSION RATES

Current new boilers designed to meet the NSPS incorporate staged combustion and/or improved burners in conjunction with the normal firing design. There has been mixed evidence for the existence or extent of accelerated waterwall corrosion with the fuel-rich conditons that may be produced in the lower part of the firebox. Therefore, a project has been initiated to fully evaluate these effects on four boilers of different firing configurations operating at or below the NSPS of 300 ng NO_x/J (0.7 lb $NO_x/10^6$ Btu). The evaluation of corrosion rates will include the use of both removable corrosion panels and ultrasonic tube thickness measurements before and after a 6 month operating period. This project, which should begin soon, will provide both a quantitative definition of any problem and identification of needed control approaches.

An advanced design low NO_x pulverized coal burner for application to both industrial and utility boilers has been developed under the EPA program. The size of individual burners in this class of boiler ranges from about 10 to 80 thermal MW (30 to 240 X 10^6 Btu/hr). The advanced low NO_x burner has been tested on an experimental scale of 15 to 20 MW and has consistently given NO_x levels below 86 ng/J (0.2 lb $NO_x/10^6$ Btu). The burner is being tested at up to 37 thermal MW with various fuels, and smaller burners are being tested in multiple burner arrays. A field evaluation of the technology is planned on two industrial boilers in the range of 30 to 150 thermal MW and on two utility boilers in the range of 100 to 300 electrical MW. A more extensive discussion of this project is in the next section of the paper.

STOKER COAL-FIRED BOILERS

The stoker boiler firing system can be used for commercial and industrial boilers in the range of 4 to 120 thermal MW, but, above approximately 40 MW, pulverized coal may be cost competitive. A project is in progress to evaluate emission control technology on a model stoker firing a variety of natural and processed coals. Results of these experiments will be used to guide the development studies using a captive spreader stoker boiler. This study will determine the degree of NO_x control using a variety of techniques, including overfire air ports for staged combustion. A new program was recently initiated to apply this technology to two field operating boilers.

The stationary engine category is composed of two general classes of engines, gas turbines and reciprocating engines.

GAS TURBINES

Current gas turbine engines use a diffusion flame combustion mode which is similar in principle to that found in boilers, but different in practice because of very high combustion intensities and high pressure operation. Gas turbines currently use clean fuels (natural gas and light oils); however, there appears to be a trend toward the use of heavier liquid fuels with significant concentrations of fuel nitrogen. For clean fuels, the NO_x emissions, which are quite high, can be controlled using water injection, although efficiency and water supply problems may be encountered. This technique is not expected to be effective on the fuel NO_x for the heavier liquid fuels. For these reasons, a combustor development project was initiated for dry control of both thermal and fuel NO_x from stationary gas turbine engines. The concept screening experiments are complete and a combustor design has been identified capable of exceeding the program goals (i.e., 50 ppmv at 15 percent O_2 for clean fuels and 100 ppmv at 15 percent O_2 for fuels with up to 0.5 percent fuel nitrogen). The successful concept is being scaled up to the size of a single combustor segment in a practical laboratory evaluation. Following successful completion of these tests, the combustor will be incorporated in a practical engine for evaluation on a test stand.

RECIPROCATING ENGINES

A similar development program is also in progress on large bore diesel and spark ignition reciprocating stationary engines. Potential engine design modification concepts are being screened by a panel of experts with the help of an analytical

model. A limited number will be selected for experimental evaluation, and the successful concept(s) will be applied to an engine under laboratory conditions.

RESIDENTIAL FURNACES

The degree of control achievable with current oil and gas fired residential furnaces is limited by the relative lack of flexibility of operating conditions and by cost constraints. This class of equipment emits pollutants near ground level in populated areas during a limited period of the year (i.e., the heating season). In addition, it consumes a significant amount of energy, almost exclusively as clean fuels (e.g., gas and light oil). An integrated residential oil furnace has been developed in the laboratory and has been tested in six residences over one complete heating season. Its performance met or exceeded the emission goals (i.e., $NO_x < 0.6$ g/kg, CO < 1.0 g/kg, UHC < 0.1 g/kg, and smoke number < 1 on the Bacharach scale), and measured cycle average efficiencies ranged from 73 to 80 percent (based on gross heating value). The furnace concept has been tested with natural gas, and shows promise for that fuel although more development is required.

FLUE GAS TREATMENT

Two bench scale evaluations of promising NO_x and NO_x/SO_x flue gas treatment processes are underway. Each evaluation will encompass four phases: (1) design, (2) procurement and erection, (3) startup, debugging, and optimization, and (4) long-term operation and assessment. The projects should be completed in mid-1980. The results will, in large measure, enable an assessment of the viability of NO_x and NO_x/SO_x flue gas treatment technology for application to United States coal-fired boilers. The NO_x project will evaluate the Hitachi Zosen selective catalytic reduction process using ammonia. Application of the process, expected to remove 90 percent of the NO_x from the flue gas, will be the first test of the technology on a coal-fired boiler in the United States. The NO_x/SO_x project will evaluate the Shell Copper Oxide process, expected to remove 90 percent of both the NO_x and SO_x from the flue gas. The project will be the first test of this technology on a coal-fired source anywhere in the world.

ADVANCED PROCESSES

Advanced processes provide engineering exploratory research for identification of advanced concepts capable of significant emission reductions from the levels achievable with state-of-the-art control technology. For example, both the low NO_x coal burner and the integrated residential furnace concepts originated from these studies. The general approach of these projects is to use versatile experimental systems to develop technology for low emission combustion of a specific fuel. Such projects now underway are discussed briefly below.

The low NO_x coal burner work is being continued for evaluation of the effects both of coal properties covering the full range of United States coal reserves, and of single and multiple burner configurations on the ultimate emission levels. A complementary study of burner design and burner furnace interactions has been initiated for tangentially fired coal boilers using a small versatile furnace (3 to 6 thermal MW).

LOW EMISSION BURNER

A low emission burner design program for heavy liquid fuel combustion is also in progress. Work has shown that over 65 percent reduction in emissions from residual fuel oils containing up to 0.8 percent N can be obtained with a staged burner design; however, beyond this limit a significant increase in carbon particulate occurs. Recent work has shown that both the fuel atomizer design and the properties of the liquid fuel have a strong effect on emission control. Promising burner designs for both firetube and watertube package boilers have been identified and are being optimized. In addition, the exploration of fuel effects has been expanded to include synthetic liquid fuels derived from coal and shale, for which the residual oil technology is expected to be directly applicable.

Several low and medium Btu gases simulating the products from three types of air oxygen blown gasifiers have been evaluated at 3 thermal MW in an experimental furnace. Burner configurations representing both boiler and kiln practice were used during the program. For ambient and elevated temperature fuel gases, the thermal NO_x emissions could be correlated with adiabatic flame temperature. When NH_3 was added to the gases for simulation of one potential component of actual coal derived fuel gases, a significant conversion to NO_x was observed. With the addition of similar amounts of H_2S, simulating residual sulfur compounds in actual gases, the

conversion of NH_3 to NO increased substantially. It should be noted that this observation relates to phenomena previously noted in fundamental combustion experiments. It was concluded that burner modification or staged combustion would be required to control NO_x from NH_3 containing gases. In a second related project, calculations showed the potential for substantial reduction of NO_x from high temperature, NH_3-containing low Btu gases by proper application of staged combustion. These calculations are being evaluated in an experimental study which will define the optimum combustor configuration based on fuel gas properties. The most promising concepts will be constructed and evaluated in bench scale experiments.

NH_3 INJECTED INTO BOILER

The homogeneous thermal reduction of NO_x by injection of NH_3 into the boiler at a specified temperature region of the postcombustion zone has been shown experimentally for oil and gas fired systems. A project is underway to evaluate the applicability of this technique to coal fired systems. A laboratory study is in progress and a feasibility study will be conducted for the use of the technique as a supplement to combustion modification on a coal fired boiler.

Catalytic combustion is an advanced combustion concept with the potential for very low levels of pollutant emissions from clean fuels (e.g., NO_x, CO, and UHC all less than 10 ppm). For application to stationary sources, further development of systems aspects are required. A detailed discussion of the results to date is given in the next section of this paper.

FUNDAMENTAL COMBUSTION RESEARCH

Fundamental combustion research studies provide the basic understanding of the phenomena responsible for pollutant formation and destruction in the combustion process. These studies emphasize the chemistry and aerodynamic aspects of combustion processes and are used to guide the development and optimization of new technology. Special attention is being directed at fuel nitrogen reactions and at the formation of primary and secondary pollutants since these species may be strongly affected by changes in the combustion process. Projects in this area examine the classes of phenomena which can be associated with specific elements of the conventional combustion process: (1) fuel pyrolysis, (2) gas phase kinetics, and (3) fuel/air mixing. All experimental aspects are complemented by analytical modeling.

The fuel pyrolysis studies have shown that a significant amount of the fuel nitrogen in both heavy oil and coal is evolved as an organic nitrogen intermediate at temperatures below 873K and that this intermediate can be further pyrolyzed almost quantitatively to HCN at 1373K. Drop-tube furnace experiments at higher temperatures (e.g., 2100K) have shown that the nitrogen can essentially be completely evolved from the coal substance with sufficient residence time. Measurements have also shown that the nitrogen and sulfur compounds from a range of coals show different evolution patterns as a function of temperature. This information is currently being examined to determine if it can be directly related to NO_x emissions as a function of combustion condition in an experimental furnace. A similar drop-tube experiment has begun to derive similar high temperature pyrolysis information for heavy liquid fuels.

HEAVY FUEL STUDY

Although the general effects of diffusion flame burner conditions on emissions from pulverized coal and oil flames have been known for some time, an understanding of the behavior of these fuels under well defined flow conditions has not been achieved due to experimental and analytical difficulties. In the past year several projects have been initiated to study these heavy fuels in simplified reactors (e.g., plug flow, well-stirred, and simple diffusion flames). Results of these studies will be utilized to define the effects of air/fuel mixing history on pollutant formation.

GAS PHASE CHEMICAL KINETICS

Finally, even for these heavy fuels, an understanding of the gas phase chemical kinetics is necessary to understand the mechanics of formation and control of fuel NO_x. The use of chemical kinetics codes coupled with experimental data has shown that the fuel characteristics can have a dramatic effect on the fractional conversion of NH_3 to NO for a given reactor type. It has also shown that a careful control of stoichiometry (rate of air addition) and temperature can have a significant effect on

fuel NO_x from a given fuel/reactor combination. This type of information can provide a direct input to development studies for practical combustors.

ENVIRONMENTAL ASSESSMENT AND FIELD APPLICATION

Environmental assessment and application testing provide for a near-term evaluation of the effects of state-of-the-art combustion techniques on the total emissions from stationary sources. The environmental assessment project has been evaluating all aspects of the problem, while field application projects have been evaluating the effects of combustion techniques on specific classes of equipment.

A preliminary environmental assessment has been completed and various aspects of NO_x control have been documented, including (1) source types, (2) fuel usage, (3) emissions baseline, (4) state-of-the-art control techniques, (5) developing control technologies, (6) potential side effects, and (7) total impact evaluation methods. The projected fuel use and emission trends have been estimated for five energy growth rate and supply scenarios. The impact on NO_x from each source sector has been estimated, based on various assumptions on level of control. Although about 30 sources contribute significant amounts of NO_x, coal fired boilers are identified as the user sector most likely to increase dramatically by the year 2000 in almost all scenarios. In addition to the system analyses in this project, a program is underway to evaluate the impact of NO_x controls on other emissions from a range of sources. These studies will compare emissions between baseline and low NO_x conditions for field operating boilers using EPA, IERL-RTP Level 1 and 2 procedures for sample collection and analysis. Several residential oil furnaces and a coal fired utility boiler have been sampled; however, results are not yet available.

In general, to ensure the environmental acceptability of the technology, the environmental assessment measurement methodology is being incorporated in some measure on developmental studies and in full on field evaluation projects.

APPLICATION TESTING

Application testing allows the evaluation of the extent of control achievable by optimization of low NO_x conditions within the constraints imposed by existing combustion equipment under field operating conditions. Projects are underway or were recently completed in several areas. A United States emission inventory based on available data has recently been updated. Two gas and oil fired industrial size boilers equipped with emission control equipment including flue gas recirculation and staged combustion have been evaluated. Emission reductions up to 79 percent were achieved for natural gas and distillate oil, while reductions up to 55 percent were achieved for residual fuel oils containing approximately 0.3 percent nitrogen. Carbonaceous emissions and unit efficiency were unaffected or improved for the optimum conditions. A long term corrosion test on a coal fired utility boiler is complete; however, data analysis is still in progress.

DETAILED DISCUSSION

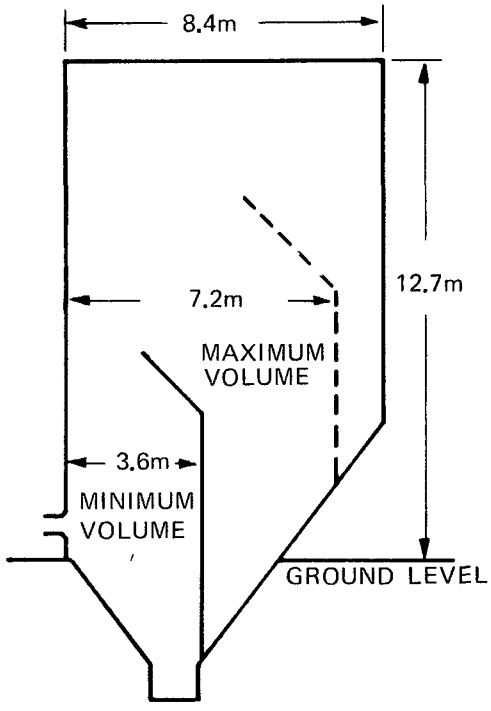
Several areas in EPA's NO_x control program will result in the ability to achieve control levels significantly higher than is currently possible. To provide a more complete understanding of the technical approach, two of the more promising areas have been selected for a more detailed discussion. The low NO_x coal burner technology has the potential for direct application to new and existing pulverized coal fired industrial and utility steam generators. Catalytic combustion is a longer-term technology that may require a significant redesign of combustion equipment to achieve its full potential; however, it offers the potential for near zero emission levels (i.e., NO_x, CO, and HC less than 10 ppm) for clean fuels commonly used in area sources.

LOW NO_x COAL BURNER

Since the control of both thermal and fuel NO_x from pulverized coal combustion is strongly dependent on the temperature and stoichiometry in the primary zone, the most direct approach is to redesign the burner to achieve the required fuel/air distribution. In 1971 the EPA initiated a small scale study to identify the important burner design parameters for NO_x control. This study identified a distributed air burner concept that had the potential for very low NO_x emissions with both high carbon utilization efficiency and acceptable flame characteristics. This pilot scale work was carried out at thermal heat inputs of 1.5 to 3.0 MW, which is a factor of 10 to 40 smaller than practical pulverized coal

SCALING CRITERIA

burners currently in use. Due to difficulties in scaling burner thermal performance by even a factor of 2, current design practice is to make incremental capacity changes, or simply install more burners of the same size. Therefore, to obtain industry acceptance of the low NO_x burner technology, it was necessary to identify scaling criteria and to evaluate the burner performance at as close to practical size as possible. A project was initiated to develop scaling criteria for low emission burners. As an essential part of the program, a unique combustion facility capable of firing coal and other fuels at a thermal input up to 40 MW was designed and constructed. The important features of this facility are shown in figure 4. The basis



- FUELS: - PULVERIZED COAL
  HEAVY OIL
- FIRING CAPACITY:
  15 - 40 THERMAL MW (50-120 X 10^6Btu/hr)
- HEAT RELEASE RATE:
  1.6 to 2.4 kW/m^3
- VARIABLE GEOMETRY
- SHEET STEEL WALLS:
  WATER SPRAY COOLED
- PULVERIZER-RAYMOND CE (MOD 473A):
  6000 kg/hr
- AIR PREHEAT TEMPERATURE:
  700K
- INDEPENDENT CONTROL OF ALL AIR STREAMS

FIGURE 4–*Large watertube boiler simulator*

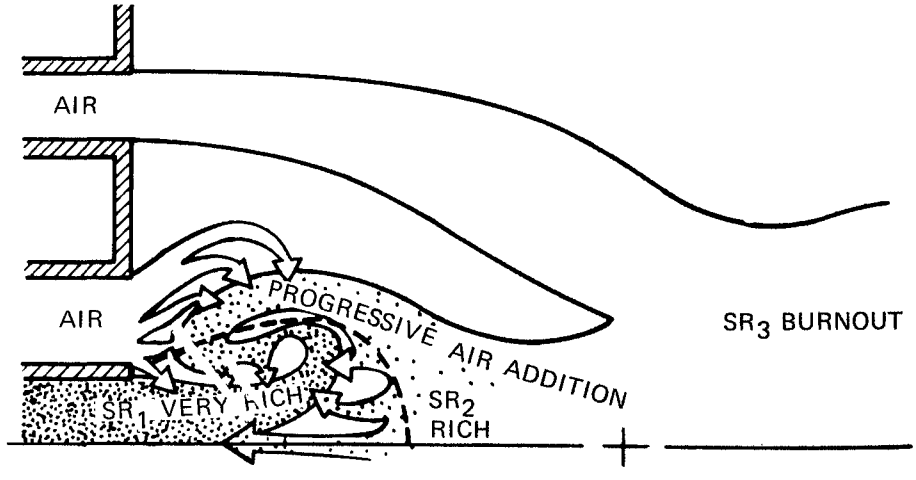


FIGURE 5–*Conceptual sketch of low NO_x burner system*

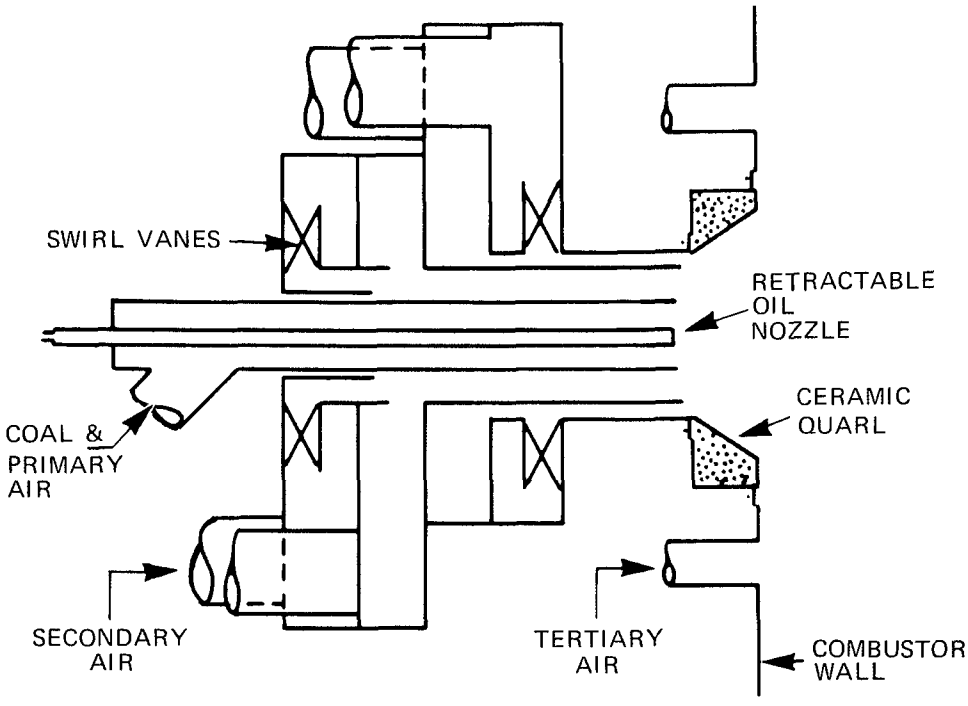


FIGURE 6—*Sketch showing major features of 15-thermal-MW distributed mixing burner*

EXPERIMENTAL BURNER DESIGN

of the low NO_x coal burner is a distribution of the combustion air to control the reaction history of the coal. This is shown conceptually in figure 5. The coal is introduced with primary air and the initial devolatilization reaction takes place at a very rich stoichiometric ratio (SR_1) which results in evolution of fuel nitrogen intermediates (XN) under conditions where oxidation to fuel NO_x is low. Secondary air is introduced in a way which provides a gradual leaning out of the reaction zone to a stoichiometry (SR_2) which is still fuel-rich. This gradual mixing allows formation of NO_x and a subsequent reduction by XN to form N_2. Both the temperature and stoichiometry history of this rich reaction zone determine the level of NO_x that can be achieved. Finally, tertiary air is mixed with the reaction products to give a lean burnout zone (SR_3). In this zone any residual XN species are converted predominantly to NO, any nitrogen remaining in the char is converted predominantly to N_2, and fuel species (char, CO, HC, H_2) are oxidized to give complete combustion. Complete reaction of the carbon in the char is especially important from the standpoint of both efficiency and emission performance. The design of the experimental burner used to achieve these conditions is shown in figure 6. The design incorporates a retractable oil gun for use on startup and a divided secondary air channel to provide flexibility on turndown. The three burner sizes used in the program are nominal thermal inputs of 4, 20, and 40 MW. A typical plot of experimental data is shown in figure 7 where NO_x emissions are shown as a function of the burner primary zone equivalence ratio (numbers greater than 1.0 are fuel-rich). The 16 MW thermal burner produces emission levels below 150 ppm (86 ng NO_x/J) for a primary zone equivalence ratio greater than 1.2, which corresponds to less than 80 percent of the theoretical air being supplied through the primary and secondary air channels of the burner. (Note that a geometrically scaled burner at 3 MW thermal produces somewhat higher NO_x levels. This may be attributable to a residence time in the fuel-rich reaction zone that increases as burner scale increases or to changes in rate of secondary air mixing rates for the larger jet diameters. Whatever the reason, it is encouraging to observe that increasing scale toward practical size appears to make the technology more effective.)

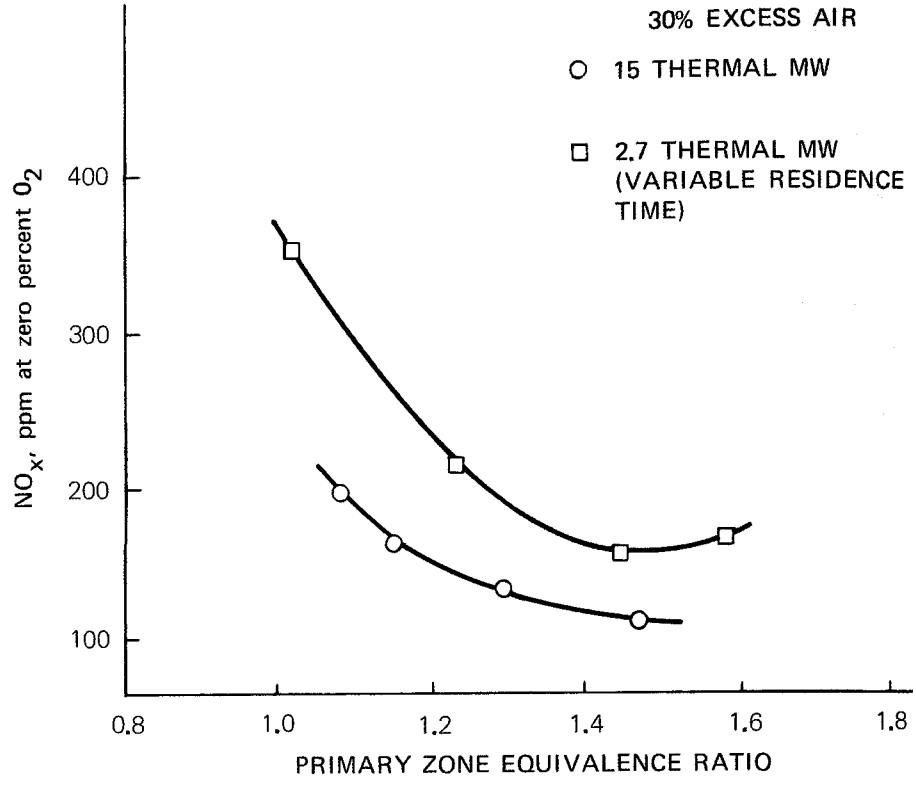


FIGURE 7—*Scale effect with distributed mixing low NO_x coal burner*

To evaluate the applicability of the technology to other fuels, a limited series of experiments was run with a high nitrogen residual fuel oil; a typical example is shown in figure 8. Although the nitrogen in the oil is high (0.77 percent) compared with the average (about 0.25 percent) for residual oil used in the United States, it provides both a worst case for conventional oils and a preview of what may be achievable with high nitrogen coal- and shale-derived oils. The results shown are for unstaged operation (i.e., a small amount of purge air through the tertiary injectors) at three thermal inputs, 2.4 MW for the small burner and both 12 and 15 MW for the intermediate burner. The intermediate scale burner operated down to 2 percent oxygen in the flue without producing carbon particulate (smoke) and gave NO_x levels of about 175 ppm. This can be compared with approximately 1200 ppm of fuel NO_x that would occur if the 0.77 percent nitrogen were quantitatively converted and 350 to 600 ppm that would occur at levels of conversion observed in conventional burners.

RESULTS OF LOW NO_x BURNER DESIGN

Development of the low NO_x coal burner technology is continuing to expand the applicability of the design and scaling criteria for the full range of United States coals. This includes small scale screening of a large number of coals followed by testing of selected coals at the three burner scales. Additional burner concepts with the potential for improved emission performance are being evaluated and the influence of multiple burner configurations on flame interaction is being assessed. To provide a comparison with commercial practice and an estimate of the effect of multiple burner interactions in practical systems, several full scale production coal burners will be evaluated in the experimental facility. A technical review panel, composed of representatives of boiler manufacturers, utilities, and research organizations, provides a continuing evaluation of the program direction as related to practical systems. A technology transfer panel, composed of representatives of government agencies and trade association members, periodically provides a broader perspective of potential users.

DEMONSTRATED TECHNOLOGY

To provide for demonstrated technology, two projects have been initiated for field evaluation of the low NO_x burners. One project covers two industrial boilers in

the range of 30 to 150 thermal MW, while the other involves two utility boilers in the range of 100 to 300 electric MW. The projects provide for (1) construction of one prototype burner of each size and validation of performance in the experimental facility, (2) baseline emission characterization of the host boilers, (3) installation of the required number of burners in each boiler and optimization of performance, (4) long term performance evaluation, including required environmental assessment and periodic operational analyses, and (5) preparation of a guideline manual for generalization of the technology. These projects should begin in late 1978 and be completed in late 1982. The goals of these projects are to show that (1) NO_x emissions below 86 ng/J are possible in practical boilers, (2) low NO_x emissions can be achieved without increased carbonaceous emissions, (3) thermal efficiency of the boiler is equal to or better than that of the baseline boiler, and (4) the burner design provides an air shield around fuel-rich zones and, as a result, waterwall corrosion is eliminated.

CATALYTIC COMBUSTION

One advanced concept that appears capable of achieving very low pollutant levels is catalytic combustion, where a catalyst is used in place of a diffusion flame burner to achieve the major energy release in a combustion system. The initial applicability is to clean gaseous and vaporizable liquid fuels, as a premixed fuel and air stream must be presented to the catalyst. Oxidation of the fuel through both

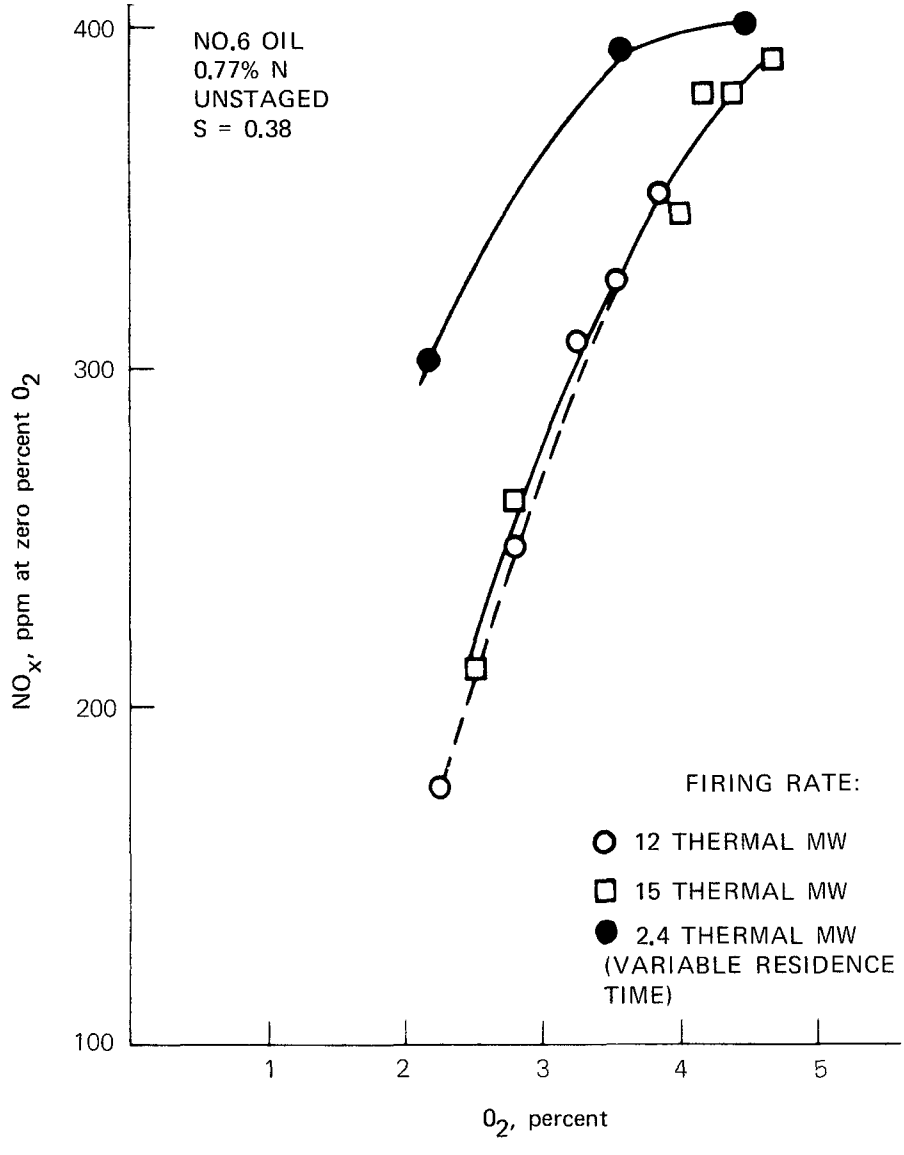


FIGURE 8—*Low NO_x burner firing residual oil*

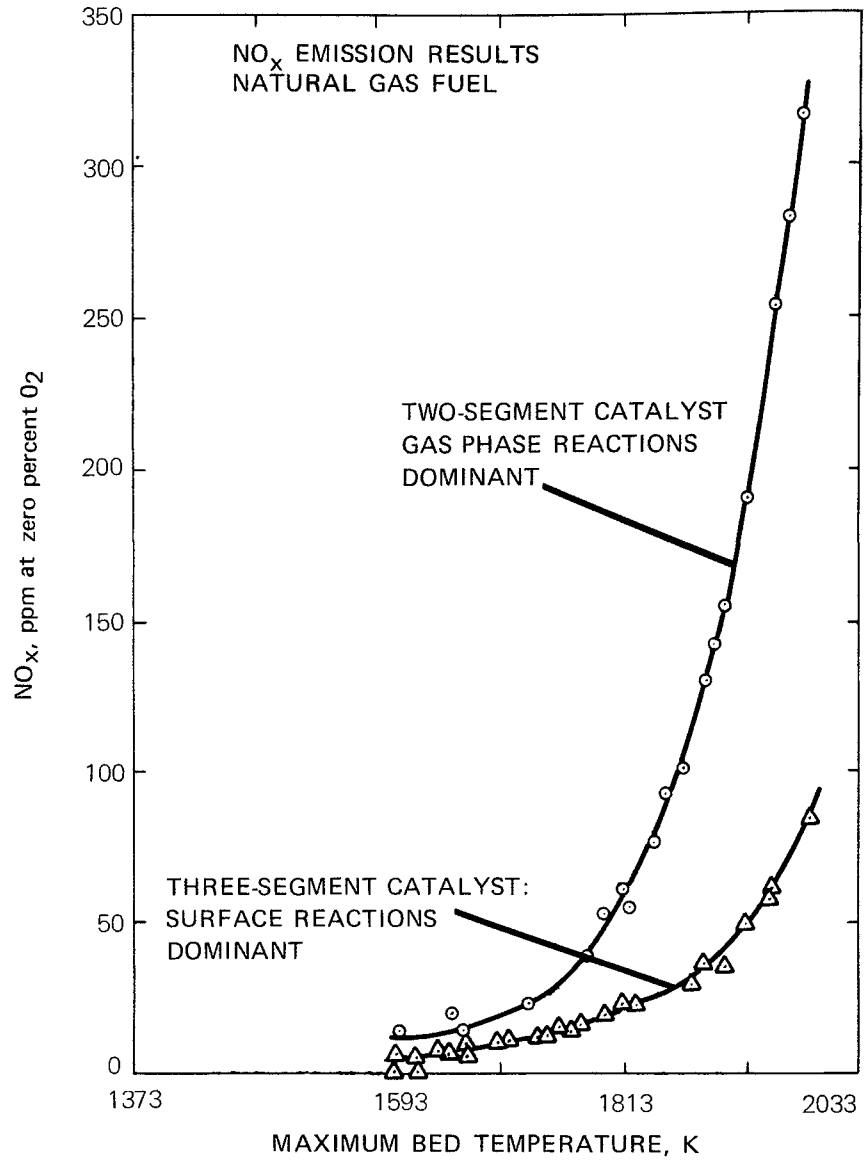


FIGURE 9—*Graded cell catalyst test results*

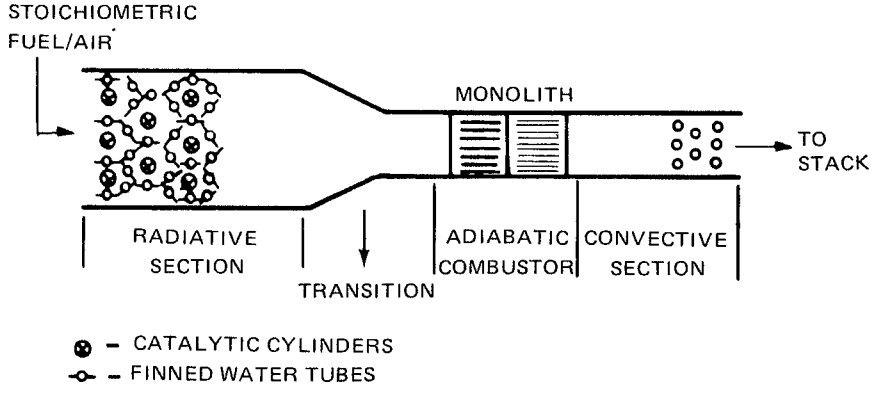


FIGURE 10—*Radiative catalytic/watertube combustion system design concept*

heterogeneous surface reactions and homogeneous gas phase reactions occurs within the channels of the catalyst bed at essentially adiabatic temperature. Complete combustion can be achieved at very short residence time and with very high volumetric heat release rates. The two apparent limits are (1) the temperature at which catalyst degradation becomes significant, and (2) the well known kinetic threshold temperature above which the rate of thermal NO_x formation becomes significant. Therefore the application of the technology to stationary combustion sources requires new system designs to achieve long life and high thermal efficiency.

STATIONARY GAS TURBINES

The most straightforward application of catalytic combustion appears to be stationary gas turbine engines. Several features of this class of equipment are ideally suited to catalytic combustion: (1) clean fuels are used extensively, (2) the normal mode of operation is at high excess air where the adiabatic flame temperature (1373K) is well within the capability of catalysts, (3) high volumetric energy release rates and compact combustors are desirable, (4) a flat combustor exit temperature profile, as produced by a catalyst bed, is highly desirable, and (5) control of emissions to very low levels by conventional techniques is difficult. Figure 9 shows typical data from a versatile test facility for several catalysts burning premixed methane/air at high excess air. The maximum bed temperature is controlled by the amount of air supplied to the fuel. At current gas turbine combustor outlet temperatures (1373K), the NO_x emissions are well below 10 ppm (about 6 ng/J) for both catalysts. This can be compared with NO_x emissions from conventional engines with water injection of about 150 ppm (about 86 ng/J). As the catalyst temperature increases, NO_x emissions increase gradually to 10 to 20 ppm at 1723K, after which the increase is more rapid. In the catalysts, where surface reactions are believed to dominate, emissions are about 80 ppm at 1973K; for the catalyst where homogeneous gas phase reactions dominate the fuel burnout, emissions are over 300 ppm at that temperature. These results illustrate two points: (1) very low NO_x emissions can be achieved even at the highest temperatures that may be achieved at the turbine inlet of advanced combined cycle systems, and (2) the catalyst plays a significant role in the level of emissions observed. For all tests CO and hydrocarbon emissions were also low. The most significant problem that was encountered was catalyst substrate degradation at the high temperature operation. Further development of catalysts and auxiliary systems is required for the incorporation of the catalyst into practical engines.

STATIONARY BOILERS

The application of catalytic combustion is more difficult for stationary boilers that must operate at low excess air to achieve high thermal efficiency. For example, the adiabatic temperature for natural gas at stoichiometric air to fuel ratio is over 2250K, or well in excess of the desirable operating range of the catalyst. Therefore, alternative concepts must be sought. One such alternative is shown in figure 10. A stoichiometric mixture of fuel and air is introduced to the radiative section and combustion takes place on the catalyst cylinders (denoted by ⊗). The surface temperature of the cylinders is controlled at about 1373K by radiation to surrounding watertubes (indicated by -0-). Approximately 50 percent of the fuel heating value would be released in this section with about 50 percent of the energy released being removed by the watertube. The radiative section is followed by a transition section in which more heat may be removed as required. The high temperature mixture of air, fuel, and combustion products is then introduced to a graded cell catalyst where complete combustion occurs at an adiabatic temperature below 1723K. The convective section then reduces the gas temperature to a flue value around 450K which, coupled with a stoichiometric air to fuel mixture, results in the minimum practical heat loss achievable without a condensing heat exchanger. The coolant flow through the radiative, transition, and convective section watertubes must be arranged to achieve the desired steam temperature and pressure. Although the total system has not been tested, a prototype of the radiative section has been evaluated experimentally: it performed as expected on heat release and heat removal parameters. Low NO_x values were measured and there is no reason to suspect an increase in the adiabatic combustor based on graded cell tests of catalysts at similar temperatures. It is also anticipated that low fuel NO_x emissions can be achieved by use of staged combustion either in the radiative concept or with two adiabatic sections. Preliminary tests have confirmed this for nitrogen doped gaseous fuels.

SUMMARY

The status of EPA's NO_x control technology development program can be summarized as follows:

- Based on fuel trends, NO_x emissions may increase significantly with current technology.
- More effective stationary source control technology can provide a means of mitigating this emission trend.
- The combustion modification techniques under development offer the potential for achieving significant NO_x reductions without adverse effects on other pollutants.
- These high levels of control can also be achieved at relatively low cost and without degradation of thermal efficiency.
- If extremely low levels of NO_x are required, advanced combustion technology and supplemental techniques such as ammonia injection and flue gas treatment are also under development.

The authors wish to thank Dr. M. P. Heap and Dr. J. Kesselring for the information used in the detailed discussion of the low NO_x coal burner and catalytic combustion, respectively.

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FLUIDIZED-BED COMBUSTION

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CONCENTRATED SOLAR ENERGY

The goals of all of us are clean, efficient, practical, economic generation of heat and power from whatever original energy sources are available. For that reason many people have become interested in solar energy. Figure 1 shows pre-packaged,

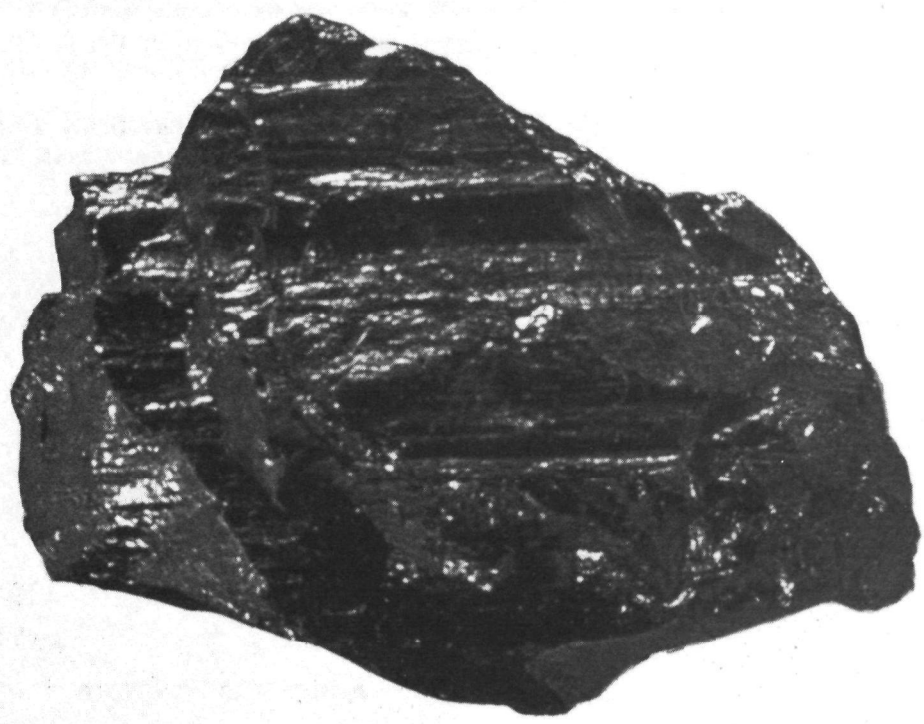

FIGURE 1—*Coal*

aged, concentrated solar energy, which we know as coal. There are large quantities of it in the U.S. We find numerous references to the abundance of coal in our nation—400 years' supply at current usage rates. The problem is how to use it in an environmentally acceptable and economic manner.

CLEAN COMBUSTION

Fluidized-bed combustion is one of the advanced concepts for the clean combustion of coal (figure 2). It is a way of burning coal, as well as agricultural and industrial wastes, in a clean, practical and economic manner. Fluidized-bed incinerators are now used to burn paint wastes and bark and log fuels from paper mills and lumbering operations. The concern of the Department of Energy is to develop this technology to burn coal while controlling SO_2 emissions. This fuel flexibility is an important practical feature of the fluidized-bed system. Fluidized-bed combustors are more compact than conventional coal combustors. This equipment size advantage is a consequence of the higher heat transfer coefficients that are inherent in the process.

TEMPERATURE ADVANTAGE

Every once in a while nature is cooperative. The temperature for fluidized-bed combustion is from 1450 to 1650 degrees Fahrenheit, which is advantageous for several reasons. It is sufficiently high for efficient combustion, below the temperature at which ash slags and forms deposits on tubes, above the temperature required to generate superheated high-pressure steam for power generation, and below the temperature at which NO_x will form from nitrogen in the combustion air. The combustion temperature is above that at which limestone and dolomite calcine to lime and below the temperature of dissociation of calcium sulfate, so that calcium sulfate is produced as the by-product of burning sulfur-bearing fuels. The lower NO_x formation is a consequence of the lower combustion temperatures. The unburned carbon in the bed offers a modest possibility for dissociating the fuel-bound nitrogen so that NO_x emissions can be reduced to the range produced by oil and natural gas-fired equipment and, in the longer-range future, perhaps even lower. The solid waste is a mixture of unreacted lime, ash, gypsum, and calcium sulfate. Some useful alternative methods of disposal have been demonstrated and will be discussed later.

COAL BURNED IN FLUIDIZED BED

Figure 3 shows coal being burned in a fluidized bed. The bed is contained in a pyrex tube so that the process can be seen. Air is injected at the bottom through a porous-plate air distributor that also supports the bed. The illustration shows a mixture of non-combustible particles—hot sand in this case—and a few coal particles which have been fluidized by the air passing through. The air rises in bubbles, which can be seen in the middle, with the particles falling back into the bed.

Figure 4 depicts schematically a fluidized-bed combustor with an integral heat exchanger. The bed is a dense phase of lime and coal particles and air, in which

ATMOSPHERIC FLUIDIZED BED COMBUSTION

- COMPLIANCE WITH SO_2 EMISSION REGULATIONS WITHOUT SCRUBBERS
- LOW NO_x EMISSIONS DUE TO LOW COMBUSTION TEMPERATURES
- FLEXIBILITY OF COAL SUPPLY, i.e. ABILITY TO BURN VARIOUS FUELS INCLUDING LOW RANK COALS
- POTENTIAL FOR SMALLER BOILER VOLUMES DUE TO HIGH HEAT TRANSFER COEFFICIENTS OF IN-BED SURFACES
- DRY SOLID WASTE MATERIAL

FIGURE 2–*Advantages of AFBC*

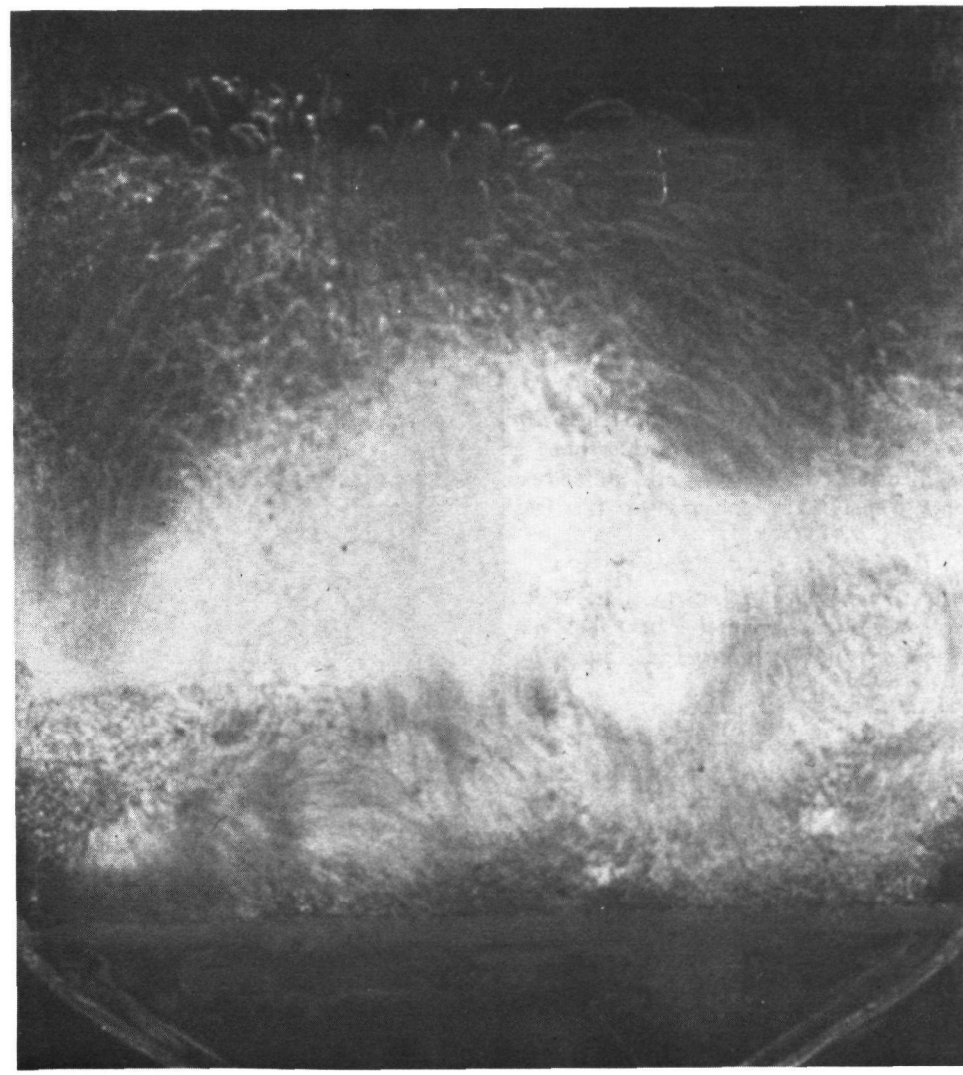

FIGURE 3–*Fluidized bed combustion of coal in a pyrex tube*

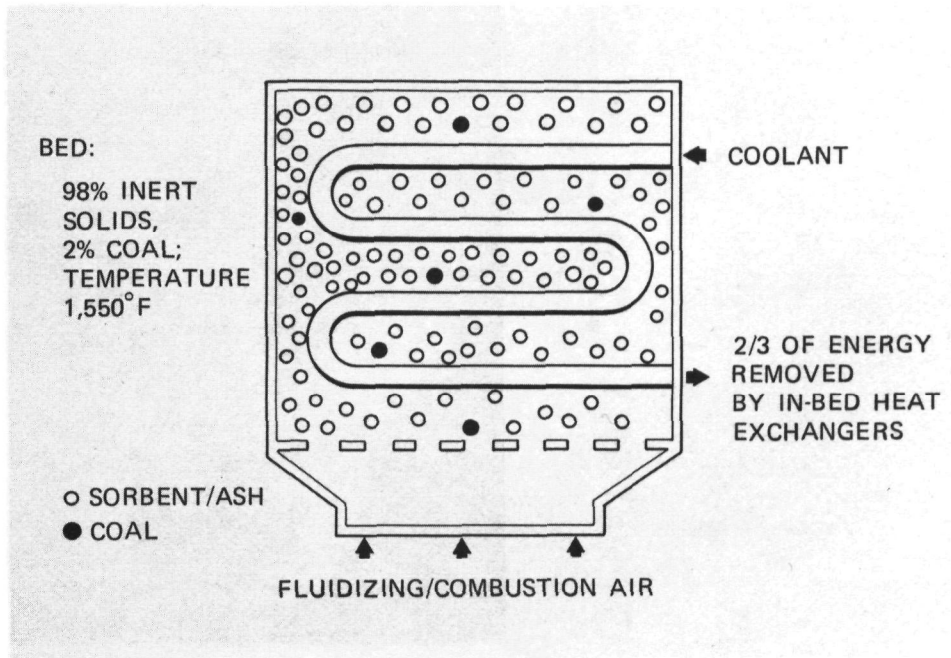

FIGURE 4–*Fluidized bed combustion–schematic*

COMBUSTOR WITH HEAT EXCHANGER

heat transfer coefficients are quite high and the gas-solid contact area is enormous, so that the SO_2 in the combustion products can react with the lime. There is a small amount of coal in the bed, about 2 percent. This devolatilizes first and then burns. The limestone calcines to lime from the heat of combustion and then picks up to SO_2 to become sulfate. The heat transfer tubes are immersed in the bed in order to control the temperature to the range of optimum SO_2 capture and combustion efficiency.

Figure 5 shows the process development unit that was in existence in our Alexandria, Virginia, laboratory from 1965 until 1977. It has been replaced with a

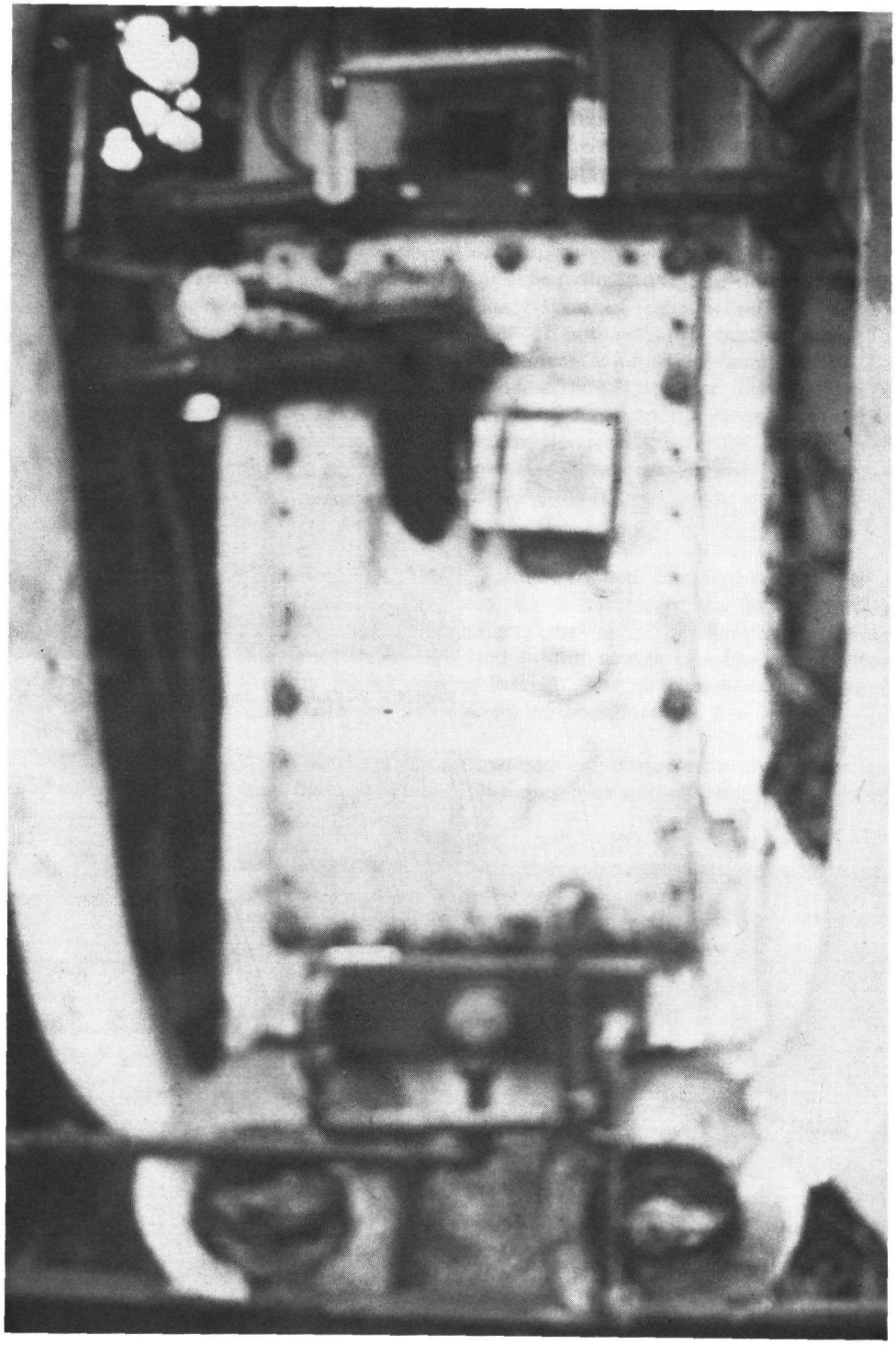

FIGURE 5—*FBC process development unit (I) Alexandria, VA—schematic*

new unit with a higher freeboard so that additional R&D can be undertaken on NO_x control, SO_2 absorption, and suppression of unburned hydrocarbons in the above-bed zone.

FBC IN A BOILER MODE

Figure 6 is a sketch of the fluidized bed in a boiler mode. This is our unit at Rivesville, West Virginia. You can see the fluidized-bed region with the in-bed tube bundle, over-bed heat exchange tubes, and the fuel injection ports.

Figure 7 shows the power plant at Rivesville, West Virginia, where the 30-megawatt experimental boiler is installed.

Figure 8 shows the Rivesville 30 MW_e boiler assembled but without insulation and all the coal injection ports connected.

Figure 9 shows the four cells of the Rivesville boiler. The three cells to the right are each 10 feet wide, 12 feet long, and 20 feet high. The in-bed heat exchanger has both steam-raising and superheating tubes. The above-bed heat exchanger includes both preheating (economizer) and steam-raising tubes. The cell on the extreme left is the carbon burnup cell.

CONTINUOUS OPERATION

Recently, the Rivesville unit achieved continuous operation over an extended period. During a forced outage this winter, the coal feed system was improved, and in May the unit operated continuously for 50 hours. During that period, the steam

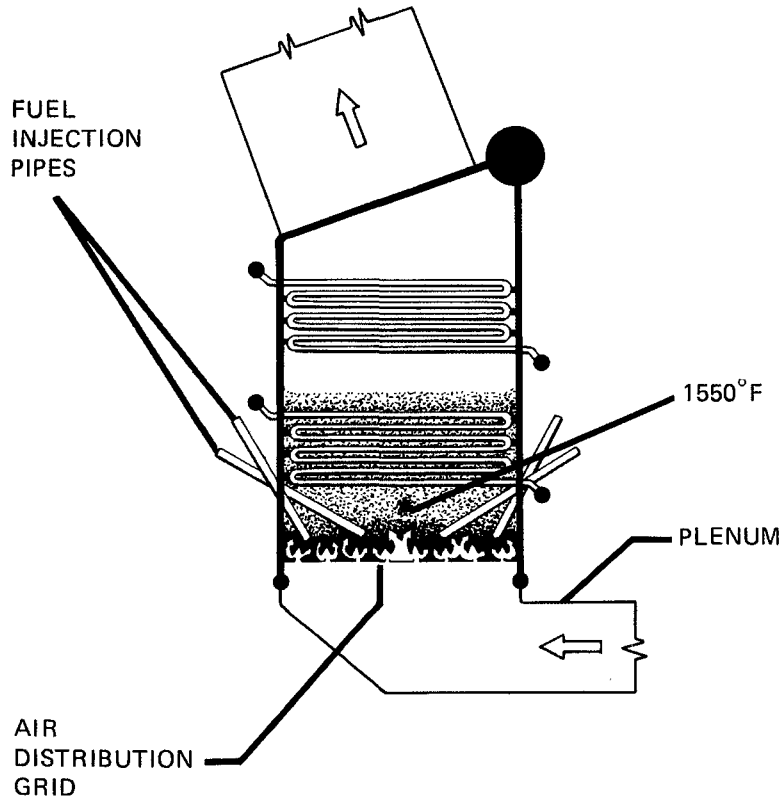

FIGURE 6—*FBC boiler*

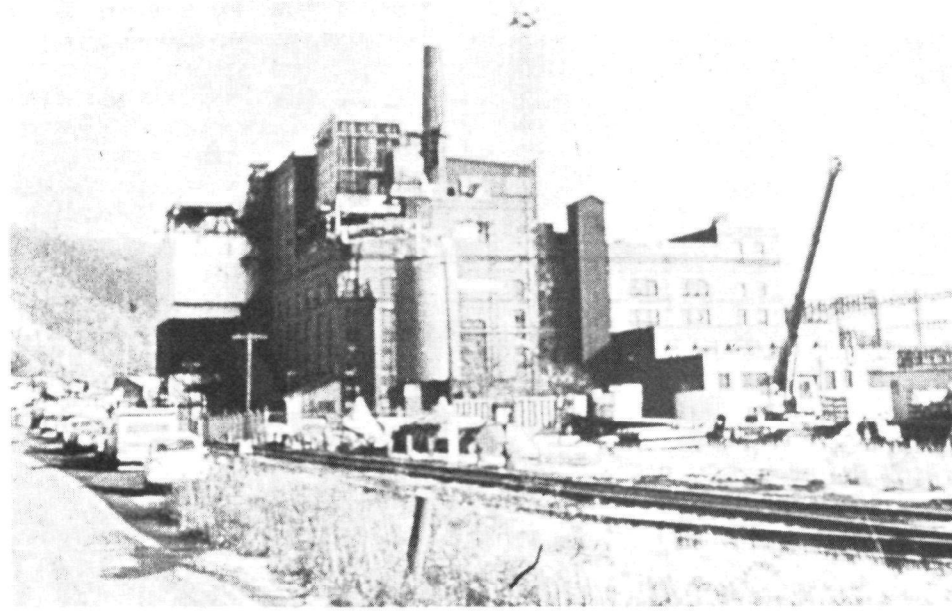

FIGURE 7–*Power plant at Rivesville, WV*

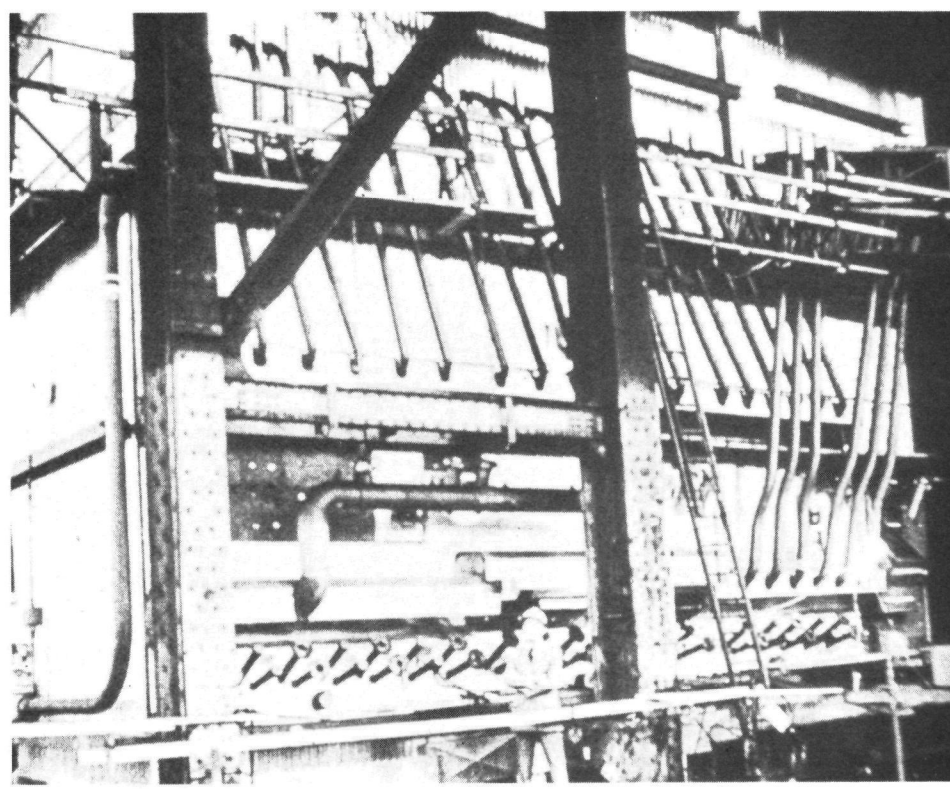

FIGURE 8–*Multi-cell fluidized bed boiler at Rivesville, WV*

generated was used by the host utility to generate power for the electric power grid. The usual 24-hour startup was adequate to achieve controlled steady-state operation that is prerequisite to connecting with the host system. Preliminary data from Rivesville indicate that the SO_2 reduction is in the range of 85 to 89 percent with the limestone feed that is presently being used there, and NO_x emitted is 0.2 to 0.3 lb. per million Btu. Presently, connections are being made in the flyash reinjection system so that the improved combustion efficiency expected with this carbon recycle feature can be demonstrated.

SOLID WASTE DISPOSAL

Solid waste from FBC units can be disposed of in the same manner as conventional flyash and stabilized scrubber wastes, at a cost of about $2 to $4 per ton. As alternatives to disposal, some useful applications for the waste product have been demonstrated. For example, cement blocks made with this waste have strength comparable to regular commercial block. The waste product can be used as a dry benign substance for parking lots, road base, and other low-grade structural applications.

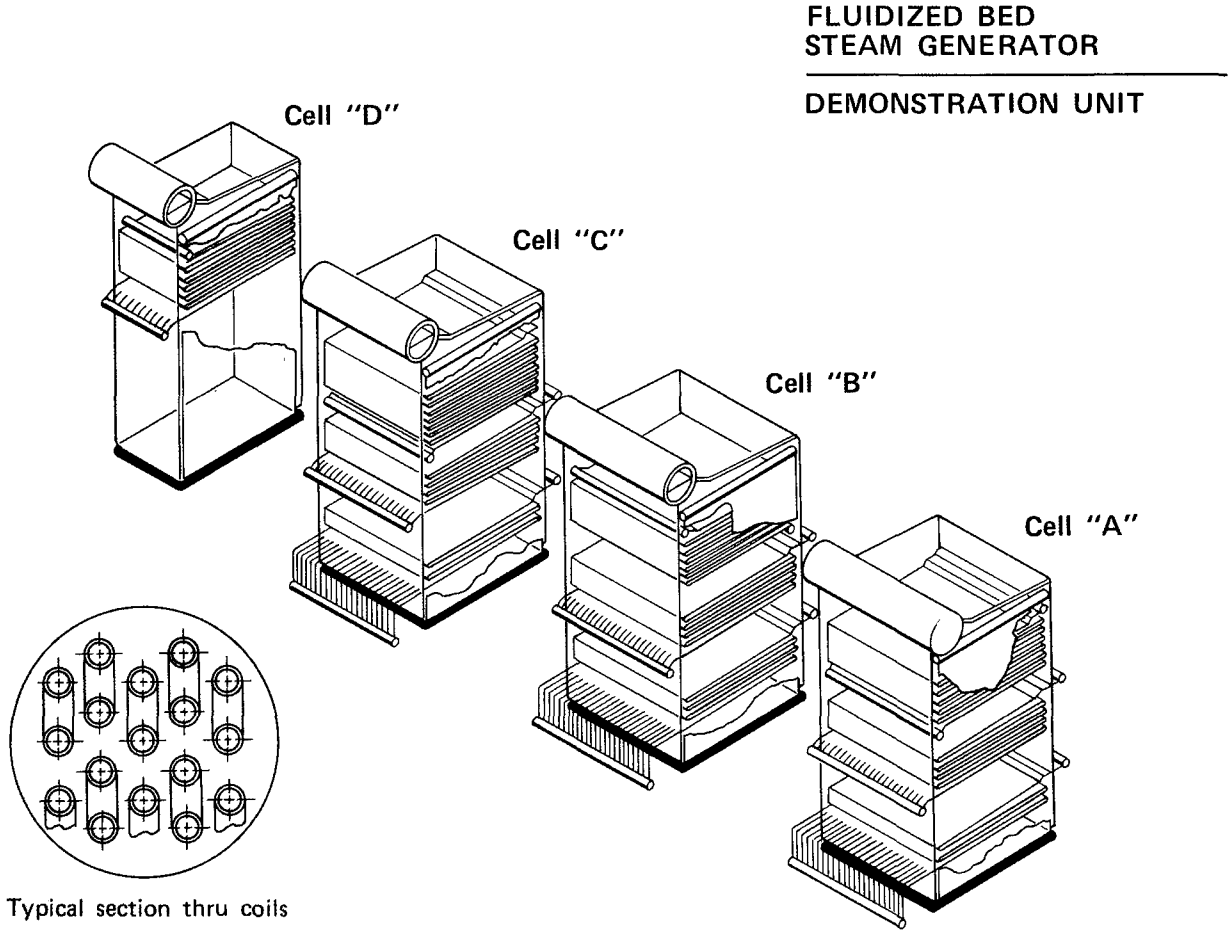

FIGURE 9–*Rivesville MFB–schematic*

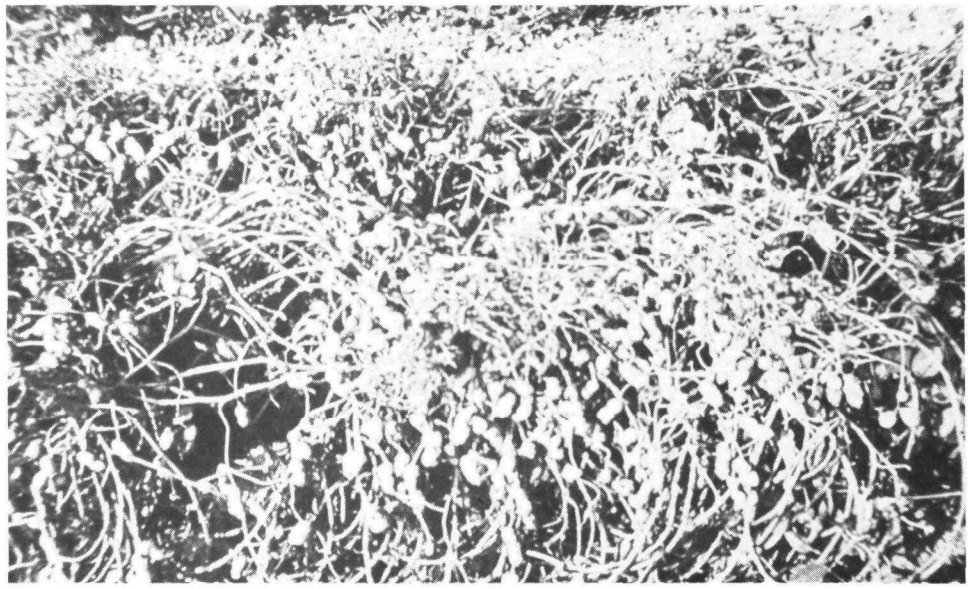

FIGURE 10—*Peanuts grown using FBC solid waste*

WASTE BY-PRODUCT

Figure 10 shows another application of waste by-product. Peanuts were grown using fluidized-bed waste as a substitute for land plaster, which is a mixture of lime and gypsum. Most crops require sulfur. A certain amount of sulfur is removed from the soil and forms part of the crop. Ordinary grass has been grown in greenhouses with sulfur-free atmospheres, as contrasted to the ambient atmosphere, which contains a small amount of SO_2, and in greenhouses with atmospheres containing controlled amounts of SO_2. With no sulfur provided, either via the air or the soil, the growth of ordinary grasses is about half of its maximum capability. That seems to be true of other crops also. FBC solid wastes can be a convenient source of replacement sulfur. We intend to continue this program of evaluating the use of fluidized-bed waste as a nutrient to soils and as a construction material.

Figure 11 shows the Georgetown University industrial boiler. The fluidized bed is the shaded area in the center, with an ordinary convective pass above it and the air distributor plate below it. The boiler will produce 100,000 pounds of steam an hour at 675 psig pressure for cogeneration application.

My discussion so far has focused on atmospheric fluidized-bed combustion, in which the combustion chamber operates at pressure within a few inches of water of atmospheric pressure. Pressurized fluidized-bed combustion (PFBC) at pressures 6 to 16 times atmospheric pressure is being investigated as a means of burning coal for gas turbines. The air for the PFBC comes from the compressor of the gas turbine that is energized by combustion products from the PFBC. By recovering heat from the gas turbine exhaust for a steam turbine unit, the overall combined cycle efficiency of extracting energy from coal is increased above that achieved with conversion cycles based on combustion at atmospheric pressure.

GREATER EFFICIENCY

The efficiency of central station coal-fired power plants several years ago was in the 39 to 40 percent range. When the need for cooling towers arose, the efficiency was reduced to about 38 percent, and the pump circulation and reheat power for scrubbers lowered this even further to about 34 percent. The atmospheric pressure fluidized bed promises to save the fan and reheat power energy losses associated with scrubbers, with an overall plant efficiency in the range of 36 to 37 percent. The combined cycle mode of operation with pressurized, fluidized beds has a potential overall plant efficiency of up to 40 percent.

Beyond the advantage of higher efficiency, and to this particular audience perhaps the prime advantage, is the fact that the data from the pressurized combustion of coal show lower NO_x, better limestone or dolomite utilization and a potential for greater SO_2 absorption.

VALUE OF CONCEPT

The fluidized-bed system is viewed as a combined environmental, energy-efficient, and economically advantageous new system. The value of the entire fluidized-bed combustion concept lies in the compliance with allowable SO_2 emissions, the opportunity perhaps to improve on that, compliance with allowable NO_x emissions, and the opportunity to achieve lower NO_x than the current standards. The NO_x emissions from FBC are down in the range of those for combustion of low nitrogen oil and natural gas. Multi-fuel flexibility is another advantage of fluidized-bed combustion. Fluidized beds have been used to burn low grade coal, high sulfur coal, wastes from coal cleaning plants, industrial wastes, and forest residues.

The materials, technology, and shop labor needed to manufacture the equipment for fluidized beds is the same as that for conventional boilers, but the higher heat transfer coefficients in fluidized beds are more compact. Because the fluidized-bed boiler requires less material, it is probably less expensive than a conventional boiler. The optimization of design and fabrication techniques is expected to convert material savings into a 10-percent saving in boiler costs.

LOW NO_x LEVELS

Fluidized-bed combustion is a cleaner, more efficient, and potentially lower cost method of coal combustion. With the continued use of coal through the year 2000, at the predicted rates, fluidized-bed combustors will permit lower NO_x levels by a substantial amount, perhaps 30 percent. The overall environmental impact of burning coal can be further moderated by employing the benign solid wastes produced by the fluidized-bed combustion process as a substitute for other extracted resources.

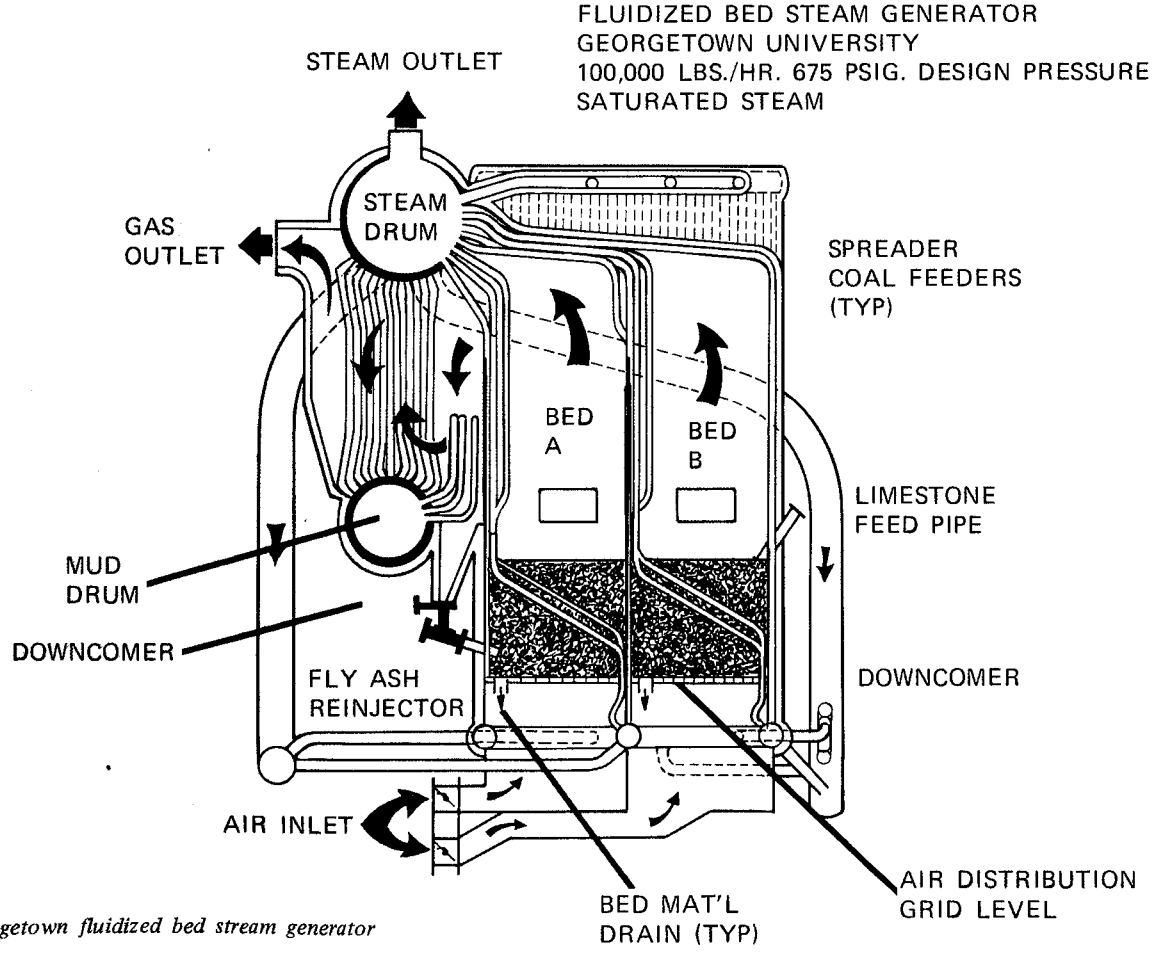

FIGURE 11—*Georgetown fluidized bed stream generator*

CONTROL OF PARTICULATES FROM COMBUSTION

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EMISSION ESTIMATES

Millions of tons of particulates are emitted into the atmosphere every year. In the year 1976, the total nationwide emission estimates were 13.4 million metric tons of which stationary fuel combustion sources contributed 4.6 million metric tons (1). Most stationary fuel combustion emissions were from electric utilities and were estimated to be 3.2 million metric tons. As of 1975, the total electric power generation for fossil fuel plants of 25 MW or greater was 347,720 MW (2). Of this total, 60% was generated with coal; 19%, oil; 21%, gas. Between now and 1990, combustion of gas and oil is expected to remain relatively constant but the combustion of coal could almost double (3). Hence, particulates from cumbustion are not only a major source of total particulates now but also a continuing problem for the future.

HIGHLY VARIABLE PROPERTIES

The properties of combustion particulates or fly ash are under intensive study and are known to be highly variable. For example, the particle size distribution can include a small or large fraction in the respirable range. Tests performed by EPA's Industrial Environmental Research Laboratory at Research Triangle Park (IERL/RTP) show that the mass median diameter can range from 9 to 50 μm(4,5,6) for fly ash from coal-fired power plants (figure 1). Because of the large size distribution of fly ash (geometric deviations of 3.3 5.0), even a mass median diameter as large as 50 μm implies a significant emission for particle sizes less than 3 μm. It has been estimated that coal-fired power plants release 0.6 million tons/year in the 1-3 μm range, 0.2 in the 0.5-1.0 μm range, and 0.1 in the 0.1-0.5 μm range (7). Coal-fired industrial boilers and oil-fired power plants and industrial boilers also have significant emissions in the 1-3 μm range of 0.1 and 0.2 million tons/year, respectively (7).

PHYSICAL STATE

Other properties of interest for fly ash are the physical state and composition. With respect to physical state, fractions of fly ash have been characterized according to relative abundance of 12 morphological classes (8). The most abundant forms were the nonopaque solid spheres and nonopaque cenospheres. Other important types were the rounded, vesicular nonopaque and the amorphous nonopaque. Variation in physical state with particle size has been noted with predominance of the opaque solid spheres in the submicron range. Morphology can be related to composition. Coal components give the opaque amorphous particles, iron with silicates give opaque spheres, and silicates give nonopaque particles.

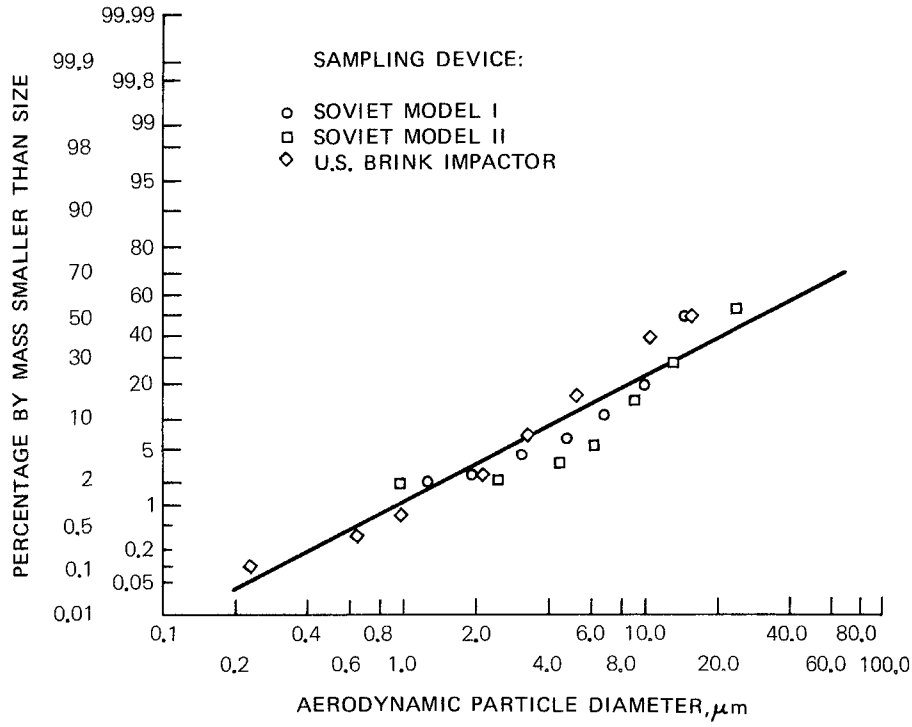

FIGURE 1—*Typical inlet size data for coal-fired power plant particulate*

TRACE ELEMENTS

Trace elements are to be found in fly ash and in some cases represent a significant fraction of the total emission of that element (9). Annual emissions in coal-fired power plant fly ash for arsenic are 493 tons; beryllium, 99 tons; lead, 706 tons; and mercury, 173 tons. Given the above trace elements, the toxic and carcinogenic effects of fly ash are suspected. Currently, biological testing has shown that both organic and inorganic mutagens are present in coal fly ash (8). Further testing is needed to determine if these mutagens are also carcinogenic.

ESP'S

For conventional combustion sources, the control options available are electrostatic precipitators (ESP's), fabric filters, scrubbers, cyclones, and combinations of devices such as an ESP followed by a scrubber. With respect to ESP applicability, IERL/RTP tested them on coal-fired utility boilers and concluded that a high level of control was possible even for very small particles (table 1 and figure 2). It is believed that the removal efficiency of an ESP would drop rapidly for particles below about 2 μm in size. This is the size at which the main particle charging mechanism called field charging begins to become ineffective. Even in the submicron range, these results indicated that significant collection, and thus particle charging, occurs. The charging process, which comes into significance on these very small particles, is termed diffusion charging. ESP's are widely used today on coal-fired utility boilers. They cost more to install than scrubbers or fabric filters, but they are less expensive to operate. The main drawback to current ESP's is their inability to effectively and economically trap certain types of fine particles—such as fly ash from low-sulfur coal. These are particles with high electrical resistivity, which makes them difficult to collect electrostatically without incurring very high initial capital costs.

SCRUBBERS

Wet scrubbers have been used as particulate collection devices since the early 1920's. Although they are inexpensive to install compared with large baghouses or ESP's, scrubbers are costly to operate. They require large amounts of water and electricity and create a sludge.

TABLE 1
Results of field tests on electrostatic precipitators

Source	Type ESP	SCA sq m/actual cu m/sec	Temperature, °C	Efficiencies, % Particle Diameter: Overall	2 micron	1 micron	0.5 micron	0.1 micron	Comments
Coal-Fired Boiler	Cold Side	54	150	99.6	98.9	97	95	98	Moderate sulfur coal
Coal-Fired Boiler	Cold Side	54	160	99.8	99.9	99.6	99	99	High sulfur coal; no impactor data
Coal-Fired Boiler	Cold Side	65	160	98.3	99	96	80	98	Low sulfur coal
Coal-Fired Boiler	Hot Side	85	375	99+	99.6	97	95	99.3	Tests completed; data not reported

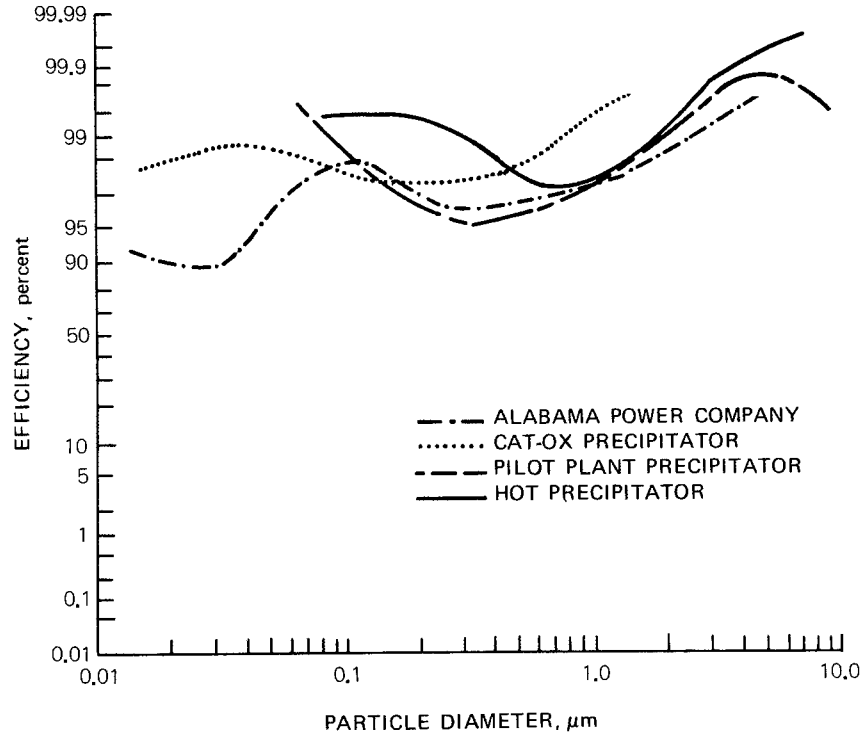

FIGURE 2—*Measured efficiency as a function of particle size for precipitators*

SCRUBBERS TESTED

IERL/RTP's Particulate Technology Branch has tested scrubbers of conventional design on a variety of particulate sources. In general, the efficiency of a scrubber drops off rather rapidly as the particle size decreases (figure 3). The efficiency is directly related to the energy consumed by the scrubber. Table 2 shows these results in terms of the cut diameter and in terms of the diameter at which the efficiency falls below 80%.

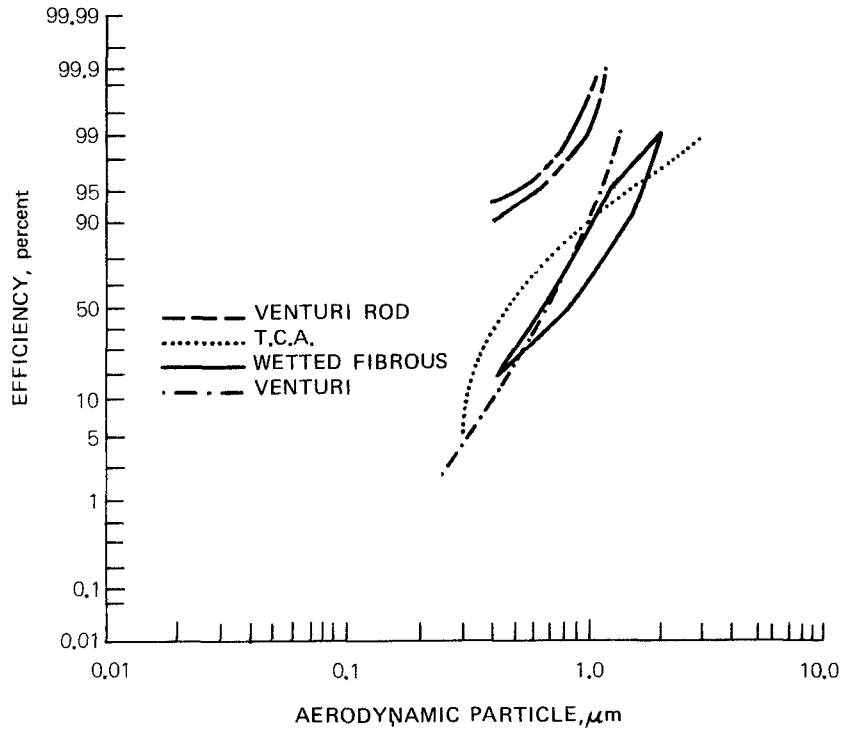

FIGURE 3–*Fractional efficiency versus aerodynamic diameter for scrubbers*

TABLE 2
Fine particle control by scrubbers

Name	Pressure Drop, cm WC	Smallest Diameter Collected at Stated Efficiency, μm	
		80%	50%
Ducon	8	1.6	1.3
Wet Fiber	19	1.1	0.6
Chemico Venturi	25	0.9	0.7
UOP/TCA	30	0.7	0.35
Venturi Rod	273	0.5	0.3

COLLECTION EFFICIENCY

The Particulate Technology Branch (PATB) has also tested collection efficiency down to 0.08 μm and found that scrubbers, have a minimum in their collection curves analogous to ESP's. The efficiency of a TCA scrubber on a coal-fired power plant decreased to 30% collection at 0.4 μm and then increased back to 97% to 0.08 μm (figure 4). As with the ESP minimum, two mechanisms are involved. For coarse particles, collection is by impaction and for very fine particles, collection is by diffusion. Since 0.4 μm diameter particles have neither a high diffusivity nor a large inertial mass for impaction, they are the most difficult to collect.

FABRIC FILTERS

Fabric filters or baghouses have the highest efficiencies in collecting particulate emissions and are the most effective in controlling fine particulates. The Particulate Technology Branch has tested two installations on utility boilers and one on an industrial boiler (10,11). The results of these tests show greater than 95% collection at all sources in all size ranges tested from 0.1 to 4 μm (figure 5). Following are the results for each site:

- At the Sunbury pulverized coal-fired power plant with glass/Teflon bags and an air-to-cloth ratio of 2, the overall mass removal efficiency was 99.9%. The outlet loading was 0.0039 grams/m^3 (0.0017 g/dscf). The efficiency was 99% at 0.1 μm, near 98% at 0.5 μm, and above 99% at 1.0 μm.

- At the Nucla stoker coal-fired power plant with graphited glass bags and an air-to-cloth ratio of 3, the overall mass removal efficiency was 99.8%. The outlet loading was 0.0071 g/m^3 (0.0031 gr/dscf). The efficiency was 99% at 0.1 μm, 99% at 0.5 μm, and greater than 99% for 1.0 μm.

- At the Kerr Industries stoker coal-fired industrial boiler with Nomex bags and an air-to-cloth ratio of 3, the overall efficiency was 99.2%. The outlet loading was 0.0046 g/m^3 (0.002 gr/dscf). The efficiency was almost 99% at 0.3 μm, about 95% at 0.6 μm, and back up to greater than 98% at 2.0 μm.

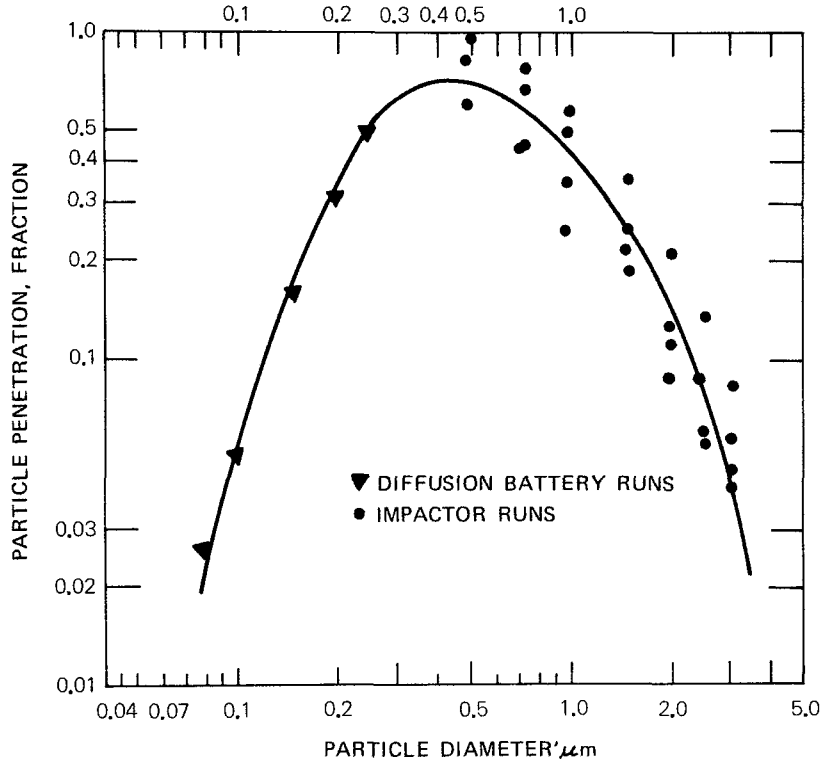

FIGURE 4—*Fractional efficiency of a TCA scrubber*

CYCLONES

Among the least expensive particulate collectors are cyclones. These are widely used to clean up industrial operations like grinding and polishing metals, crushing stone and gravel, and woodworking. Though cyclones are very efficient for large particles, they are only about 40% efficient for fine particles. The efficiency of cyclones can be improved by increasing the velocity of the airflow—but only at the cost of substantially more energy. As a result, cyclones work best on sources that do not emit great numbers of fine particles such as combustion sources.

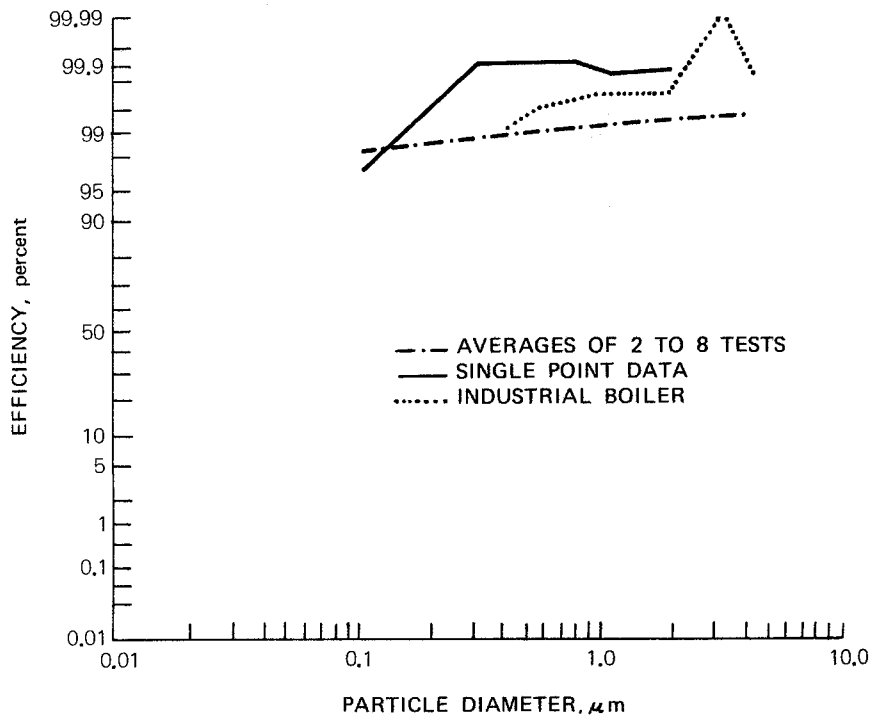

FIGURE 5—*Baghouse performance on utility boilers*

CONTROL DEVICE COMBINATIONS

Recently, combinations of control devices have become of interest. The use of scrubbers for SO_2 control combined with other devices for particulate control offers some potential advantages. If the particulate control device treats the flue gas before the scrubber, the scrubber circuit will be relatively free of fly ash, allowing easier treatment or reuse of scrubber products. If one of the control devices must be taken out of service for maintenance, the remaining control device will continue to collect the primary pollutant for which it was designed and may also provide some collection for the other pollutant. If the combination of interest is an ESP followed by an SO_2 scrubber, both the control devices provide particulate collection and the ESP may be designed smaller than one not followed by the scrubber. This last conclusion resulted from a PATB in-house study using pilot scale equipment and computer models which produced the results shown in figures 6 and 7. Figure 6 shows the penetration curves for each control device by itself. As noted previously, the efficiency of the scrubber decreases rapidly with decreasing particle size, and efficiency of the ESP decreases more slowly to a minimum around 0.5 μm. Comparing the 95% efficient ESP and the scrubber with a 25 cm. pressure drop shows that the scrubber is more efficient above 0.8 μm and the ESP more efficient below 0.8 μm. In combination they add to each other's capability with the result shown in figure 7. To achieve this result with a scrubber alone, the pressure drop would have to be increased greatly to collect the very fine particles. Similarly, with an ESP alone, the specific collector area (SCA) would have to be increased greatly to collect large particles as efficiently as the ESP/scrubber combination. Working together, the ESP and scrubber can provide collection capabilities equal to more expensive single devices because of the different ways ESP's and scrubbers collect different particle sizes.

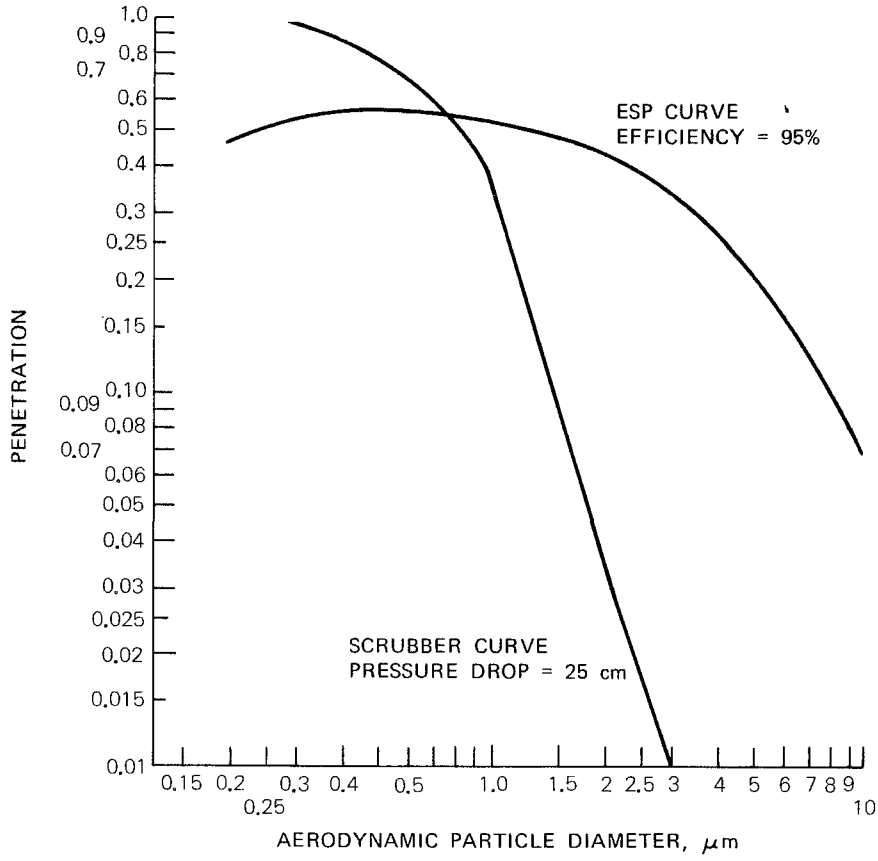

FIGURE 6—*Predicted penetration as a function of particle diameter*

ADVANCED POWER CYCLES

For advanced power cycles, control options include granular beds, ceramic filters, dry scrubbers, and high temperature/pressure ESP's. These devices must be applied to the specialized requirements of coal gasification, magnetohydrodynamics (MHD), or fluid bed combustion (FBC). In coal gasification, coal is converted to synthetic gas by burning under carefully controlled conditions at high temperature and pressure—temperatures as high as 1830°C at 1 atmosphere and pressures up to 100 atmospheres at 930°C. Much of the energy in the coal is retained by the synthetic gas to be burned in gas turbines, boilers, furnaces, kilns, or heaters. As supplies of natural gas become less abundant, it is proposed to use synthetic gas produced by coal conversion in pipelines to industries and homes, eliminating the need to replace gas-burning equipment now in use.

PRESSURIZED FBC

Another important coal conversion process is pressurized FBC. Here, coal is burned under pressure in a bed of limestone or similar material resulting in 820°C combustion gases to be cleaned. The sulfur in the coal is removed by the limestone in the bed. The combustor generates both steam for electric power or industrial uses, and hot pressurized gases, which can be used to drive gas turbines. Typical gas parameters and particulate characteristics of gasifier and FBC streams are shown in table 3.

Since these processes are at high pressure, the control device must be contained in a pressure vessel and hence it is economically imperative to keep the control device small. Since operating temperatures for the control device are above 820°C, ceramic materials must be used as collection media. Granular beds and dry

CONTROL DEVICE

scrubbers use discrete ceramic particles as collection sites. In a granular bed, the ceramic particles are fixed or moving with the particulate laden gas passing through the bed. Collection is by impaction, interception, and diffusion. In a dry scrubber, the ceramic particles fall through the particulate-laden gas which can be accelerated as in a venturi scrubber in order to maximize impaction collection. The ceramic filter can be either a ceramic membrane barrier or a ceramic baghouse. The high temperature/pressure ESP is likely to be similar to conventional low temperature wire-and-pipe designs.

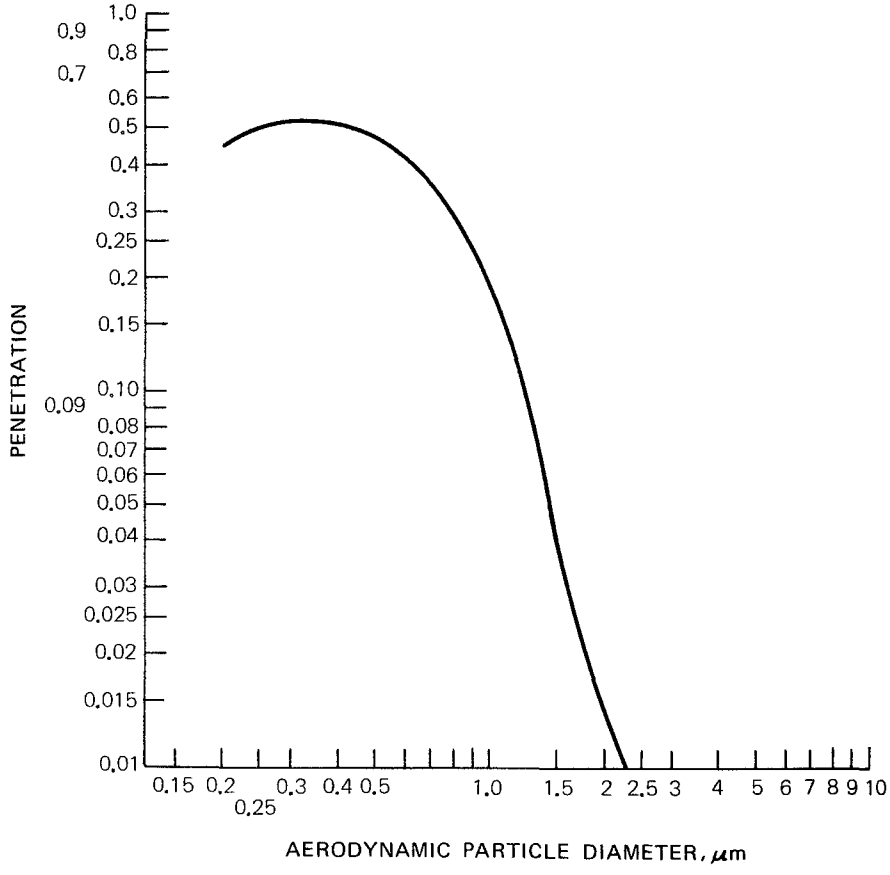

FIGURE 7—*Predicted penetration as a function of particle diameter for ESP and scrubber*

TABLE 3
Ranges of gas steam and particulate characteristics for advanced energy processes

	FBC	Gasifier
Temperature, °C	760-980	150-1,100
Pressure, atm	1-10	1-70
Mass Loading, g/Nm^3	0.09-4.8	18-230
Mass Median Diameter, μm	1.2-8	⩽300
Gas Composition (Major Components)	N_2, CO_2, O_2	H_2, CO, CO_2, N_2
	H_2O, SO_2, NO, CO	H_2O, CH_4, H_2S

PARTICULATES

Particulates are one of the six air pollutants thus far identified by the Environmental Protection Agency (EPA) as having "potential for widespread adverse effects on human health and welfare." Acting on the authority of Section 109 of the Clean Air Act, December 1970, EPA has set a primary National Ambient Air Quality Standard of 75 micrograms per cubic meter (annual average) for total suspended particulates. Within the same act, Section III, EPA was also given the authority to set standards of performance for new stationary sources. The Act as revised by the 1977 Amendments states that the standard should reflect "the degree of emission limitation achievable through the application of the best system of continuous emission reduction which (taking into account the cost of achieving such reduction and any nonair quality, health and environmental impact and energy requirements) the Administrator determines has been adequately demonstrated for that category of sources." For particulate emissions from utility boilers, the current limit is 43 ng/J (0.1 lb/million Btu)(12). A revision in this standard is currently under consideration. Preliminary drafts suggest that the standard might be 13 ng/J (0.03 lb/million Btu). Another possible control standard which would apply to particulate from combustion sources is Section 112 of the 1970 Clean Air Act Amendments which deals with national emission standards for hazardous air pollutants. This standard would apply to an air pollutant which may cause an "increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness."

NATIONAL R&D PROGRAM

As part of the development and enforcement of air pollution standards, Section 103 of the 1970 Clean Air Act Amendments states that EPA will establish a national research and development program which will, among other activities, do the following:

- Conduct and promote the acceleration of research, experiments, and demonstrations relating to prevention and control of air pollution.
- Conduct investigations and research and make surveys concerning specific problems of air pollution.
- Develop effective and practical processes, methods, and prototype devices for the prevention or control of air pollution.

It has been estimated that, in the next 15 years, coal consumption will increase dramatically because of dwindling supplies of oil and natural gas. By 1990, total coal consumption is expected to be close to 1.3 billion tons annually, which is almost twice the current rate.

LOW SULFUR COAL

Much of the coal burned today is eastern coal mined in Pennsylvania, Illinois, West Virginia, and Kentucky. However, since the early 1960's the use of western coal has expanded dramatically, partly because of increased western energy needs and stricter SO_2 emission control requirements. Some of the low sulfur western coal is being shipped to eastern plants to avoid the need for flue gas desulfurization. With the enactment of the Clean Air Amendments of 1977, SO_2 emissions from new coal combustion sources must be reduced by a constant percentage whether western or eastern coals are fired. This will make it more difficult to comply with future federal new-source performance standards by firing low sulfur western coal without flue gas treatment. Consequently, expanded use of low sulfur western coal to meet SO_2 control regulations will be tempered. In spite of this mitigating factor, it is expected that there will be a substantial increase in the use of western low sulfur coal.

CONDITIONING AGENTS

Unfortunately, combustion of low sulfur coal produces fly ash with high electrical resistivity which is difficult to collect. Current solutions to the low sulfur coal particulate control problem include conditioning of the fly ash and changes in operating temperature of the ESP. Experience with conditioning agents can be summarized as mixed. They work sometimes and don't work other times. It is impossible to predict in advance which additive and how much of it will allow a given ESP to work. Probably the major unresolved problem with conditioning agents is their environmental impact. Even under best case conditions, the use of conditioning agents changes the chemical composition of the particulate, and in

some cases the gaseous emissions of a power plant. At least in some cases, this change in chemical composition may have adverse environmental impact.

HOT-SIDE ESP'S

If the operating temperature of the ESP is either lowered or raised, the resistivity of the fly ash is lowered and performance of the ESP enhanced. The typical application of this effect is to place the ESP before the air preheater instead of after the preheater in the power plant flue system. The precipitator is then on the hot side of the air preheater and operates at 400°C instead of 150°C. Although hot-side ESP's used by eastern utilities are satisfactory, hot-side ESP's used to control particulate emissions from power plants in the west burning low sulfur western coal perform worse than expected. The reason for the poor performance of these hot-side ESP's in the west is at present unknown.

In addition to problems with particulate from combustion in conventional systems, a new set of problems arise in advanced power cycles. Process constraints dictate control of particulate emissions at high temperature and pressure where materials problems are a major concern. The particulate matter under these conditions may be sticky or tend to agglomerate and blind the collection surface of the control device. Potential control devices are by and large only in an early state of development and high temperature cyclones will not meet current, much less revised, standards applied to conventional power systems.

Granular bed filters are being evaluated at the Exxon miniplant and at Air Pollution Technology, Inc. Difficulty in cleaning the bed has resulted in efficiencies falling from 92% to 46% during a 24-hour run at Exxon. Work at APT shows that good fine particle removal can only be obtained when using deep beds of fine granules. Unfortunately, because of entrainment of granules during bed cleaning, deep fine beds are the most difficult to clean.

PROBLEMS AND LIMITATIONS

Problems and limitations of high temperature and pressure control devices can be summarized as follows:

Device or Technology	Major Problems *or Limitation*	Can Meet *13 ng/J?*
Granular beds	poor efficiency	no
Ceramic filters	difficult to clean	yes
Dry scrubbers	high pressure drop	yes
Ceramic bags	unknown bag life	yes
Electrostatic precipitators	unknown operation	unknown

Use of coal cleaning may also present some future problems in particulate control. Although the percent ash in the coal will be reduced, the removal of sulfur gives rise to a high resistivity fly ash as experienced with low sulfur western coals. Problems with high resistivity ash were noted above. Another potential problem is that combustion of cleaned coals will produce a very fine particulate emission which will be difficult to collect because of its size.

EPA has completed work to determine the electrical conduction mechanisms in fly ash at high temperatures (390° C). Work in this area is being extended to low temperatures. An outcome of this work has been the demonstration of sodium as a potential conditioning agent to reduce fly ash resistivity. EPA has evaluated and published reports on conditioning agents such as SO_3 and NH_3. Conditioning appears to be a possible solution to retrofit problems, but not for new installations. Conditioning will not be a solution if it causes adverse environmental effects. IERL/RTP will conduct further tests to assess the total impact of conditioning. One test has already been completed; preparation for others is currently in progress.

PARTICLE CHARGING

Specially designed charging or precharging sections are a possible means of improving the collection of fine high-resistivity particles. A fundamental study and limited pilot-plant work on particle charging was begun in FY-74. This work was continued through FY-76 and resulted in a laboratory demonstration of the feasibility of the concept. A pilot-scale demonstration was funded in FY-77.

ESP MATHEMATICAL MODEL

A mathematical model for the design of ESP's was completed in FY-75. This model is in two forms: a design and selection manual for the plant engineer and a programmed computer version for the design engineer. The model predicts well the performance of ESP's down to particle sizes approaching 0.01 μm. Programs in FY-76 and -77 resulted in improvements in this model in the areas of defining the effects of gas distribution, rapping, and reentrainment.

The major thrust of EPA's scrubber program has been aimed at developing and demonstrating flux force/condensation (FF/C) scrubbers. In an FF/C scrubber, water vapor is condensed in the scrubber. When the water vapor condenses, additional forces and particle growth contribute to particle collection. When the water vapor or steam is free, FF/C scrubbers are low energy users. However, when water vapor or steam has to be purchased, FF/C scrubbers require additional energy for efficient particle collection. Answers to questions of how much steam is needed and how much is free are major unknowns. Answers to both questions are likely to be source specific. Thus, pilot demonstrations on a variety of sources are necessary to provide required data. One pilot demonstration has been completed; a second is underway.

ENTRAINMENT SEPARATOR

Overall efficiency of a scrubber system is determined by the efficiency of the scrubber and the efficiency of the entrainment separator. Recent field data indicate that in some cases inefficient entrainment separator operation is a major cause of poor fine particle collection by scrubbers. The EPA has recently completed a systems study of entrainment separators. In FY-76 the design of these separators was optimized for fine particle control. This design is now ready for demonstration.

Filtration work performed under IERL/RTP's PATB has been aimed at acquiring information for a two-fold use: incorporation into mathematical models and addition to the empirical knowledge used by designers and operators for everyday operation. This work has included studies of fiber property and fabric-type effects, evaluation of new fabrics, development of mathematical descriptions for specific parts of the filtration process, characterization of fabric filters in the field, investigation of electrostatic effects, support of a pilot (and now a demonstration) program to apply fabric filtration to industrial boilers at a several-fold increase over normal filtration velocity, studies of cleaning and energy consumption in bag filters, and a pilot program for control of municipal incinerators.

The fabric filter has recently become important as a control device for utility boilers burning low sulfur coal; fly ash is very difficult and expensive to control with ESP's. In FY-77 the EPA funded a demonstration test of a baghouse installed on a 350 MW boiler burning a low sulfur coal.

FABRIC EVALUATION

Accomplishments of the fabric evaluation program include the following:

- Demonstration of superior filtration performance by spunbonded fabrics, compared with similar weights of woven fabrics of the same fiber. The laboratory evaluation justifies field evaluation of this fabric.

- Confirmation of the unique filtering action of one of the classes of polytetrafluoroethylene (PTFE) laminate fabrics. The fabric filtered fly ash very effectively, especially for particle sizes in the respirable range (0.01 to 3 m).

- Identification of polyester as suitable for filtering cotton dust.

- Measurement of the performance of uncalendared needled felt fabrics in the pulse-jet unit and measurement of the endurance of variously coated fibrous glass fabrics in the high temperature baghouse.

MOBILE COLLECTORS

A fleet of mobile conventional collectors that can easily be transported from source to source and tested has been constructed for use in support of this program.

The fleet includes a mobile fabric filter, a mobile scrubber, and a mobile ESP unit. These highly versatile mobile units are used to investigate the applicability of control methods to control fine particulate emitted from a wide range of industrial

MOBILE UNITS IN OPERATION

sources. Relative capabilities and limitations of these control devices are being evaluated and documented. This information, supplemented by data from other IERL/RTP particulate programs, will permit selection of collection systems that are technically and economically optimum for specific applications.

The mobile fabric filter unit has been operated on effluents from a brass and bronze foundry, a hot-mix asphalt plant, a coal-fired boiler, a lime kiln, and a pulp mill recovery boiler. It has also been used to determine the performance of a fabric filter on air emissions from a cyclone collector used on the St. Louis Refuse Processing Plant. The filter unit most recently was operated at a Southwest Public Service Company site to obtain preliminary data for an EPA funded demonstration of a fabric filter on a 350 MW boiler burning low sulfur coal. The mobile wet scrubber unit has been operated on a coal-fired power plant, a lime kiln in a pulp and paper mill, and on a gray iron foundry. The mobile ESP is operating in the field for the first time, on an industrial boiler burning a mixture of coal and pelletized refuse. This was used at a field site to evaluate the effects of sodium conditioning on a low sulfur western coal, and is currently being used on the hot side of the air preheater at a western power plant to help determine the reasons behind the failure of hot-side ESP's to perform as well as design would predict when used to control fly ash from western low sulfur coals.

TEST RESULTS

In the high temperature/pressure particulate control area, bench scale work on ceramic filters and ceramic bags has shown that the media can survive operating conditions and provide high collection efficiencies (table 4). As with aqueous-scrubber results, study results for dry scrubbers prove that they will require high pressure drops to achieve good fine particle control unless an analog to the charged droplet scrubber can be developed. The ESP tests have demonstrated stable corona; however, no efficiency data or projections are available yet.

TABLE 4
Developments in high temperature/pressure particulate control

	Completed to Date	Measured Efficiency, %	Problems	Conclusions
Ceramic Filters	850 m^3/hr tests	93-100 at 820°C[13]	Difficult to clean sticky particles	Requires in-house tests on cleaning of more open geometries
Dry Scrubbers	Feasibility Study	90 at 1.0 μ[14]	Efficiency falls rapidly with decreasing size	Need to improve submicron capture efficiency
Ceramic Bags	Screening Tests	56-90 for felts using 0.3 μ particles and no filter cake[15]	Long term endurance unproven	Requires media development and life testing
Electrostatic Precipitators	Map of Stable Corona	N/A	Only static tests with clean plates to date	Need to evaluate a flow system to predict efficiency

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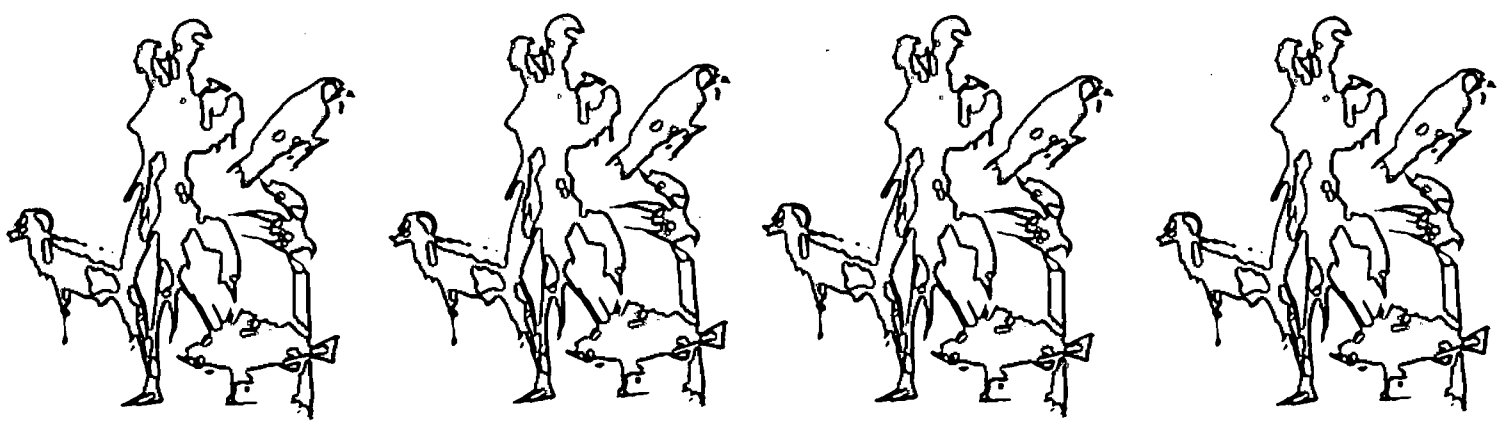
panel discussion



CONTROL TECHNOLOGY PANEL DISCUSSION

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MR. PRINCIOTTA: On the basis of what we have heard about sulfur control, we are going to have to rely for the next 5 or 10 years upon conventional coal combustion with scrubbers, perhaps supplemented by coal cleaning. Norman Kaplan's paper presented a relatively optimistic view of the status of the technology. I would like to ask what our panelists think is the current status of scrubbers or flue gas desulfurization, and on what problems they think we should focus our research over the next 5 or 10 years.

MR. ELDER: Mr. Kaplan left us with the impression that this technology was ready, near-term, and cost-effective. From the utility viewpoint, at this stage we see it as a potentially viable technology. When it is ready, it will be expensive. The EPA program in control technology for pilot plant and prototype work has been a good program. We have learned a lot in the past 10 years about the factors that affect scrubber operation, particularly the chemistry-related factors. It has, however, involved fairly small-scale research testing, which does not face up to the real problems of reliability. At the current stage of scrubber development the problems with reliability are more mechanical factors than process factors.

Mr. Kaplan mentioned plugging and scaling as the problem areas. These are related primarily to how we react the limestone, lime, or sodium, the SO_2 and the flue gas. What is the variability of the SO_2 in the gas? What is the variability in the absorbent or the raw materials used? We have fairly good understanding of these process questions now. If we can control the inputs to the scrubber system, we can avoid these problems rather well. What we do not yet know enough about is the mechanical design of many of the components, such as dampers, pumps, and valves—components that control flow of both gas and liquid in the absorber itself. These are the areas that we need to concentrate on to improve reliability so that we can design a system and expect it to operate at the designed conditions.

In regard to cost, Mr. Kaplan told you that fuel gas desulfurization (FGD) would add 10 to 20 percent to the cost of power generation. I think those numbers are based on a new plant at maximum capacity. The numbers we have developed show that the net increase in cost is about 20 to 25 percent if we take into account the full-term life of the scrubber installed in a new power plant. For retrofit, to build a scrubber in an already existing plant, it becomes even worse. It can double that number. For example, in one of our TVA systems, an existing 500 megawatt plant has been equipped with scrubbers. At that single plant the cost for generation of power has gone up 50 percent. But it was a retrofit, and the investment had to be amortized over a short period. All these things influence the percentages that are shown in cost estimates.

MR. YEAGER: At the present time, in scrubber technology application in utilities we need a site-specific design basis. Our ability to predict, design, build, and operate a plant by current scrubber technology with predictable results is very poor. Although I appreciate Mr. Kaplan's curve on the improvement and availability, from the same data we have not been able to derive the same kind of relationship. We have found very little change in the performance of scrubber systems that have been put in over the last 5 years. In the high-sulfur eastern coal region, those systems that have worked well from an availability standpoint benefit from having a load factor which permits continuous maintenance and cleaning of some portion of the scrubber system at all times and an unrestricted maintenance requirement on the part of the particular utility. We do not feel, therefore, that this is the solution to the problem. This is not to indict scrubbers; it is simply a statement about our current technology and where it should be going.

Given the regulatory direction in terms of air and by-product disposal, by-product disposal problems will become increasingly important, so a second major objective is to avoid sludge production, whether it be gypsum as a dry by-product, sulfur, or sulfuric acid. Most importantly, it will mean a retrofit capability to systems which are going in now, almost all of which produce sludge, to avoid the necessity within 5 to 10 years of ripping out all the hardware and replacing it with something new.

The third item on the development agenda is a realistic ability to produce elemental sulfur. By realistic, I mean one which does not require reducing natural gas or putting a coal gasifier on the scrubber. Elemental sulfur is certainly not the product we would propose for all portions of the country, but certainly, in many areas of the east, the land, environmental, and market requirements will drive people in that direction.

DR. BELDING: Previous speakers have talked about reliability, solid waste, and cost. They are important. But it may require a combination of coal cleaning and scrubbers to solve the problem. I am not convinced that we can lay the whole responsibility on scrubbers. We have to look at a combination of things in the future. We have to scale up and look at reliability and cost. We need to look at the whole system.

MR. PRINCIOTTA: Obviously, there are problems with flue gas desulfurization systems. In view of that, which of the emerging energy technologies—such as fluidized-bed combustion, solid refined coal, low Btu gasification, or chemical coal cleaning—is most likely to displace conventional pulverized coal technology with scrubbers, and in what time frame?

MR. SINGER: The Department of Energy is taking quite an aggressive approach to the commercialization of these emerging technologies. It is too early to say which technology might replace scrubbers, but we have formed about 14 task forces within the Department to look at the different emerging technologies. The task forces are just beginning to get some preliminary indications of the readiness of each of the technologies for commercialization.

I am personally participating in the coal liquids technology. There has been some indication of user interest in coal liquids. We foresee the first application of these products for electric power generation in the 1990's. We expect to be working over the summer to develop a marketing plan for the commercialization of the technology. All the task forces will be doing much the same thing.

DR. BELDING: The Department of Energy is looking at a variety of technologies. In addition to the atmospheric fluidized bed and the pressurized fluidized bed, we are also looking at combined cycle systems, which have the potential of being fairly efficient, low-cost machines.

I do not think the Department is going to decide which technologies are viable; it will, instead, be the user. We have to look at the economics. Can we, in fact, meet the EPA requirements? Can we do better than the requirements? These are questions that users will be interested in. Mr. Yeager and Mr. Elder can address these questions better than we in the Government can, because they will be buying the machines. They would like a variety of products to choose from, to foster competition and, perhaps, lower some of the current rates.

MR. YEAGER: On a national basis, with the uncertainties of economic and environmental considerations, we probably cannot afford not to develop all the options we have. From the utility standpoint, liquids, as a probable retrofit fuel for oil-based capacity, as well as peaking fuel, are going to be important contributors to the industry at some future time. When we look at options for base load capacity, however, we start having some problems.

Pursuant to Dr. Belding's comments in the environmental area, let me add one comment. We are qualitatively changing our environmental definition and specifications concerning what we consider "clean." In the past we considered technologies clean because of the low sulfur content or low sulfur oxide emissions. With the introduction of toxics requirements, however, such as a very stringent NO_x restriction, the technologies need to be re-examined. While the requirements can generally be met, the economic relationships change considerably. Technologies such

as gasification combined-cycle processes seem to, and may actually, be competitive with or superior to conventional plants from an economic and environmental standpoint. We must now re-examine the economics in terms of what it takes to totally isolate any toxic emissions from the environment. Great interest has been shown in fluidized-bed combustion, particularly AFBC, both because of its relative simplicity and because of its ability to burn a variety of fuels, solving what is a real industrial problem as coal sources change considerably over the lifetime of a plant. AFBC offers the opportunity to solve the problem, but whereas AFBC was, at one point, capable of meeting all the environmental requirements of the combustor, we now have to re-examine the designs in light of more stringent SO_2 and NO_X requirements. This, again, affects the practicality of the technology of the industry. As environmental specifications become more important in our social environment, we must be able to forecast the requirements to the engineers so they can be considered during the development phase and not as an afterthought.

MR. ELDER: Taking a realistic view of the scrubber situation, if low-sulfur coal in the east is not a viable option, it is clear that fuel gas desulfurization is the way to go for the near-term, at least 10 to 15 years. That means a lot of scrubbers are going to be built. There is a lot of incentive for getting that technology to the point where it is productive. We must develop conversion alternatives as quickly as possible so we can ascertain the costs. Although many interesting estimates have been made, they are not yet very informative, and they will not be until we build some full-scale systems and find out what the real costs are. Then we will have an idea of what oil and gas will really be worth to us in the future.

questions & answers

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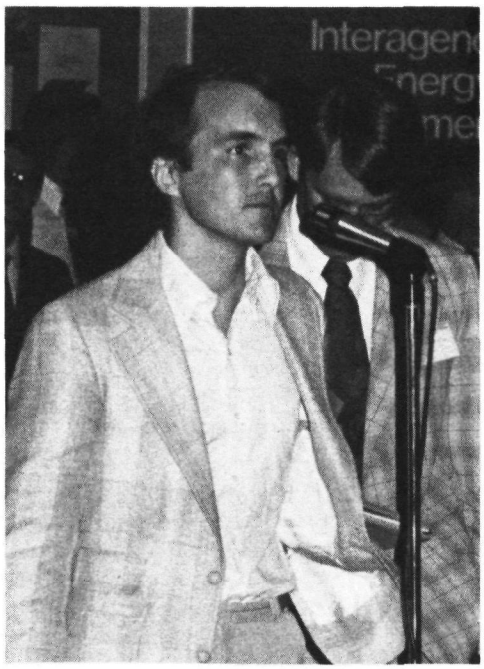


QUESTION

One way to improve the performance of electrostatic precipitators is by flue gas conditioning or improving the resistivity of properties of flue gas. Over 10,000 megawatts of capacity utilize this technology and the effect on resistivity has been the major reason for that utilization. Recently, there has been some indication that we can affect the factor we are most concerned with: We can increase the particle size distribution. What does Research Triangle Park think?

RESPONSE: Dr. Dennis C. Drehmel (EPA)

We have an active conditioning-agent program. Both SO_3 and sodium carbonate are effective conditioning agents. They restore efficiency through a precipitator on a power plant by changing high sulfur coal to low sulfur coal. Unfortunately, our results are mixed and we have problems: Perhaps only three-fourths of the previous capability is returned by the use of conditioning agents or the agents plug up various parts of the boiler. We have had problems with other compounds, precursors or nitrosamines, being formed in laboratory tests on conditioning agents. For the entire story, we need to know what environmental impacts are associated

with conditioning agents, even with SO_3. The overall logic of control strategy has to be questioned. If a low sulfur coal is used to lower the SO_2 which, presumably, is there to reduce sulfates, and an SO_3 agent, which adds back SO_4, is introduced, sulfates are put back. What is the tradeoff on this?

QUESTION

Are the benefits of precombustion desulfurization taken into consideration in the definition of compliance, compliance being 85-percent or 90-percent?

RESPONSE: Mr. Frank T. Princiotta (EPA)

The Clean Air Amendments are quite specific. They indicate that in any percentage, EPA should take into account reduction standards such as the 85-percent sulfur dioxide standard. This includes any precleaning, so that coal cleaning or any other cleaning approach would not be precluded by the standard. It would be counted within the overall percentage removal. In other words, the percentage is counted from the mined coal all the way to the sulfur that ends up in the flue gas.

QUESTION

Similarly designed FGD systems were installed in Japan and in the United States, but their performance has not been equivalent. In evaluating the systems, what significant factors have been noted?

RESPONSE: Mr. H. William Elder (Tennesse Valley Authority)

Technical reasons make the situation in Japan different from that in the United States. First, most of the FGD in Japan is by oil-fired generating capacity, and oil-fired capacity design conditions are very close to the operating condition. The designer knows in advance what the emitted SO_2 concentration is. He designs the system to handle that concentration. SO_2 concentration with oil is much lower than with coal so that the range of operating conditions in the design is different in Japan from that in the United States. The second point is political rather than technical. In Japan, almost without exception, the installed FGD systems have monitoring equipment that telemeters the outlet concentrations directly into the environmental group in the local prefecture or state. They know immediately when a system is not in compliance and crack down on the utility. As a result, we visited several installations that had no violations for a period of 3 to 5 years. Their enforcement mechanism is rigorous.

QUESTION:

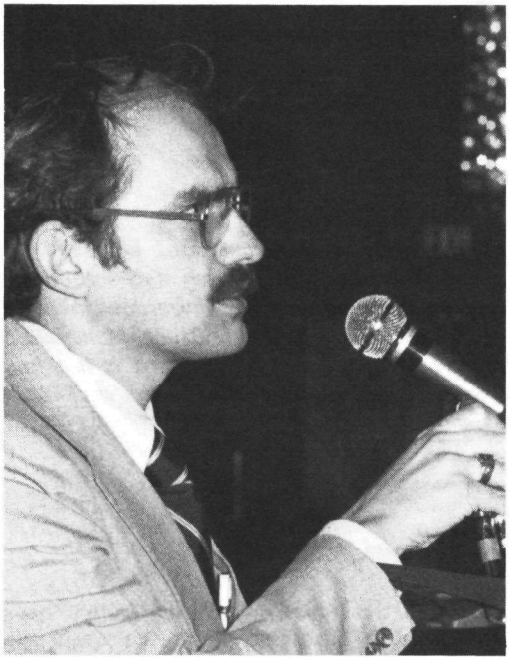
What was your reaction to coal-fired facilities in Japan?

RESPONSE: Mr. Elder

Surprisingly, their average for the sulfur content of coal is 0.7 percent. The sulfur level in the feed stream for the scrubber is normally less than 1/10 variation. To keep that low variability, they are careful about blending and/or selection of the fuel. The system is treated as a chemical plant. There is no redundancy in installed gas equipment or, on the liquid side, in pumps and spare trains and spare modules. Although a little incriminating to the utility industry, a company subsidiary to the utility company usually operates their scrubbing systems. Japanese companies are large and have many subsidiary companies. They therefore can assume the liability for the control system and farm out its operation to a chemical company that is part of the overall group. They have, therefore, paid more attention to process control than the United States has.

QUESTION:

Are there any additional comments?



RESPONSE: Mr. Norman Kaplan (EPA)

Of the 10 systems visited in Japan, the majority were getting 90-percent or more SO_2 removal, with 98-percent availability. At the end of 1977, we have 131 units plus several industrial boiler units, adding up to less than 200 units. Japan has 500 FGD plants. They total 28,000 megawatts—almost three times as much as ours—that are divided 50-50 between utilities and industrial boilers. The only way to determine whether costs are high or low is to compare them with the potential or the real health benefits to our population. Until better information is available from the health benefits people, we cannot make a judgment about our costs. I do not feel that they are high.

Retrofit systems usually cost more than new systems, but when observing new source performance standards, we mean new systems and increased costs for new systems.

The systems in Japan are more dependable. In the United States, we find that where no bypass of the flue gas desulfurization system is allowed, the flue gas desulfurization system is more reliable or more dependable. We can almost legislate the dependability of a flue gas desulfurization system. Another item on dependability is redundancy. At a little higher cost, systems can be designed with redundancy to improve the reliability of the system as is commonly done in the chemical industry. A pump critically required to be in operation all the time is spared. If the pump has a problem, a switch is pushed and the pump goes off while another comes on. Many of the critical components, including the scrubber, can be designed with a certain amount of redundancy. There are answers to the problem.

QUESTION

For sulfur control, the current emphasis is on sulfur dioxide. This is because sulfur dioxide control also reduces the sulfate in the atmosphere. In addition to the sulfur dioxide removal, suppose there are alternative methods of reducing sulfate, namely, changing the effective stack height or changing the seasonal pattern of the emission. Will the Clean Air Amendment benefit methods other than direct emission control of sulfur dioxide?

RESPONSE: Mr. Princiotta

A very careful reading of the Clean Air Amendments shows that they are aimed primarily at direct emission control. There is no leeway for any dilution approaches, such as extending the height of the stack. Right now the pollutant that is regulated is sulfur dioxide. We have an ambient air quality standard for SO_2 but we do not, as yet, have a specific standard for sulfates. If that happens, there may be changes in the regulatory approach to the control of that particular pollutant.

QUESTION

When the hazardous waste regulations are finally promulgated, a certain amount of fly ash and scrubber sludge is probably going to be classified hazardous. What happens with disposal ponds, like the Bruce Mansfield sludge pond, already in existence? Assuming it is not in a hazardous disposal site, suppose that were declared hazardous. What should be done?

RESPONSE: Mr. Princiotta

As I understand the hazardous waste regulation, assessment of the inherent hazardous nature of waste is independent of how it might be controlled. For example, disposal of waste in a pond would not necessarily be related to whether or not the waste is hazardous. Those variables are separate. There are two separate regulations, as I understand: one to define what the hazardous waste is, and the other, if the waste is hazardous, to determine the most appropriate way to control that waste.

QUESTION

Dry lime scrubbing systems based on the use of spray dryers have recently been tested; they can reach reasonable efficiencies and produce a dry particulate when scrubbing flue gas for sulfur removal. Are there comments on this new type of system?

RESPONSE: Mr. Kurt E. Yeager (Electric Power Research Institute)

Several of them are being installed now in the western United States. We hope that they will be a practical alternative. The experience shows that the dry removal mode may be limited in some of the high sulfur applications, although to resolve that there is considerable development work to be done. The usable removal material has typically been a sodium-based by-product. Will the hazardous substance regulations put unrealistic limitations on the disposal of those kinds of by-products?

QUESTION

Since last fall, a large number of coal cleaning plants on the East Coast have tried to come into operation but have been prevented on PSD basis. Those plants with thermal dryers have had a hard time meeting the PSD increments. Are we paying adequate attention to control technologies for coal preparation plants, specifically to alternative types of dewatering devices, and will this be yet another impediment to this technology?

RESPONSE: Mr. James D. Kilgroe (EPA)

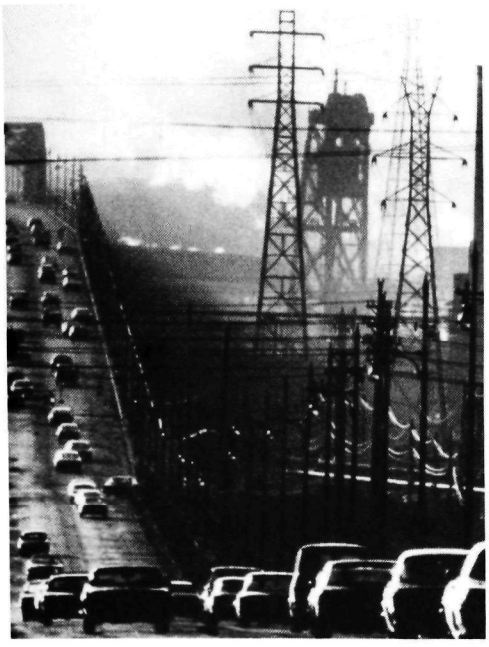
We are working on the environmental assessment of coal cleaning technologies and are investigating new technologies to control pollution from coal preparation plants. We are in the early phases. Our earlier work on coal cleaning has concentrated primarily on coal cleaning for removal of sulfur from coal as an emission control. A lot needs to be done; in fact, the Effluents Guidelines Divisions are under court mandate to examine coal preparation and mining. They are studying 129 varieties of pollutants, and the results are just now becoming available. With those studies and others on different coal preparation plants, we might be able to determine the kinds of new costs to add to coal preparation costs when considering an SO_2 emission control technology.

QUESTION

On another trip to Japan, there was a difference of opinion as to whether Japanese FGD systems achieved closed loop operation. Would the participants comment on whether they are achieving this?

RESPONSE: Mr. Elder

They are not closed loop. As a matter of comparing one process with another, the Japanese go to great lengths to calculate the extent of the open loop. The liquid blowdown from the scrubbing system, however, is treated in waste water treatment facilities before it is discharged into the sea. Suspended solids, pH, and oxygen demand are controlled, but a significant amount of water is blown down from the system to allow freshwater makeup for keeping the surfaces clean. They are admittedly open loop; that question has been resolved.



integrated technology assessment

chapter 6

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integrated technology assessment

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INTEGRATED TECHNOLOGY ASSESSMENT

INTEGRATED ASSESSMENT OF ELECTRIC UTILITY SYSTEMS

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INTEGRATED ASSESSMENT

As a significant energy supplier, consumer of primary fuels, and producer of wastes and emissions to air, water, and land, the electric utility industry through its investment and operating decisions influences the nation's economy and the environment. In turn, the utilities' decisions are influenced by various factors: government energy and environmental policies, economic conditions, and technological considerations. Teknekron has developed a framework for assessing in an integrated manner the impact of these factors on the future investment and operating decisions made by utility firms. Figure 1 shows that the growth and development of the U.S. electric utility industry will be influenced by regulatory constraints, electricity demand, the costs and availability of technologies for electricity generation and pollution control, and conditions in the nation's economy. Utility investment and operating decisions, in turn, will be reflected in revenue requirements, which determine electricity prices, and in fuel consumption, which leads to releases of air and water pollutants and to the generation of solid wastes.

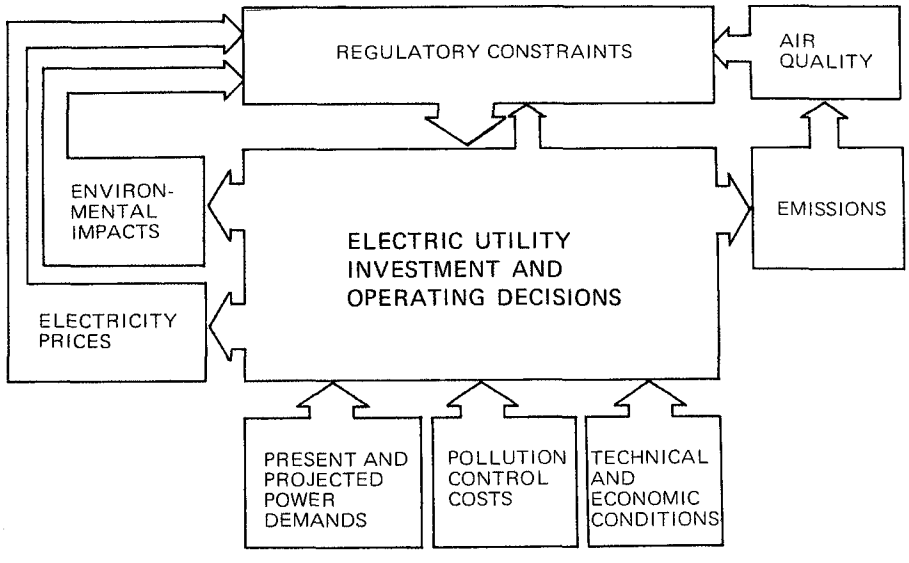


FIGURE 1—*Integrated assessment process*

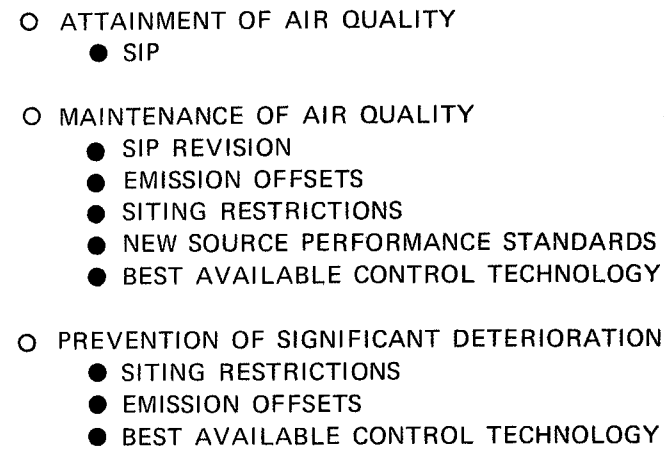


FIGURE 2—*Air pollution control goals and policy tools*

ONE MAJOR FOCUS

One major focus of this integrated assessment has been to analyze the regional air quality impacts of the decisions utilities are likely to make in response to alternative energy and environmental policies and economic and technical conditions. For each set of alternatives, we have determined the probable air quality impacts first by forecasting the spatial distribution of power-plant emissions (by county) and then by applying statistical analyses of historical meteorological data and air transport models. Several of the results obtained so far have profound implications for the EPA in terms of the Agency's meeting the requirements of the Clean Air Act as amended in 1977.

Figure 2 shows three of the most important goals of the Clean Air Act. Teknekron's electric utility integrated assessment has focused on evaluating the economic and environmental implications of several alternative policies EPA might adopt to achieve these goals. Listed in figure 2 are some of the policy tools available to the Agency.

UTILITY SIMULATION MODEL

The integrated assessment process depends on Teknekron's Utility Simulation Model (USM), which consists of interconnecting computer modules and data bases that simulate decisions for system planning and operation, utility finance, and the operation of individual technical processes such as pollution control devices. The model is driven by a set of exogenous scenario elements that include electricity demand levels, financial market conditions, fuel prices and availabilities, advanced technology deployment, and environmental regulations. For each scenario, the model calculates the following by geographical region, for each county or state, for future years up to 2010:

- Factor demands, including
  - fuel use, by type and by region of origin
  - electricity generated, by type of unit and for individual units
  - capital requirements, by source (e.g., debt, common equity, preferred equity)
  - plant and equipment requirements
  - releases of air and water pollutants and generation of solid wastes, by county
- Financial statistics for utility firms
- Average electricity prices

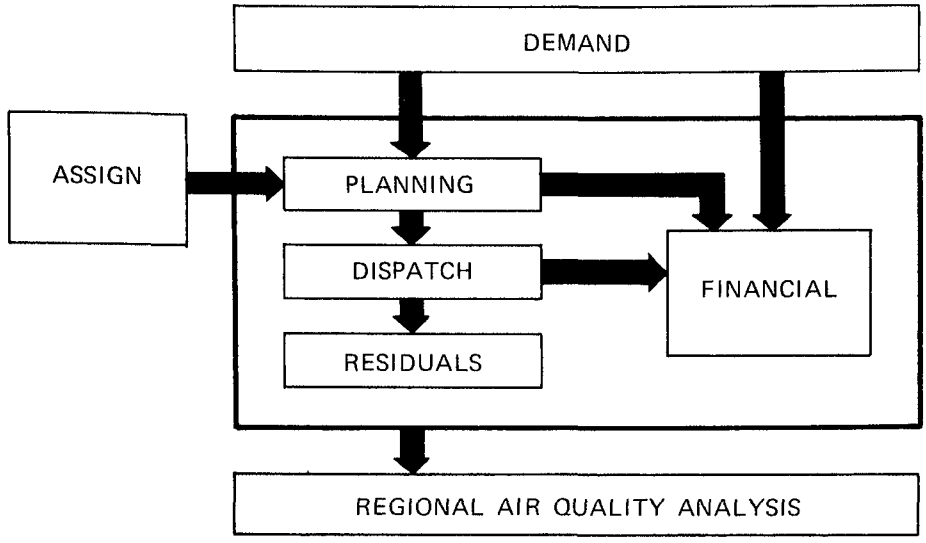


FIGURE 3—*Teknekron utility simulation model*

GENERATING-UNIT SITES

In order to produce these calculations at the required level of detail, the model considers generating-unit sites located in each county in the 48 contiguous states where electricity is produced, fuel and water are consumed, and pollutants are released. Since utilities operate as integrated systems, the model presently simulates the joint operation (i.e., dispatching) of generating units owned by utilities within a state. Finally, the responses of utility firms to the external environment in which they function may be changed by the model user by modifying present data bases or by specifying alternate choices for future system planning operation. For example, the particular scenarios evaluated in Teknekron's review of alternative New Source Performance Standards encompass a range of futures for electricity demand, fuel selection, technology choices, and pollution control regulations specified by the EPA. Some results of that analysis will be presented in the following section.

USM MAJOR COMPONENTS

Figure 3 is a simplified diagram of the USM. The model includes the following major components:

- Demand projection by year, including
  - retail and wholesale sales and purchases
  - energy generation (i.e., average load growth)
  - peak load growth
- System planning projection by year, including
  - choice of generating-unit type
  - choice of fuel type, quality, and coal region of origin
  - choice of pollution control technology
  - expansion of transmission and distribution networks
  - siting of generating units by county
- Dispatch seasonally for typical days, including
  - calculation of unit capacity factors for each typical day of operation, by class of unit
  - calculation of total fuel, operation, and maintenance expenses for electricity generation
  - projection of fuel consumption, by type and region of origin
  - calculation of pollution control costs and operating characteristics for the various types of pollution control devices

FINANCIAL CONSIDERATIONS

- Financial considerations by year, including
  - integration of projected production expenses with construction expenditures
  - projection of the firm's balance sheet, income statement, sources and uses of funds, and other financial statistics
  - calculation of revenue requirements and electricity prices
- Residuals released and resources consumed, including
  - projection of release rates at the generating-unit site for numerous air and water pollutants and for solid wastes
  - projection of consumption of water and other resources
- Regional air quality analyses, including
  - forecasts of the counties that will have high emissions from utility and industrial boilers
  - analysis of historical meteorolgical data to yield preferred paths for the downwind transport of emissions from source locations
  - analysis of emissions, air quality, and meteorological data to develop source-receptor relationships for SO_2 emissions and sulfate concentrations
  - application of air quality models to determine ambient concentrations of SO_2, NO_x, particulates, and sulfates

A number of detailed data bases—including data on each installed and announced generating unit in the U.S., financial and operating statistics submitted by utilities to the former Federal Power Commission, and fuels data—provide inputs to the major components of the model.

USM PROJECTS COSTS

The USM is not a linear program that seeks to minimize the national cost of producing electricity. Rather, it projects year-by-year investments, operating costs, fuel usage, and pollutant releases, making maximum use of data sets that reflect the current condition and composition of utility systems, using 10-and 20-year projections made by individual utility firms, and reflecting the factors influencing utility decision makers in their current and future choices.

In response to an exogenously specified forecast of demand, the System Planning module builds new capacity consistent with the announced plans of utility firms modified to reflect specified reserve requirements. For coal-fired capacity, the Assign module reviews delivered prices and pollution control costs for 18 different coal types and selects that combination of coal supply source and pollution control equipment that results in compliance with state and federal air pollution control regulations at least cost. The Planning module also effects announced plans for fuel conversion and plant retirement and calculates capital investment requirements for each year of simulation. Investment needs serve as one input to the Financial module.

DISPATCH MODULE

The Dispatch module reviews the operating costs for the available generating capacity and apportions the electrical load so that the total system cost of producing electricity is minimized for the system of existing plants and new plants built by the Planning module. Thus, the Dispatch module makes it possible to calculate both fuel consumption by category of plant and total system operating costs. Operating costs are input to the Financial module, while fuel consumption results are passed on to the Residuals module.

RESIDUALS MODULE

The Residuals module calculates releases of air and land pollutants and the generation of solid wastes for individual generating units located by county. This fine level of geographical detail is necessary for assessing environmental impacts and allows us to forecast the spatial and temporal distribution of emissions resulting from the investment and operating decisions made by the Planning and Dispatch modules. The highly disaggregated emission forecast is essential for proper evaluation of the regional and subregional impacts of alternative pollution control policies. By

impacts here we mean, for example, the distribution of price increases and pollutant reductions arising from pollution control regulations, shifts in the market for coals from different supply regions, and the existence of high-emission areas that can lead to deterioration of regional air quality.

FINANCIAL MODULE

The Financial module performs annual updates of the base-year income statement and balance sheet for the utility firms merged at the state level. Needs for external financing to accommodate the investment requirements forecast by the Planning module, as well as the cost of this financing, are calculated by source of capital. Average prices for each succeeding year are calculated considering all costs of operation, including a return on the rate base. Separate treatment is provided for investor-owned and non-investor-owned utilities in each state because of their different financial status.

How have these tools developed by EPA's Office Of Research and Development been applied in support of the Agency's programs? Three important applications of the models, data bases, and analytical techniques developed in this integrated assessment have been (1) to quantify the impacts of revised New Source Performance Standards (NSPS) requiring Best Available Control Technology (BACT), (2) to identify local air quality problem areas, and (3) to determine the extent of the need for regional, rather than national, environmental policies (figure 4). In the remainder of this discussion, we review each of these applications in turn.

KEY ANALYTICAL TOOL

In response to a petition by the Sierra Club and to Section 111 of the Clean Air Act as amended in 1977, EPA's Office of Air Quality Planning and Standards (OAQPS) is investigating alternatives for revising the New Source Performance Standards for emissions of SO_2 and particulate matter from coal-fired utility boilers. Teknekron's Utility Simulation Model is the key analytical tool being used by OAQPS to investigate the regional, economic, and environmental impacts of revisions specified by EPA.

BASELINE PROJECTIONS

The impacts of alternative policies are most effectively revealed through comparison with baseline projections of the impacts of continuing with current policies. The baseline projections developed in our NSPS evaluation take into account many elements of current national and subnational environmental policies, including the curtailment and phasing out of natural gas as an electric utility boiler fuel, the coal conversion program under ESECA, siting restrictions in Class I or nonattainment areas, retrofitting of cooling towers and other required pollution control measures, and compliance with current State Implementation Plan (SIP) and New Source Performance Standards for SO_2, NO_x, and particulates.

- O IMPACTS OF REVISED NSPS (BACT)
  - ● EMISSION REDUCTIONS
  - ● ELECTRICITY PRICES
  - ● REGIONAL COAL DEMAND
  - ● SPATIAL DISTRIBUTION OF EMISSIONS
- O IDENTIFICATION OF LOCAL PROBLEM AREAS
  - ● THE NEED TO CONTROL EXISTING PLANTS
- O THE NEED FOR REGIONAL POLICIES

FIGURE 4—*ITA applications*

EMISSION STANDARDS ASSUMED

For the analysis of alternative NSPS revisions, the following emission standards were assumed to apply:

- For generating units on line prior to 1977: SIP limits
- For generating units on line between 1977 and 1982: current NSPS
- For generating units on line after 1982: revised NSPS

The SIP limits vary by state and county. Current NSPS for emissions from coal-fired boilers are 516 ng/J (1.2 lb/10^6 Btu) for SO_2, 43.0 ng/J (0.10 lb/10^6 Btu) for particulates and 301 ng/J (0.7 lb/10^6 Btu) for NO_x. Among the several possible SO_2 options we evaluated was adoption of a standard stipulating Best Available Control Technology (BACT), which implies the use of flue gas desulfurization, and 90 percent mandatory post-combustion SO_2 removal with an upper limit on emissions of 1.2 lb/10^6 Btu. The baseline case, continuation of the current NSPS, involves no mandatory percentage post-combustion SO_2 removal. For particulates, we considered a revised NSPS of 12.9 ng/J (0.03 lb/10^6 Btu). Other NSPS alternatives were included in the analysis but, because of space limitations, are not presented here. Furthermore, the results given here include only those obtained under the "high demand" case—that is, under the assumption that growth in electricity demand will be 5.8 percent per year nationally until 1985 and 5.5 percent per year thereafter.

CAPACITY MIX

Table 1 shows the capacity mix for the U.S. electric utility system in 1976 and in 1995 under two nominal projections of growth in electricity demand. The simulation model projects capacity additions for the investor-owned and publicly-owned sectors by year and by state, at the county level. For each year the model also simulates a least-cost dispatch of the available units in each state to meet the projected load curves for typical weekdays and weekend days in each of the summer and winter seasons. The shapes of the load curves can be varied to examine the effects of different rates of growth in peak and average electricity demand. However, for the NSPS review, peak and average loads were assumed to grow at the same rate, leaving the shape of the load curves unchanged.

TABLE 1
U.S. electric utility system

Capacity Type	1976 Capacity (GW)	1995 Capacity (GW) Moderate Growth*	1995 Capacity (GW) High Growth*
Nuclear	40.5	314.4	328.5
Coal	196.9	411.5	568.8
Oil	87.3	119.0	119.7
Gas	60.3	5.5	5.5
Combined Cycle	1.2	17.6	23.3
Hydro	67.6	100.3	109.4
Turbines	45.7	115.4	124.7
Geothermal	0.3	3.6	4.6
Total (GW)	509.	1088.	1285.

*Capacity mix varies with scenario.

EMISSION REDUCTIONS

One benefit of revising the NSPS will come from substantially reduced SO_2 emissions. The reduction in SO_2 emissions (assuming high growth of electricity demand) is illustrated in figure 5 by the difference between the top curve (current NSPS) and the middle curve (revised NSPS with 90 percent SO_2 removal). The revised SO_2 standards will have the greatest relative impact in those regions that do not presently have a large base of coal-fired generation: compared with current standards, the revised NSPS will reduce emissions by 56 percent in the West South Central region, by 53 percent in the North Mountain region, by 47 percent in the South Mountain region, by 42 percent in the Pacific region, and by 23 percent in

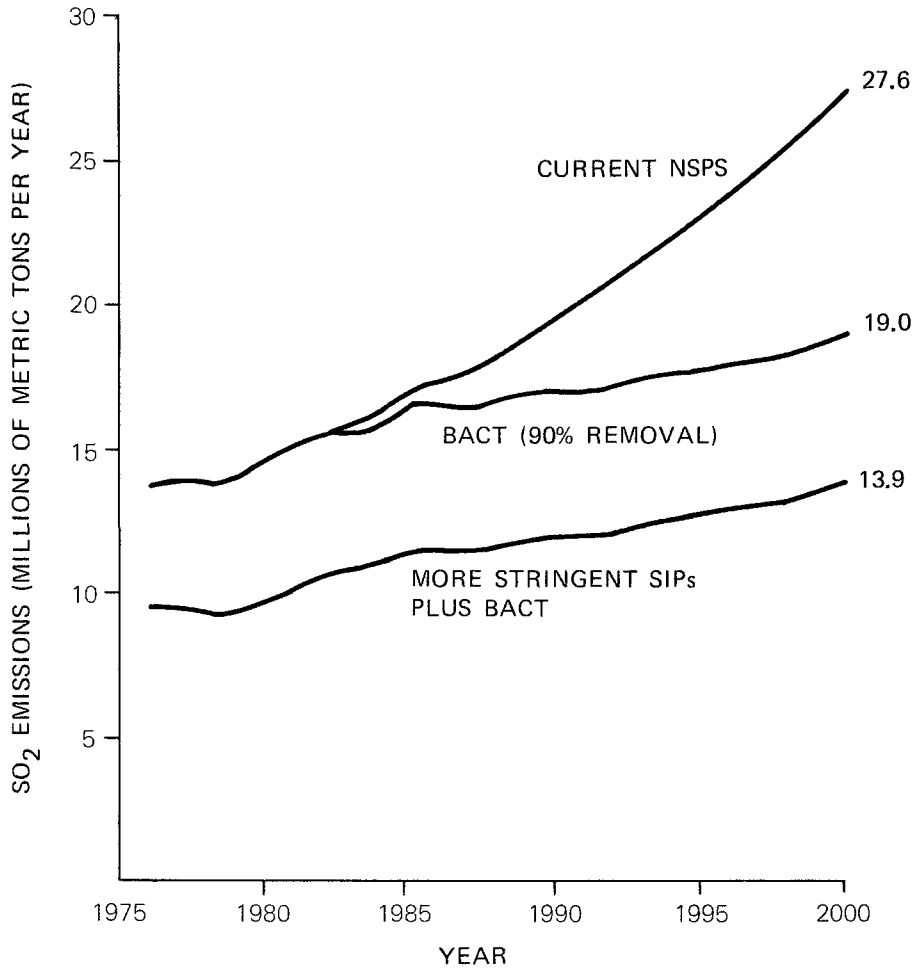


FIGURE 5—*National power-plant SO_2 emissions under alternative control scenarios, high growth*

the New England region. The spatial distribution of these percentage emission reductions is indicated by the darkest areas in figure 6. In terms of reduced SO_2 emission tonnages, the West South Central, East North Central, and South Atlantic regions will have the largest reductions. However, even with the imposition of BACT and a standard of 90 percent SO_2 removal, national SO_2 emissions will increase over the 1976 level as a result of added coal capacity and the continued utilization of existing plants covered by SIP regulations. If all SIPs that now allow SO_2 emissions to exceed 2.0 lb/10^6 Btu were changed to permit no more than that amount, national SO_2 emissions in 2000 could be kept at roughly 1976 levels, as indicated by the lowest curve in figure 5. Later we shall show that the imposition of tighter SIPs would have the most dramatic impact on SO_2 emissions in the eastern third of the nation.

PARTICULATE EMISSION REDUCTIONS

As for particulates, total emissions nationally under current standards will increase only slightly above the 1980 full-compliance level and will grow slightly in the 1990s. Revising the NSPS for particulates downward from 43 ng/J (0.10 lb/10^6 Btu) to 12.9 ng/J (0.03 lb/10^6 Btu) will reduce national aggregate emissions by 11 percent in 1990 and by 22 percent in the year 2000. Particulate emissions from units coming on line after 1982 will be reduced even more, which may have important local impacts. Finally, emissions of NO_x from electric power generation will increase substantially under current standards, even under an effective conservation program to curb electricity demand. Under high demand, NO_x will increase from 5.7 million metric tons in 1980 to 15.6 million metric tons in 2000; under moderate growth, NO_x will increase to 8.6 million metric tons in 2000.

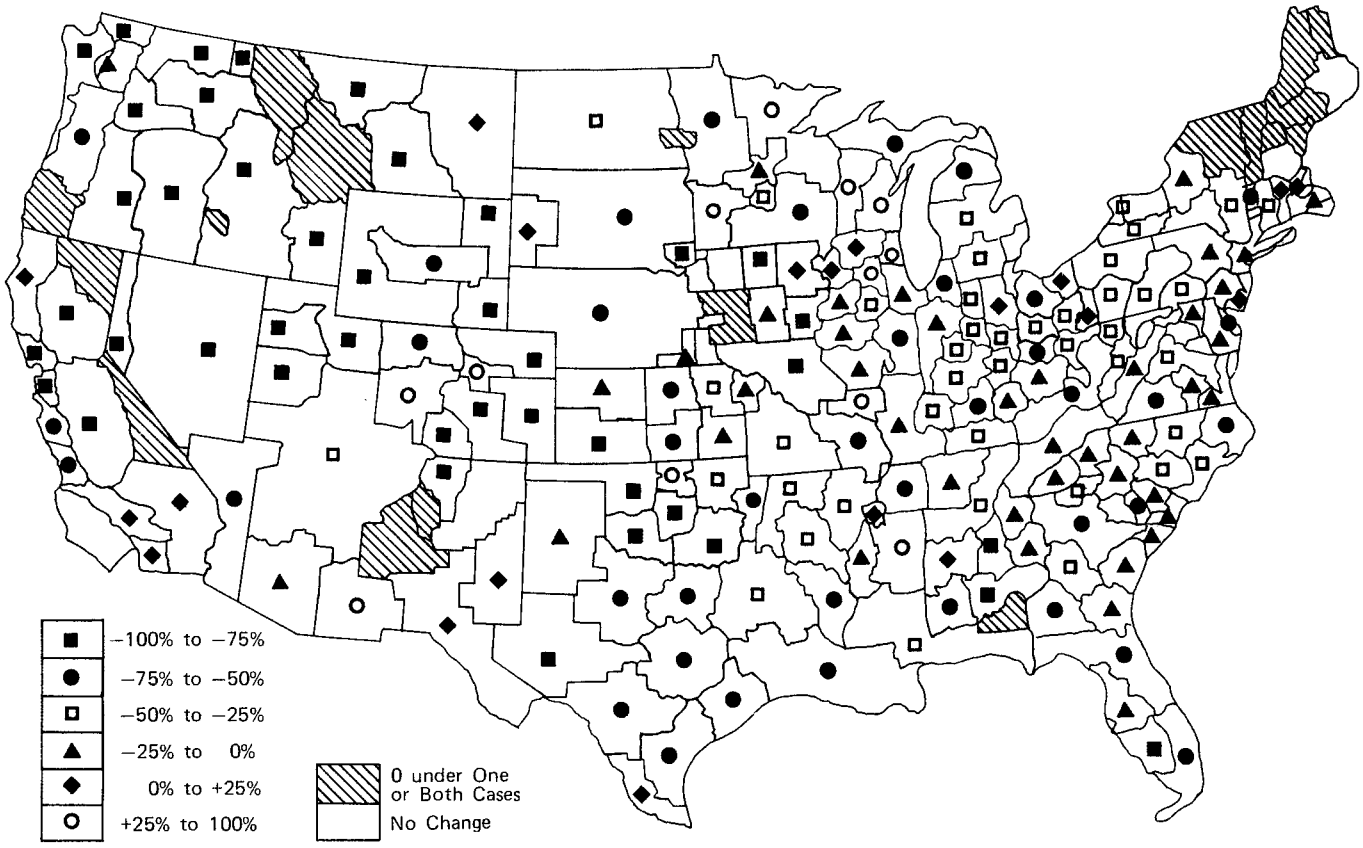


FIGURE 6—*Percentage change in SO_2 emissions in year 2000 (BACT with respect to current NSPS)*

TABLE 2
National economic impacts of revised NSPS (1975 dollars)

	Baseline (Current Standard)	Revised NSPS (90% SO_2 Removal)	Percent Change
1995 Retail Price (¢/kWh)	3.10	3.23	+4.2
1995 Per Capita cost	$685	+$27*	+3.9
Pollution control costs (1986-1995, $10^9$$)	$40	+$16*	+41
Pollution Control Investment (1986-1995, $10^9$$)	$18	+$34*	+195
Total Investment, Excluding Pollution Control (1986-1995, $10^9$$)	$519	+$5.5*	+1.1

*Change from Baseline.

FINANCIAL IMPACTS

Who will pay for the benefits of reduced emissions? NSPS revisions will have regional economic and financial impacts and will increase national pollution control costs. Between 1986 and 1995, pollution control costs under the 90 percent SO_2 removal standard will be 41 percent higher than under the current standard. However, since pollution control costs represent a relatively small fraction of electricity costs, the revised standard in 1995 will result in an electricity price increase of only about 5 percent. A detailed breakdown of yearly costs, balance sheets, and other financial statistics are calculated by state in the financial module of the USM. National results for the baseline and the 90-percent-removal standard are given in table 2.

TABLE 3
Regional price impacts of a proposed NSPS revision

	Baseline Value (¢/kWh)*	Percent Increase in 1995 With Revision**
Nation	3.1	+ 4.2
Region		
West South Central	2.9	+12
North Mountain	2.3	+ 7.4
West North Central	3.0	+ 5.4
East North Central	3.3	+ 4.8
South Atlantic	3.3	+ 4.6
East South Central	1.4	+ 2.8
Mid Atlantic	3.8	+ 2.1
South Mountain	2.9	+ 1.7
Pacific	2.9	+ 1.0
New England	4.3	+ 0.2

*Average for all retail customers, measured in 1975 dollars.
**Mandatory FGD on all post-1982 plants; particulate limit reduced.

The regional price impacts of revising the NSPS to include 90 percent SO_2 removal and a lower particulate limit are shown in table 3. These regional percentage price increases are influenced by the amount of anticipated coal capacity relative to current coal capacity, particularly in the West South Central states (now dependent on natural gas for electricity generation) and in the Mountain states (where coal resources are rapidly being developed). In New England, for example, the continued dependence on nuclear generation and the distance from coal supply sources will prevent substantial increases in coal-fired capacity and hence in the relative costs of stricter SO_2 controls.

REGIONAL COAL DEMAND

Coal consumption will be significantly influenced by the growth rate in electricity demand after 1985. Figure 7 illustrates national coal consumption in metric tons under a high post-1985 growth rate of 5.5 percent per year and under a moderate growth rate of 3.4 percent per year. The projection is based on currently announced utility plans for installing coal plants and on the operation of these plants projected by the Utility Simulation Model. National Energy Plan goals for 1985 coal consumption may be achieved by the electric utility sector, which now consumes two-thirds of the coal produced nationwide. It will be difficult, however, for the industrial use of coal to expand as rapidly.

Alternative New Source Performance Standards will have a significant impact on the use of local coals and on the markets for western coals. Our analysis suggests that the consumption of Powder River Basin coal after 1985 may change substantially under a standard requiring 90 percent removal of SO_2 (figure 8).

SCRUBBERS FOR SO_2 CONTROL

The USM projects the needed requirements for flue gas desulfurization (FGD) devices in order to meet specified emission limits. For the case of high growth in electricity demand, scrubbers will be used in 1995 to clean roughly 355 GW of coal capacity under a standard requiring 90 percent post-combustion SO_2 removal but for only about 80 GW under continuation of the current standard. The regions of the country with the highest installed scrubber capacities by 1995 under the revised standard will be the West South Central region (84 GW), the East North Central region (82 GW), and the South Atlantic region (76 GW). These three regions will contain 60 percent of the total installed FGD capacity in that year.

Table 4 illustrates the projected amounts of sludge produced and water consumed by FGD systems under the two SO_2 standards. Approximately 3.8 percent of the primary coal energy will be required to operate FGD scrubbers in 1995 under the 90-percent-removal standard.

The Utility Simulation Model has been used to identify counties that will have high pollutant emissions in the future. By combining data on emissions and

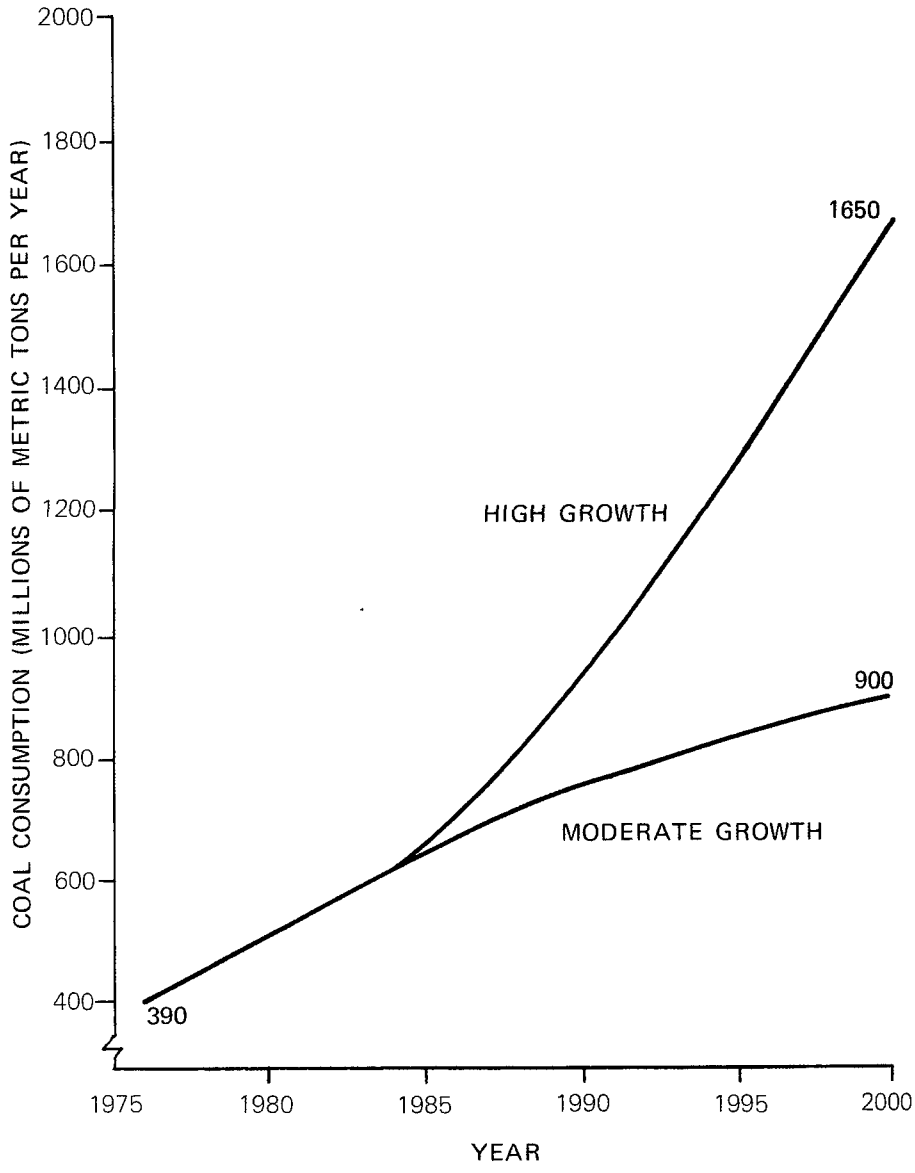


FIGURE 7—*Projections of electric utility coal consumption*

meteorology with air quality analyses, we have determined the areas where regional studies are required and have identified subregional and local problem areas as well.

FIVE GEOGRAPHIC SCALES

Our air quality impact analyses are over five geographic scales: subnational (e.g., the eastern United States), regional (the six-state Ohio River Basin area), subregional (the Lower Basin area), local (the portion of the Lower Basin between Louisville, Kentucky, and Cincinnati, Ohio), and site-specific (specific power plants). The approach has been to prepare the emissions, air quality, and meteorological data bases for each of these five scales and to conduct an integrated analysis as a necessary prelude to performing air quality impact predictions using dispersion models. We illustrate this approach by describing some results from our analyses of the Lower Ohio River Basin.

OHIO RIVER BASIN STUDY

Early in the integrated assessment, Teknekron identified the Lower Ohio River Basin, particularly the area from Cincinnati to Louisville, as one of the most prominent air quality problem areas. Coincidentally, concerns of local citizen groups over the potential concentration of coal-fired power plants in this area provided the impetus for another major OEMI program, the Ohio River Basin Energy Study. In the Teknekron work, the focus has been in determining the local and medium-range

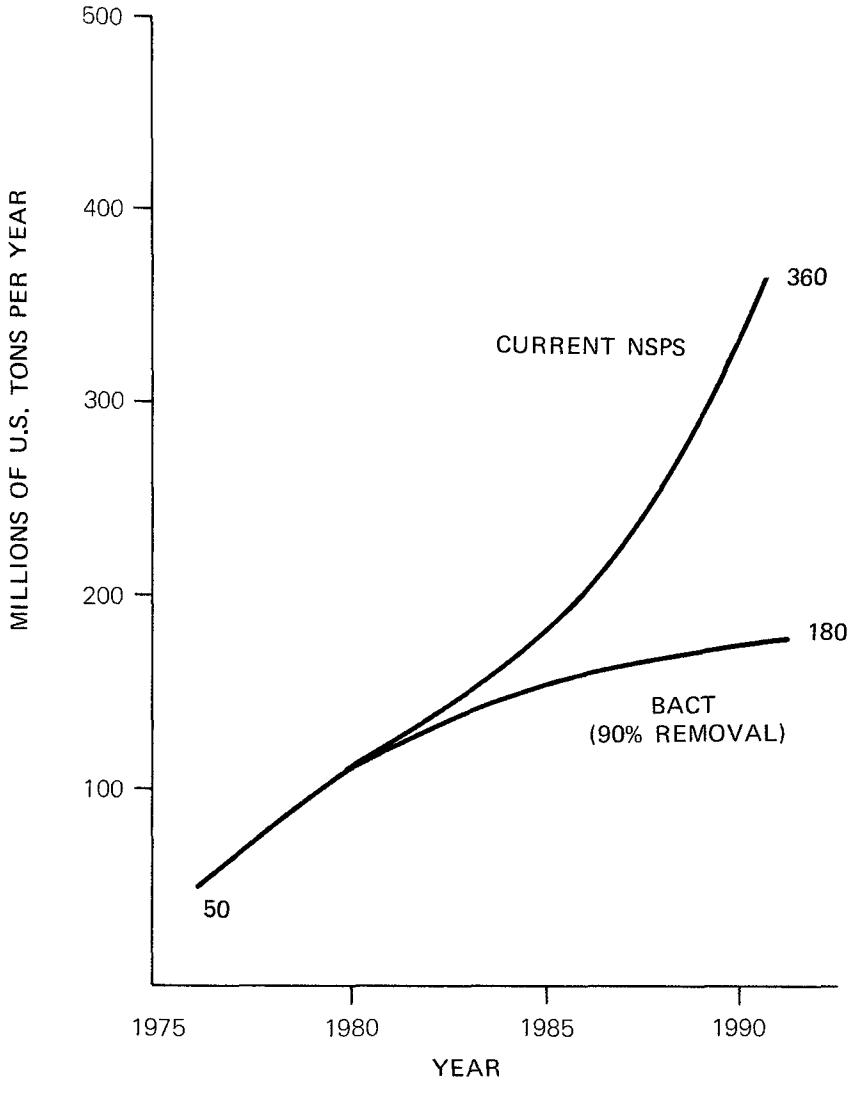


FIGURE 8—*Consumption of Powder River Basin coal*

TABLE 4
1995 national FGD projections

	Current NSPS	Revised NSPS (90% Removal of SO_2)
FGD Sludge Produced* (10^6 dry tonnes)	12	55
Cumulative Disposal Area (km^2, 1990-2000) †	15	92
FGD Water Consumed ($10^6 m^3$)	110	607
FGD Energy Consumed (% Total Coal Energy)	0.7%	3.8%

*Total coal ash production: 101×10^6 tonnes.

†Nine-meter depth.

air quality impacts of clustered power plants and the additive long-range impacts of multiple clusters of plants. EPA is concerned that the operation of large new coal-fired plants may lead to further degradation of air quality in existing nonattainment areas or to consumption of the entire increment for SO_2 specified in regulations for the prevention of significant deterioration.

LEVELS OF POLLUTION EXCEED STANDARDS

The clustering of power plants in the Lower Basin area near Louisville is shown in figure 9. Also shown are air quality monitors indicating where levels of SO_2 and particulates exceeded the ambient air quality standards in 1975. The four power plants near Louisville are associated with the exceeded standards. Moreover, the north-south line of these plants coincides with the direction of extremely persistent winds (winds blowing at 10 to 15 miles per hour for periods of about 6 hours or more in a sector less than 22.5° wide). These wind conditions occur at least several times each year. When the direction of persistent winds coincides with the location of power plants, additive (frequently large) pollutant concentrations can be transported downwind. High background levels of SO_2 or sulfates are frequently associated with these meteorological conditions. EPA's Point-Multiple Point (PTMTP) dispersion model has been used to estimate the additive ground-level SO_2 concentrations caused by the four power plants near Louisville (figure 10). Under certain conditions these concentrations may cause violations of the 3-hour SO_2 air quality standard, and if the violations are of sufficient duration, even the 24-hour standard may be exceeded.

PROPOSED POWER PLANTS AFFECTED

These results have implications for proposed power plants downwind along the Ohio River. It is conceivable that the level of background emissions under persistent-wind conditions may be so high that the siting of new sources will be precluded by the regulations for the prevention of significant deterioration. Note the locations of the three proposed power plants in figure 9. It is doubtful that these locations can be justified without a reduction in emissions from existing sources. Any judgment regarding the proposed plants should be backed up by ambient air quality data from additional monitors and by further air quality analyses.

PREDOMINANT SO_2 SOURCES

Table 5 indicates that, under current or revised NSPS, the predominant sources of SO_2 emissions will be plants regulated by State Implementation Plans.

More particularly, in all years, the predominant SO_2 emission sources will be post-1950 units subject to SIP emission limits. In the high growth case, up to 70 percent of SO_2 emissions in 2000 could be due to SIP-regulated plants (plants on line before 1977), and 23 percent will be due to plants on line after 1982 (plants assumed to be subject to a revised NSPS). The predominance of SIP-regulated plants as emission sources suggests that SO_2 emission levels might be substantially reduced if existing SIP standards were made more stringent. In another study in which the USM was used, in that case to investigate potential markets for physically cleaned coal, one scenario included changing all SO_2 SIP limits to allow no more than 2.0 lbs $SO_2/10^6$ Btu. If that hypothetical policy were to be implemented uniformly, SO_2 emissions in 1985 would be reduced by 31 percent nationally. Regionally, there would be reductions of 51 percent in the West North Central region, 45 percent in the East South Central region, 30 percent in the South Atlantic region, 29 percent in the East North Central region, and 26 percent in the Mid Atlantic region. These emission reductions are illustrated by the lowest curve in figure 5 and by the darkened areas in figure 11. Note that dramatic reductions in SO_2 emissions are not observed in the western U.S. The reason is that SIP limits in that part of the country are already more stringent than the upper limit postulated in this scenario. These integrated assessment results suggest that existing plants in specific subregional areas of the country will need to be controlled in order to permit future growth.

LONG-RANGE TRANSPORT

Another primary application of the integrated assessment approach has been the analysis of long-range pollutant transport. It is essential to consider long-range transport when developing strategies for implementing the Clean Air Act amendment. Pollutants can be carried for long distances over a region, affecting the attainment of air quality standards in areas far removed from the emission source and hence influencing the potential for long-term regional growth consistent with air quality constraints.

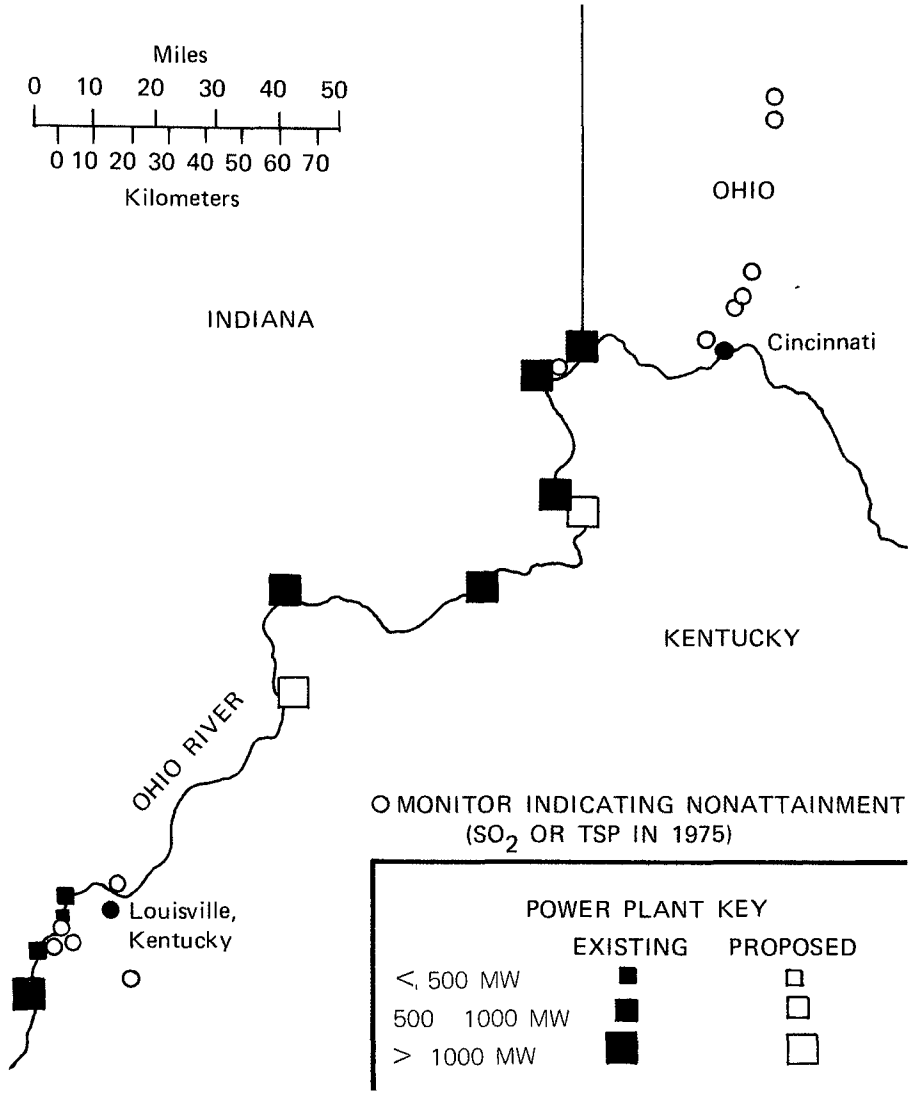


FIGURE 9—*Fossil steam plants and monitors indicating nonattainment*

TABLE 5
Projected SO_2 emissions by coal plant regulatory category

	1985	2000
Percentage of Total Emissions		
SIP Units	89%	70%
NSPS Units	9%	7%
BACT Units	2%	23%
Total Emissions (10^6 Tons)	16.0	19.5

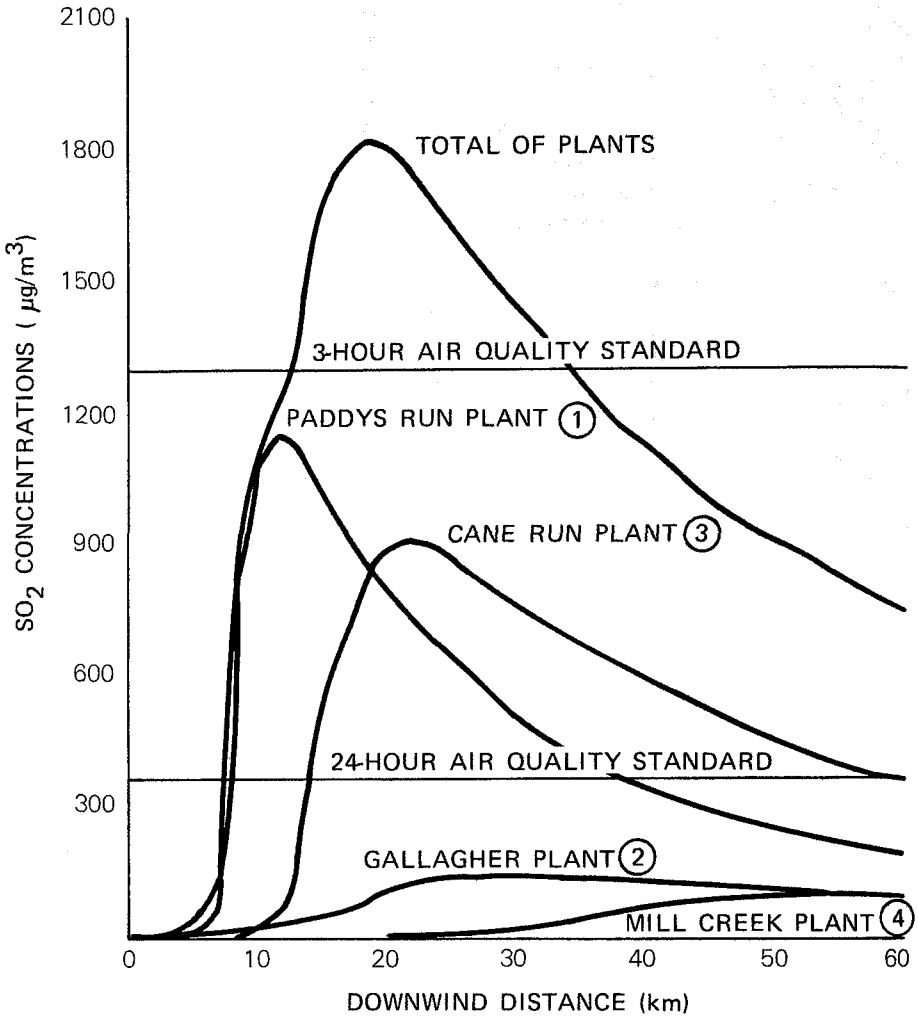


FIGURE 10—*Ground-level SO_2 concentrations from four power plants along a north-south line near Louisville (from the EPA/PTMTP model)*

CONTROLLING SO_2 SOURCES

Teknekron has recently assisted EPA in evaluating the effects of the long-range transport of pollutants into the State of Pennsylvania. In 1976 EPA Region III notified Pennsylvania that every Air Quality Control Region in the state was a nonattainment area for particulates and that Pennsylvania should therefore revise its State Implementation Plan. In the Fall of 1977, Dr. Maurice Goddard, Secretary of the Pennsylvania Department of Environmental Resources, asked EPA Administrator Douglas Costle to investigate the degree to which SO_2 sources in upwind states were contributing to Pennsylvania's ambient concentrations of particulate matter. Dr. Goddard pointed out that preliminary results of Teknekron's integrated assessment and of studies performed at Carnegie-Mellon University indicated that a significant portion of Pennsylvania's nonattainment problem could not be addressed by revision of the Pennsylvania SIP but rather had to be dealt with by controlling SO_2 sources in the upwind states of Ohio and West Virginia. Dr. Goddard's petition was made in accordance with Section 110 of the Clean Air Act, as amended, which requires that SIP revisions in a given state not prevent or interfere with attainment or maintenance of air quality in other states. At issue here were the implications for Pennsylvania of Ohio's proposed SIP revision and of the proposed relaxation of SO_2 limits for two power plants in West Virginia.

Figure 12 conceptualizes the long-range-transport process, and figure 13 shows the configuration of fossil steam plants in the three-state problem area. Under certain meteorological conditions these power plants are upwind of Pennsylvania. In cooperation with EPA Regions III, IV, and I and EPA's Office of Air and Waste

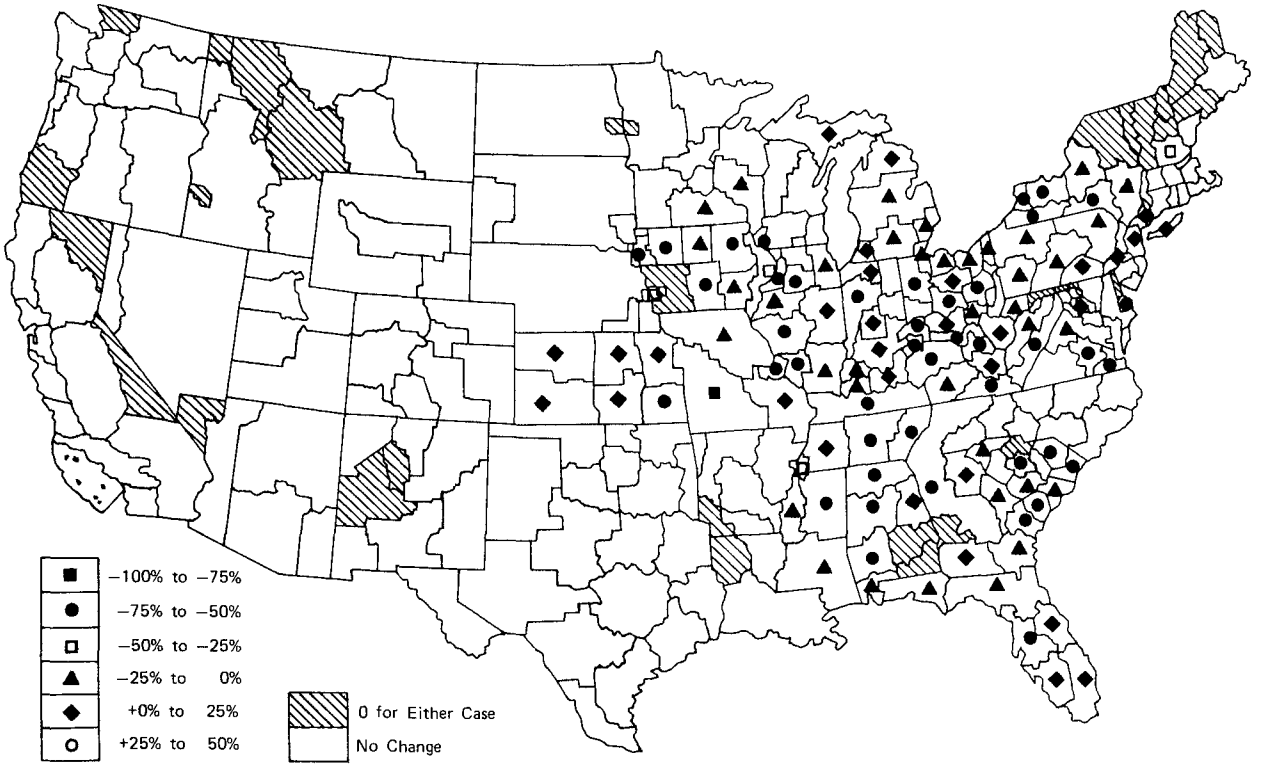


FIGURE 11—*Percentage change in SO_2 emissions in year 2000 (BACT with more stringent SIPS)*

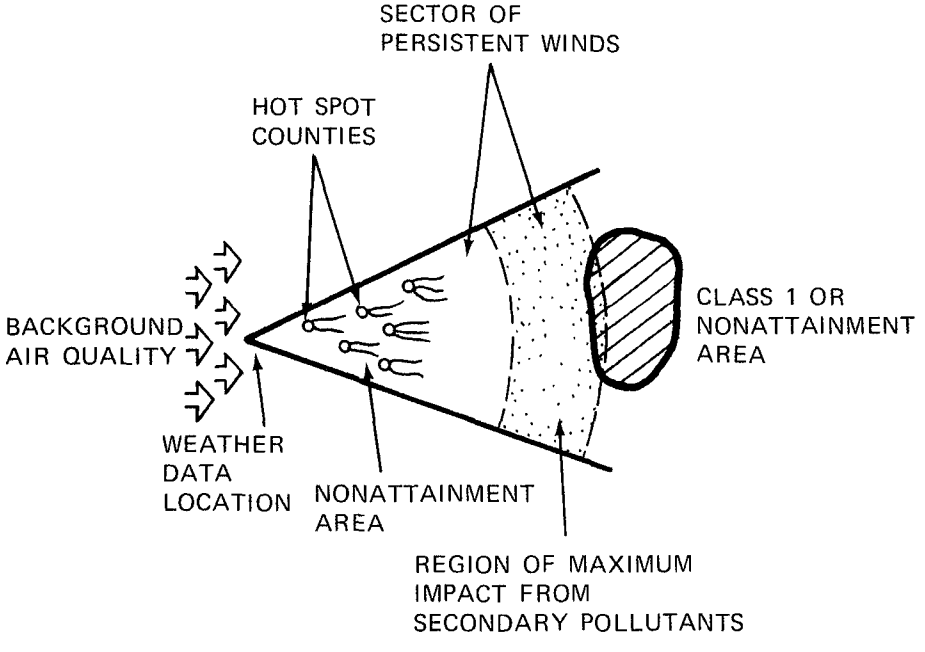


FIGURE 12— *Long-range transport (approximately 180 miles or 360 kilometers)*

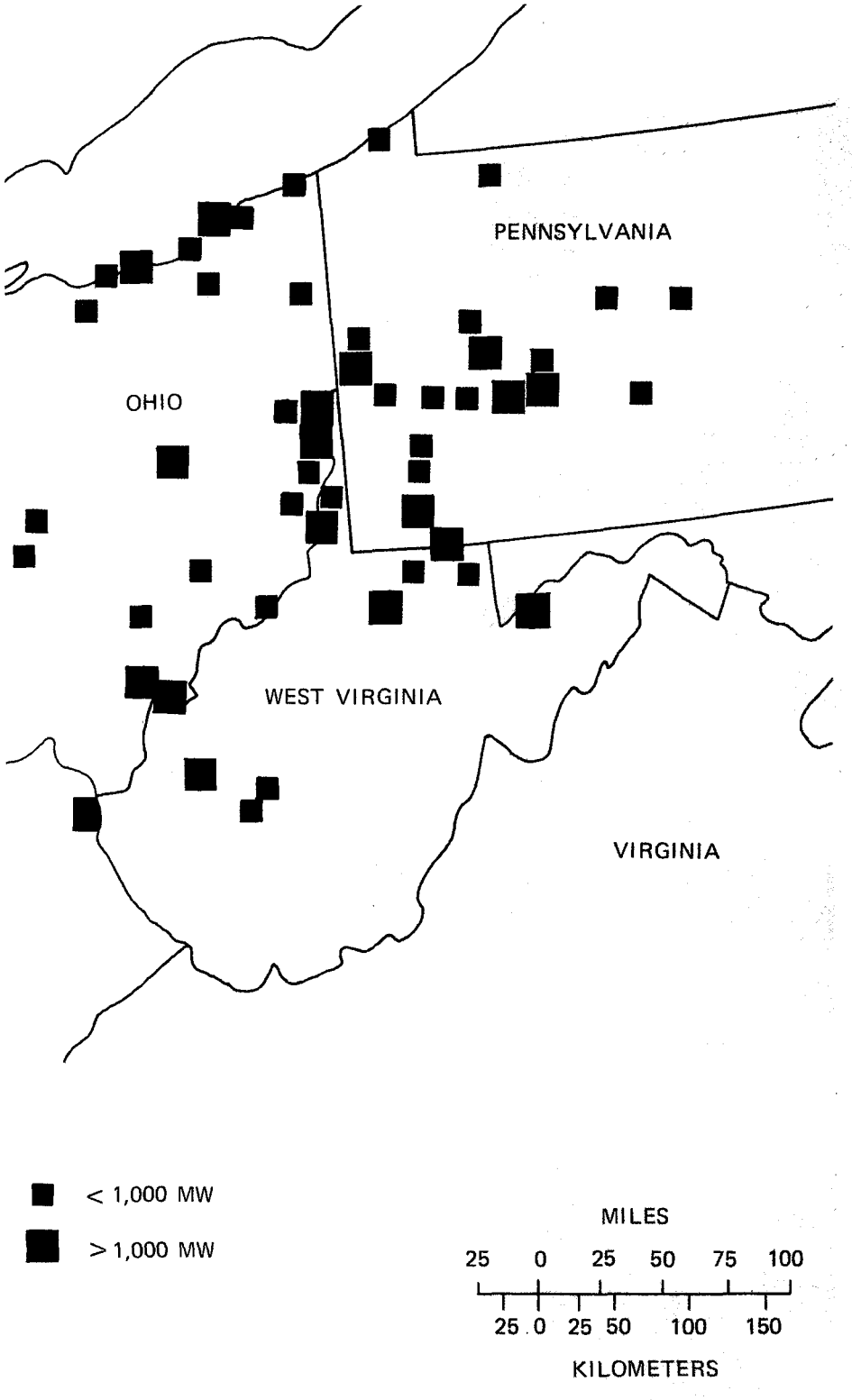


FIGURE 13–*1976 fossil steam power plants*

Management, Teknekron has conducted meteorological and air quality analyses to determine the contribution of these SO_2 sources in Ohio and West Virginia to particulate levels in western Pennsylvania.

SOURCE RECEPTOR RELATIONSHIP

Our study of 5 to 10 years of conventional weather data from National Weather Service stations, as well as 1 to 2 years of special meteorological tower data for a number of locations in the subregional problem area, has shown that the extremely persistent winds in this area blow most frequently toward western Pennsylvania from either Ohio or West Virginia. These conditions occur on the average at least 30 times a year. Our analysis of the spatial correlation of extremely persistent winds has revealed a source-receptor relationship in which pollutants from the Huntington, West Virginia, area are transported over distances of 150 to 300 kilometers within a narrow sector downwind in the general direction of western Pennsylvania.

WHEELING LEVELS EXCEED PA. STANDARDS

Teknekron's analysis of measured sulfate levels in Wheeling, West Virginia, from the Sulfate Regional Experiment (SURE) program shows that Wheeling's average sulfate levels exceeded the Pennsylvania sulfate standard (10 $\mu g/m^3$) in every month of the 1974-1975 period. Preliminary analysis of total suspended particulate levels in Pennsylvania suggests that, for days when long-range-transport conditions occurred, the sulfates coming from upwind sources provided the additional increment needed to push Pennsylvania's particulate levels over the secondary standard.

Figure 14 illustrates one instance of long-range sulfate transport across state borders. This sulfate episode occurred during several days in July 1974. Following the passage of a high-pressure area, which led to stagnation of the air mass, persistent winds developed. These winds transported the accumulated pollutants into Pennsylvania. Further work is now being undertaken to determine more precisely the impacts of long-range transport.

ANALYTICAL TOOLS

In evaluating the implications of environmental policies, one must always undertake some form of integrated technology assessment, whether or not such an approach is explicitly recognized. The analytical tools developed by Teknekron for OEMI have utilized inputs from EPA's other research programs and have been employed in the examination of a number of significant environmental issues. The aim of these integrated analyses has been to provide EPA and other decision-making bodies with a technically correct analytical framework and with self-consistent quantitative results, enabling a consistent comparison of alternative strategies and technical choices. The examples described in this paper are leading to further refinement of EPA's analytical tools and to a better understanding of the likely results of future decisions affecting our environment.

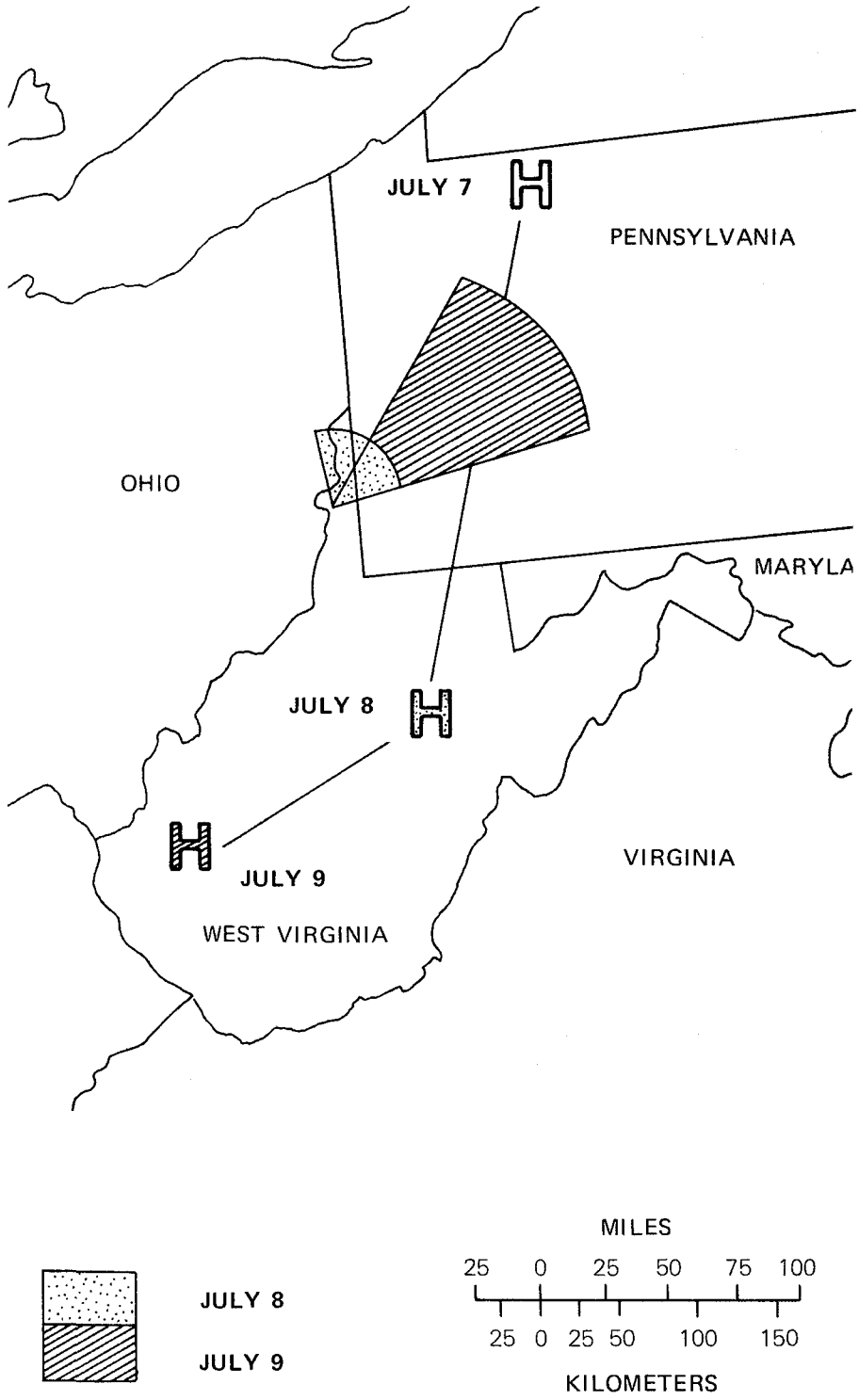


FIGURE 14—*Sulfate episode on 7-9 July 1974*

TECHNOLOGY ASSESSMENT OF WESTERN ENERGY RESOURCE DEVELOPMENT

Irvin L. White, Ph.D.
Science and Public Policy Program
University of Oklahoma

INTRODUCTION

The Western Energy Study or Technology Assessment of Western Energy Resource Development was the first regional assessment sponsored by the Office of Energy, Minerals and Industry as a part of the Integrated Assessment Program. The 3-year study is being conducted by the Science and Public Policy Program of the University of Oklahoma with the assistance of two major subcontractors: the Radian Corporation of Austin, Texas, and the Water Purification Associates of Cambridge, Massachusetts; several other subcontractors; numerous consultants; and an advisory committee whose members represent a variety of interests and perspectives, agencies, and levels of government.

The overall purpose of this study is to determine the consequences of western energy resource development and what can be done about them. Specific objectives are to:

- Determine and analyze impacts
- Identify and define policy problems and issues
- Identify and describe development alternatives
- Evaluate and compare alternative policies and implementation strategies
- Identify and describe research and data needs.

GEOGRAPHIC SCOPE

The study includes the eight Northern Great Plains and Rocky Mountain States shown in figure 1: Arizona, New Mexico, Utah, Colorado, Wyoming, Montana, and North and South Dakota. The development of six energy resources in this eight-state area is assessed: coal, oil shale, uranium, oil, natural gas, and geothermal. The time period covered by the study is 1975-2000.

The development alternatives considered are listed in table 1.

STUDY STRUCTURE

Six site-specific scenarios and one aggregate eight-state scenario are used to structure the study. The scenarios for the six sites identified in figure 1 combine representative local conditions (such as topography, meteorology, population, and community services and facilities) and energy development technologies (from among those listed in table 1). Analyses of the impacts likely to occur from the development called for in these scenarios are intended to provide a basis for generalizing about and identifying locational and technological factors which are critical in determining development impacts that actually occur. Developers and policymakers must control these factors to produce the desired energy product at acceptable costs and risks. The aggregate eight-state scenario serves the same analytical purpose for two levels of development within the study area. It also provides a basis for studying impacts and policy problems and issues that are nonlocal, such as a river basin, a subarea of the region, the region, and the nation.

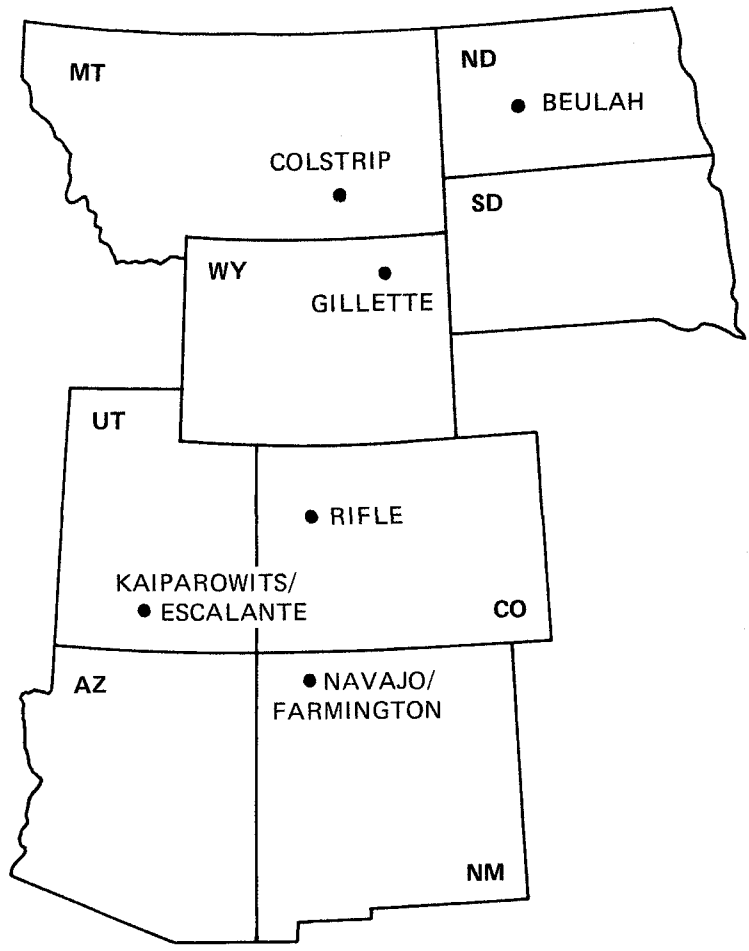


FIGURE 1—*Western energy study area*

PARTICIPATORY RESEARCH

Another structural design feature emphasized is the involvement of stakeholders or interested parties in the research. In fact, one of the distinctive features of the Western Energy Study is this participatory research approach that was initiated at the research design phase and has continued throughout the study. Contact and communication was established and maintained with a broad range of public and private officials and interest groups, as well as the advisory committee mentioned above. This has incurred extensive field work, numerous meetings and presentations, and a circulation of more than 500 copies of draft reports for external review.

The Western Energy Study is in the final month of its third year and a final project report is being prepared. The study was designed to produce major reports to provide the information and analytical base for the final report. These are listed in table 2.

SUBSTANCE OF STUDY

The above introduction and background information have, in general, described what the Western Energy Study is, how it is being conducted, and the products it is expected to produce. The broad scope of the study makes it impossible to give you more than this brief overview. In order to be more specific and to give you a better feel for the substance of the study, I want to focus attention on water availability (1). As you probably know, water availability problems and issues are among the most significant that will arise as a consequence of western energy development.

Very early in the Western Energy Study it was determined that water availability could be a constraint on large scale energy development, especially on regional coal and oil shale conversion. Water availability estimates vary widely. The

WATER AVAILABILITY ESTIMATES

1922 Colorado River Compact divides water rights in the river between the Upper and Lower Basin states (2). Under the provisions of this compact, Upper Basin states guarantee Lower Basin states 75 million acre-feet over each consecutive 10-year period or an average of 7.5 million acre-feet/year. In 1944, the United States agreed to guarantee Mexico 1.5 million acre-feet/year (3). Whether this water for Mexico is to be provided by both the Upper and Lower Basin states or only by the Lower Basin states is still being debated. If it is assumed that each basin supplies half or 750,000 acre-feet/year, on the average, a total of 8.25 million acre-feet would have to flow from the Upper Basin into the Lower Basin each year. The availability of water in the Upper Basin for all uses would be the difference between this 8.25 million acre-feet/year and the total flow in the Colorado River.

COLORADO RIVER COMPACT

The 1922 Compact divided rights to water in the river based on an estimated annual virgin flow of 16.2 million acre-feet/year (4). Other frequently cited virgin flow estimates are 13.8 million acre-feet/year (5) and 13.5 million acre-feet/year (4). (figure 2).

TABLE 1
Development alternatives

Coal:
- Surface and Underground Mining
- Direct Export by Unit Train and Slurry Pipeline
- Electric Power Generation
- Gasification
- Liquefaction
- Transportation by Pipeline and EHV

Oil Shale:
- Underground Mining
- Surface Retorting
- Modified In-Situ
- Transportation by Pipeline

Uranium:
- Surface and Solutional Mining
- Milling
- Transportation by Train

Oil and Natural Gas:
- Conventional Drilling and Production
- Enhanced Oil Recovery
- Transportation by Pipeline

Geothermal:
- Hot Water and Hot Rock
- Electric Power Generation
- Transportation by EHV

VIRGIN FLOW ESTIMATES

Virgin flow estimates include all of the water which flows in the river. But flows can also be estimated and measured at a particular point on the river in which case the estimate or measurement does not include water consumed upstream of the point on the river where the estimate or measurement is made. The most significant measuring point of the Colorado River is Lees Ferry, Arizona, the official dividing point between the Upper and Lower Basins specified in the Colorado River Compact.

LEES FERRY FLOW DATA

The Department of the Interior has published flow data for a point very close to Lees Ferry for the period 1941-1974. The average annual flow over this 34-year period was 10.4 million acre-feet (6). For the decade 1960-1969, the average annual flow was 8.0 million acre-feet (6) and in 1974, measured flow at Lees Ferry was 8.9 million acre-feet. (6). (figure 2.)

TABLE 2
Western energy study reports

Two work plans or research designs:

- First Year Work Plan for a Technology Assessment of Western Energy Resource Development (1976)
- Work Plan for Completing a Technology Assessment of Western Energy Resource Development (1978)

A description of development technologies:

- Energy From the West: Energy Resource Development Systems (forthcoming)

Two impact analysis reports:

- Energy From the West: A Progress Report of a Technology Assessment of Western Energy Resource Development (1977)
- Energy From the West: Impact Analysis Report (forthcoming)

A policy analysis report:

- Energy From the West: Policy Analysis Report (forthcoming)

Subcontractor or consultant reports on:

- Water requirements (Water Purification Associates)
- Holding ponds (Radian)
- Ponded effluents (Radian)
- Planning and growth management (Western Governors' Policy Office)
- Development on the Navajo Reservation (University of Oklahoma)
- Transportation (University of Illinois)
- Air quality (Teknekron)

UPPER BASIN WATER AVAILABILITY

The best available estimates of the quantity of water currently being consumed above Lees Ferry range from 3.2 million acre-feet/year (7) to 3.7 million acre-feet/year (8). Lacking a better data base, these consumption numbers, the three estimates of virgin flow, and the flows actually measured at Lees Ferry can be used to estimate the availability of water in the Upper Colorado. As indicated in figure 2, these range from a deficit of 250,000 acre-feet/year, if the average acre-feet/year measured flow for the period 1960-1969 is used, to a surplus of 4.25 million acre-feet/year, if the 1922 compact virgin flow estimate is used. This is the range of estimates of water available in addition to 8.25 million acre-feet/year flowing into the Lower Basin and the estimated 3.7 million acre-feet/year currently being consumed in the Upper Basin.

ANTICIPATED WATER DEMANDS

The Department of the Interior's estimate of increased water use by nonenergy users is 1.5-1.6 million acre-feet/year by the year 2000 (8). The Western Energy Study's estimates of water demand for energy development by the year 2000 range from 600,000 acre-feet/year for a low energy demand case with prudent water management to 1.1 million acre-feet/year for a high energy demand case and business as usual water management (9). As shown in figure 3, this analysis leads to the conclusion that it is very probable that by the year 2000 there will not be enough water to meet all of the anticipated demands for water in the Upper Colorado River Basin. This finding indicates that policymakers will have major water availability problems and issues to deal with if large-scale western energy

development occurs. Within the eight-state study area, the most difficult political decision will be to decide who among the competitors is to receive water? Will Upper or Lower Basin water supplies be cut or will water be made available to energy users by limiting the quantity of water made available to other uses such as agriculture?

FIX-OPTION IDENTIFICATION

Public officials often have some discretion with regard to which problems and issues they choose to deal with and how they deal with them. Almost without exception, finding technological fixes for dealing with problems is more politically attractive than requiring significant changes in behavior. Knowing that this is the case, when it became clear that water availability could be a significant constraint on western energy development, Water Purification Associates was commissioned to conduct a study of configuration and process design changes which could reduce the water consumption of energy conversion technologies. A preliminary analysis was also conducted to identify water conservation opportunities in agriculture.* Both of these analyses were undertaken to identify technological fix options for policymakers faced with making difficult policy choices when there will not be enough water in the Upper Colorado River to meet the anticipated demand if current practices and energy and nonenergy development continue.

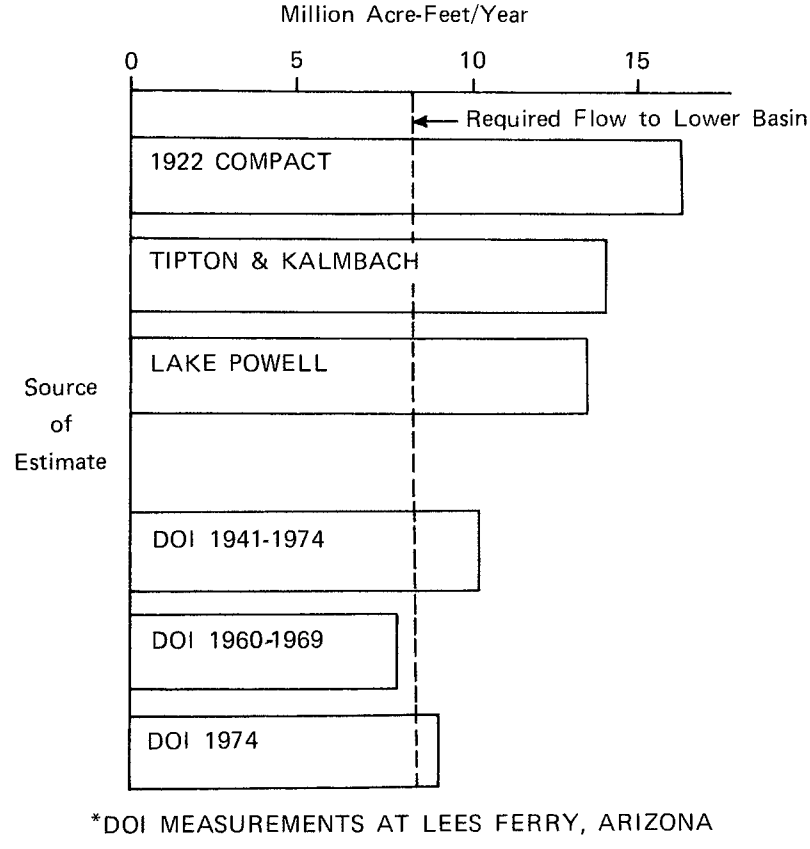


FIGURE 2—*Estimates of average flow in Colorado River*†

*Water Purification Associates will pursue this analysis of conservation alternatives in agriculture during the fall of 1978.

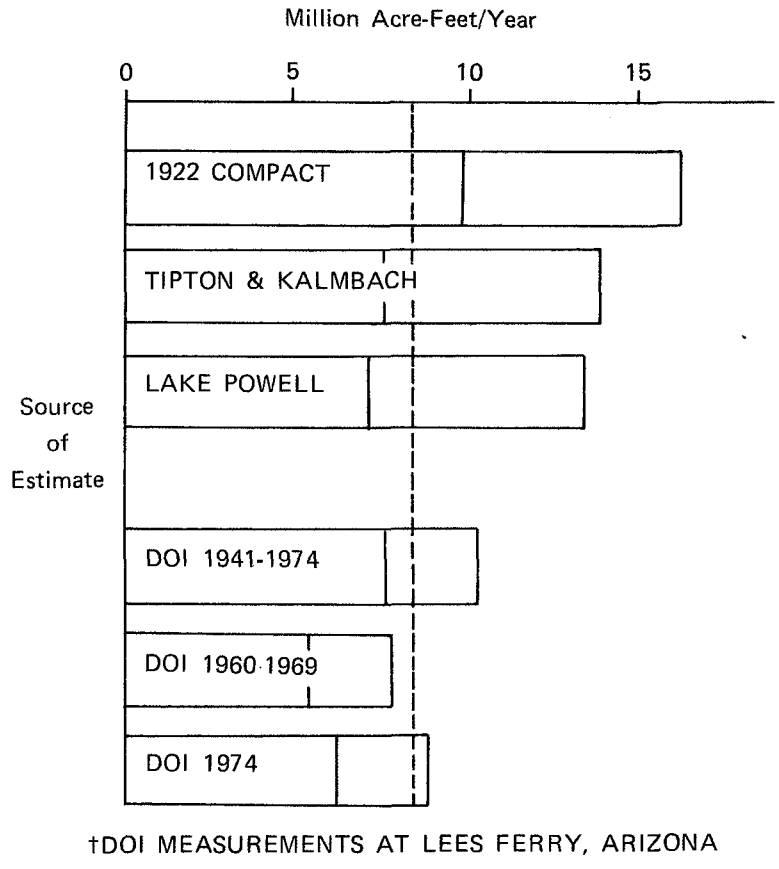


FIGURE 3—*Projections of average flow in Colorado River, year 2000**

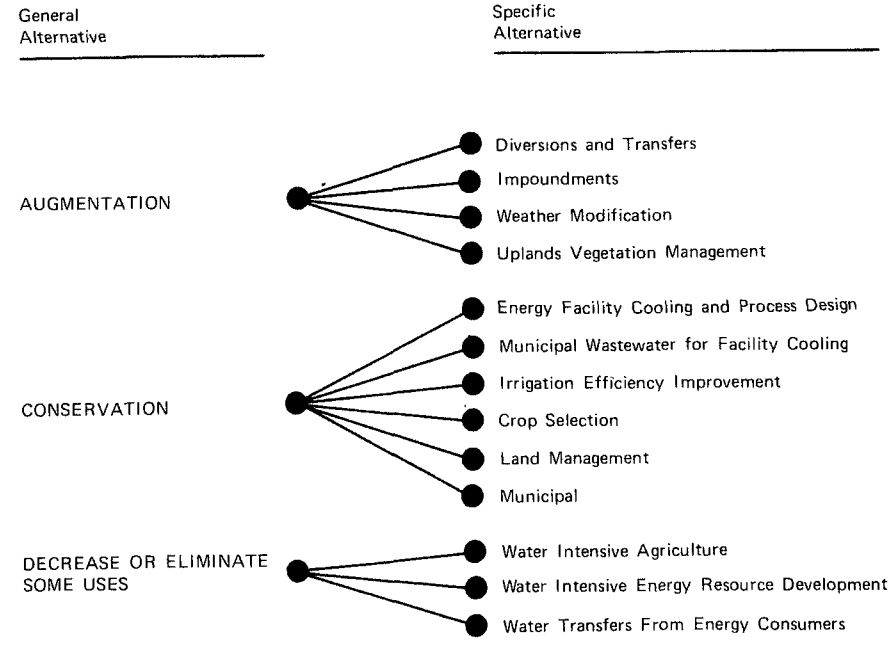


FIGURE 4—*Policy alternatives for water availability issues*

WATER AVAILABILITY ALTERNATIVES

Figure 4 shows several water availability alternatives now being evaluated in the Western Energy Study, including water conservation in both energy and agriculture. Augmentation and conservation are two kinds of alternative approaches for meeting the overall water needs of Upper Basin users. Augmentation would achieve this objective either by adding to the overall water supply or using impoundments to make water available where it is needed. On the other hand, conservation or increased efficiency would get more use out of the existing water supply. For example, more efficient irrigation technologies or wet/dry or dry rather than wet cooling might be used to reduce the quantity of water required for continued agricultural and energy development.

Each alternative is being evaluated in the Western Energy Study on the basis of five criteria: effectiveness, efficiency, equity, flexibility, and acceptability. Figure 5 shows how these criteria are applied to water availability alternatives.

POTENTIAL SAVINGS

Figure 6 shows two estimates of the water required by the energy conversion technologies being considered in the Western Energy Study. Table 3 summarizes the water conservation opportunities when wet/dry or dry cooling rather than wet cooling is used. As the table shows, there are potential water savings with these alternatives. However, the dollar cost to realize these water savings may also be large. The most economical cooling alternative for all coal conversion technology is wet cooling when water costs less than 20 cents per 1,000 gallons. For synthetic fuel technologies, some dry cooling becomes economic at a water cost of about $1.50 per 1,000 gallons** and, for power plants, at about $3.65 to $5.89 per 1,000 gallons depending on the site. The added dollar per Btu cost to save water is generally low for synthetic fuels. For example, in the case of Synthane when water costs 20 cents per 1,000 gallons, from 1,900–2,300 acre-feet/year can be saved at a cost ranging from 0.9–1.5 cents per million Btu's. At a product gas price of $3.00 per million Btu's, the cost of water savings would increase the price of the gas by about 0.3 to 0.5 percent.

The price increase would be greater for electric power. If electricity is priced at 2.5 cents per kilowatt hour, a 0.1-0.2 cost per kilowatt hour price increase to save water would represent an increase of about 4 to 8 percent in the price of electricity.

TRADE-OFFS FOR ALTERNATIVES

I have explicitly discussed only the effectiveness and efficiency of wet/dry rather than wet cooling. The analysis goes on to evaluate also on the basis of the other criteria mentioned earlier. Rather than draw a conclusion that one alternative is either preferable or better than another, we attempt to show what the trade-offs would be for each alternative. Implementation alternatives are also evaluated and compared.

SUMMARY

An overview has been given of the Western Energy Study, the objectives it is intended to achieve, how it has been structured and conducted, and the kinds of results it is producing. Water availability was chosen to demonstrate how we went about identifying and defining the problems and issues policymakers are likely to have to deal with, how this led to additional analysis to identify alternative courses of action, and how these alternatives were analyzed to inform policymakers concerning the consequences of their policy choices. Specifically, I illustrated the water and dollar cost of energy tradeoffs associated with the choice of cooling options. Knowing these trade-offs, both public and private sector policymakers can make better informed choices. Certainly they will still have to make choices under conditions of uncertainty; but the level of uncertainty can be considerably reduced by studies such as the Western Energy Study.

**These costs vary by site but are approximately correct for all sites.

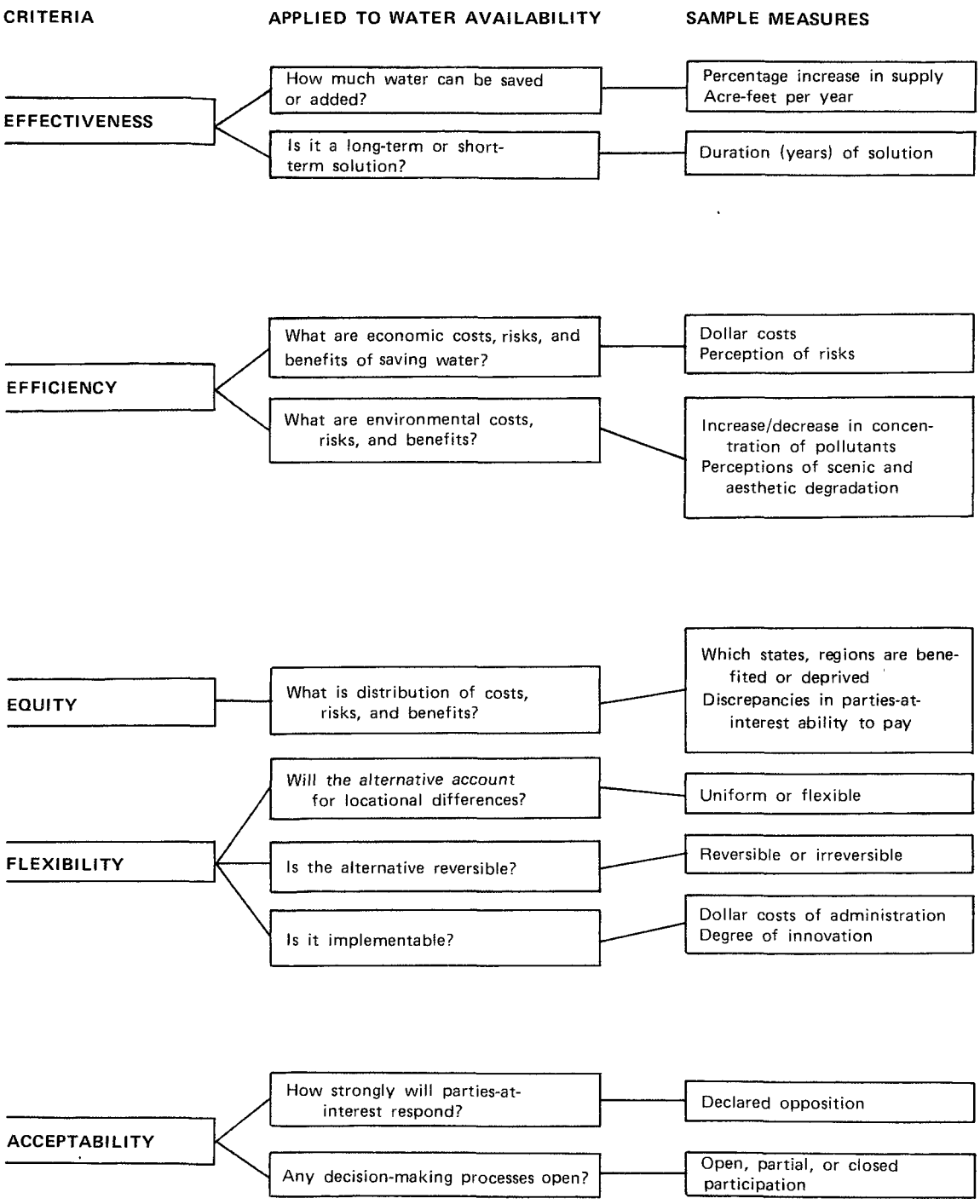
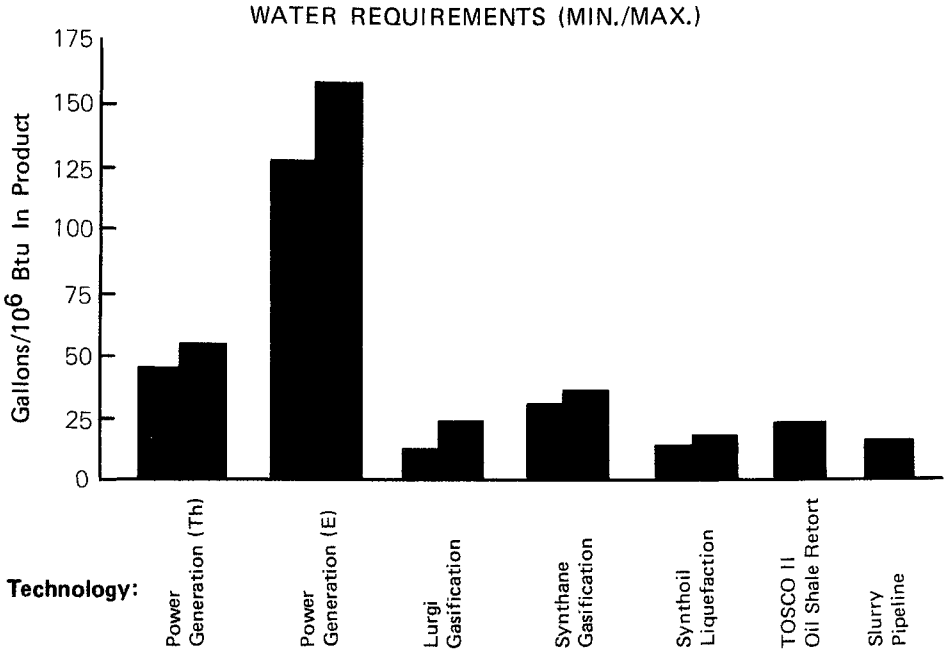


FIGURE 5—*Criteria for evaluation*



FACILITY	LOAD FACTOR	SIZE
Power Generation	70%	3,000 MWe
Lurgi Gasification	90%	250 MMscfd
Synthane Gasification	90%	250 MMscfd
Synthoil Liquefaction	90%	100,000 bbl/day
TOSCO II Oil Shale Retort	90%	100,000 bbl/day
Slurry Pipeline	100%	25 MMmtpy

FIGURE 6—*Water requirements for energy conversion technologies*

TABLE 3

Water conserved on an equivalent basis (gallons/million Btu)

Technology	Water Consumed for Wet Cooling	Maximum Conservation Wet/Dry Cooling		Maximum Conservation Dry Cooling	
		PERCENT	GALLONS	PERCENT	GALLONS
Power Generation					
Btu (e)	116-144	61-68	78.9-88.5	80-91	105.1-115.5
Btu (th)	39-49	61-68	26.4-30.1	80-91	35.3-39.3
Lurgi Gasification	14-24	41-72	9.8-10.1	54-96	12.9-13.4
Synthane Gasification	32-36	48-52	16.7-17.4	65-69	22.2-23.3
Synthoil Liquefaction	15-19	65	9.7-12.4	68-86	12.9-13
TOSCO II Oil Shale Retort	23	18	4.2	23	5.4

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questions & answers

Walter B. Smalley
Peanuts International Limited

C. Thomas Bruer
Georgia Power Company

COMMENT

When Frank Press made his keynote address he spoke, hopefully, of building a consensus as to which path we should take toward assuring a future with adequate energy. Yesterday, in their excellent presentations on sulfates and acid rain, Drs. Hussar and Dochinger approached that consensus and also put it on a world level by comparisons with Europe.

EPA's recent releases mentioned that June 5 is World Environment Day. The fact sheet with the release quotes world-famed ocean man, Jacques Yves Cousteau, as saying, "Each month we now pour so many millions of tons of poisonous wastes into the living seas and in perhaps 20 years, perhaps sooner, the oceans will have received their mortal wound and will start to die. I do not say this lightly." As a member of the American Oceanic Organization and the Cousteau Society, I wish to share with you a short but important quote from the Cousteau Society's Calypso Log of March, 1978, that relates directly to what has been said here the last 2 days. It has made clear that the increase in human population since the time of Aristotle has increased human wastes by the same order, that it is the amount of human waste that has become a problem.

"Pollutants are not inherently bad. They are almost always valuable commodities in the wrong places. The basic cause of human pollution is an inefficient technology and a failure of humans to develop closed-loop systems. It is easier, but never more economical, to discard wastes than to recycle them. Then we modern humans worry that we are running out of resources. The chemicals are not gone; they are misplaced. They are scattered throughout the environment in a way that we cannot reuse them."

For nearly 5 months, the crew of the Calypso worked to determine the concentrations of these toxic materials in the marine plants and animals of the Mediterranean. It might take another 6 months or more for laboratories to analyze the thousands of samples we have sent them. While we are waiting for the results, we might well ponder Aristotle's question, what are we as a

species doing to ourselves? We do not have to answer Aristotle, but we do have to answer to ourselves because pollution, a modern concept, is not a figment of anyone's imagination. Now, this is leading up to asking, have we reached a reasonable consensus and where do we go from here?

QUESTION

In modeling work, has there been any explicit attempt to incorporate the uncertainty that the purchasing utility incurs in choosing a technology or are only best-guess costs used? Is there an attempt to incorporate a possible spread of costs?

RESPONSE: Dr. Peter M. Cukor (Teknekron, Inc.)

We recognize that there is uncertainty, not only in the costing technology but in the ability to obtain a construction and operating permit. We have handled this, in part, through what we call scenarios; that is, running cases where there are relatively high uses of nuclear or coal-fired units, higher uses of oil-fired units, and higher yet of gas-fired units from a base case. As our base case projection, we use the announced plans of the individual utility firms as submitted to the Federal Power Commission with their 20-year forecast each April 1. From those we do deviations as our technology mix. The results I presented, however, involve the base case.

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FEDERAL AGENCY ACRONYMS

DOE	Department of Energy	
EPA	Environmental Protection Agency	
	EMSL	Environmental Monitoring and Support Laboratory
	ERL	Environmental Research Laboratory
	ESRL	Environmental Science Research Laboratory
	HERL	Health Effects Research Laboratory
	IERL	Industrial Environmental Research Laboratory
	OEMI	Office of Energy, Minerals and Industry
HEW	Department of Health, Education and Welfare	
	NIEHS	National Institute of Environmental Health Sciences
	NIOSH	National Institute of Occupational Safety and Health
HUD	Department of Housing and Urban Development	
NASA	National Aeronautics and Space Administration	
TVA	Tennessee Valley Authority	
USDA	U.S. Department of Agriculture	
	ESCS	Economics, Statistics and Cooperative Service
	FS	Forest Service
	SCS	Soil Conservation Service
	SEA/CR	Science and Education Administration, Cooperative Research
	SEA/FR	Science and Education Administration, Federal Research
USDC	U.S. Department of Commerce	
	NBS	National Bureau of Standards
	NOAA	National Oceanic and Atmospheric Administration
	OEA	Office of Environmental Affairs
USDI	U.S. Department of Interior	
	BOM	Bureau of Mines
	FWS	Fish and Wildlife Service
	USGS	U.S. Geological Survey

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/9-78-022	2.
3. RECIPIENT'S ACCESSION NO.	
4. TITLE AND SUBTITLE ENERGY/ENVIRONMENT III Proceedings of the Third National Conference on the Interagency Energy/Environment R&D Program, Washington, D.C., June 1 & 2, 1978	5. REPORT DATE Date of Publication October 1978
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Decision Series Editor: Richard M. Laska, EPA/ORD Technical Editor: Elinor Voris Associate Editor: Kathleen E. Dixon	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Automation Industries, Inc. Vitro Laboratories Division 14000 Georgia Avenue Silver Spring, MD 20910	10. PROGRAM ELEMENT NO. 626
	11. CONTRACT/GRANT NO. EPA 68-01-2934
12. SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental Protection Agency Office of Research & Development Office of Energy, Minerals & Industry Washington, D.C. 20460	13. TYPE OF REPORT AND PERIOD COVERED Decision Series-thru June '78
	14. SPONSORING AGENCY CODE EPA-ORD-OEMI

15. SUPPLEMENTARY NOTES
This project is part of the EPA-planned and coordinated Federal Interagency Energy/Environment R&D Program.

16. ABSTRACT

This publication is the complete Proceedings of the Third National Conference on the Interagency Energy/Environment R&D Program.

Energy/Environment III provides an update of Interagency research programs in particular areas, including health effects, transport processes and ecological effects, mining methods and reclamation, control technology and integrated technology assessment. Complete texts of all papers are presented, along with addresses, panel discussions, and question and answer periods. The volume is illustrated with tables and figures.

Composed of more than a dozen Federal agencies, the Interagency Energy/Environment R&D Program is designed to assure that unresolved environmental issues are not a barrier to timely and safe development of our domestic energy resources. The Office of Energy, Minerals and Industry within EPA's Office of Research and Development has, as coordinator, invested approximately $100 million a year in the Program since its inception in fiscal year 1975.

17. (Circle One or More) KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Environments; Energy Conversion; Combustion; Refining; Other:	Control Technology: Energy Extraction, Coal Cleaning, Flue Gas Cleaning, Direct Combustion, Synthetic Fuels, Nuclear, Thermal, Improved Efficiency, Advanced Systems; Processes & Effects: Transport Processes, Ecological Effects, Charac., Meas. & Monit., Health Effects, Integrated Assessment; Energy Cycle: Extraction, Processing, Conversion, Utilization; Fuel: Coal, Oil/Gas, Oil Shale, Nuclear, Geothermal, Solar, Waste as Fuel, Hydroelectric, Multi-Fuel (5 or more); Other	(6F) 8A 8F 8H 10A (10B) 7B 7C (13B) 7A

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 385
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

☆U.S. GOVERNMENT PRINTING OFFICE: 1978 O—620-007/3725 REGION 3-1