COPAC—2

ABATEMENT OF SULFUR OXIDE EMISSIONS FROM STATIONARY COMBUSTION SOURCES

COPAC—2

ABATEMENT OF SULFUR OXIDE EMISSIONS FROM STATIONARY COMBUSTION SOURCES

Prepared by
Ad Hoc Panel on Control of Sulfur Dioxide from Stationary Combustion Sources
Committee on Air Quality Management
Committees on Pollution Abatement and Control
Division of Engineering
National Research Council

Washington, D. C.
1970

This is the report of a study undertaken by the Committee on Air Quality Management *Ad Hoc* Panel on Control of Sulfur Oxide from Stationary Combustion Sources for the National Academy of Engineering in execution of work under Contract No. CPA 22-69-31 with the National Air Pollution Control Administration, Environmental Health Service, Public Health Service, U.S. Department of Health, Education, and Welfare.

As a part of the Division of Engineering of the National Research Council, the Committees on Pollution Abatement and Control perform study, evaluation, or advisory functions through groups composed of individuals selected from academic, governmental, and industrial sources for their competence and interest in the subject under consideration. Members of these groups serve as individuals contributing their personal knowledge and judgements and not as representatives of any organization in which they are employed or with which they may be associated.

PREFACE

Because the air, water, and land on earth are limited, we, as a nation, must plan and work together to ensure the preservation of an acceptable environment. In this report of a study on the control of sulfur oxide emissions into the atmosphere, primarily from electricity generating stations, an effort has been made to place the findings of the study in perspective with the entire problem of environmental quality management.

On the basis of problem definition, a study of need, a study of engineering constraints, and an *analysis of technological requirements and alternatives*, this report outlines a government-industry program for research, development, and demonstration of potential control processes.

No attempt has been made, however, to deal with such problems of sulfur oxide emissions as their effect on health and other biological aspects. Important though such studies may be, they are outside the scope of the *Ad Hoc* Panel on Control of Sulfur Oxide from Stationary Combustion Sources.

The members of the panel, along with the members of the Committee on Air Quality Management, share the objectives of the Congress as representing the determination of the people to restore and maintain the quality of our air resources and the objectives of the National Air Pollution Control Administration of the Department of Health, Education, and Welfare as the Federal "lead agency" to assure significant progress by an early date. The panel hopes that the results of its study will be useful in the attainment of these objectives.

The panel's estimation of the present status of sulfur control technology is based primarily on presentations by 23 research and industrial organizations that came to Washington to discuss the results of their process studies and their proposals for further work. In addition, 23 other organizations provided information by correspondence.

The panel appreciates the cooperation received from industrial and research organizations with active programs in sulfur oxide control. The panel is particularly grateful to Mr. Paul W. Spaite, Director, Bureau of Engineering and Physical Sciences, National Air Pollution Control Administration, and his staff for their outstanding support.

A summary of the study and a brief statement of conclusions are presented first in the report for the benefit of those who may wish to gain an overview of the panel's efforts. These are followed by an introduction covering the background of the study, the roles of the National Academy of Sciences and the National Academy of Engineering, and the nature of the sulfur oxide emissions problem. The remaining sections of the report cover the impact of the nation's growing requirements for electricity upon the sulfur oxide emissions problem and review the possibilities for abatement of sulfur oxide emissions through the widespread use of nuclear power plants, the use of sulfur-free or low-sulfur fuels, and the development and application of technology to control sulfur oxide emissions. A strategy for the research, development, and demonstration of this technology is presented.

Appendixes to the report contain lists of organizations that made presentations and correspondents who supplied information for the study, lists of research and development activities in sulfur oxide pollution control in the United States and abroad, and a selective bibliography.

It is hoped this report will provide a basis for increased governmental and public understanding of the problems of sulfur oxide abatement and control, and will direct attention and adequate assignment of resources to the orderly and expeditious solution of this portion of the nation's problems of environmental quality management.

Thomas H. Chilton, *Chairman*

NATIONAL ACADEMY OF SCIENCES-
NATIONAL ACADEMY OF ENGINEERING
NATIONAL RESEARCH COUNCIL
Division of Engineering

COMMITTEE ON AIR QUALITY MANAGEMENT
AD HOC PANEL ON CONTROL OF SULFUR OXIDE
FROM STATIONARY COMBUSTION SOURCES

Thomas H. Chilton, Retired, E.I. du Pont de Nemours & Co., Inc., *Chairman*
Richard E. Chaddock, Hercules Incorporated
Vance R. Cooper, General Electric Company
George T. Cowherd, Jr., Consolidated Edison Co. of New York, Inc.
H. L. Falkenberry, Tennessee Valley Authority
C. Howard Hardesty, Continental Oil Company
Robert L. Hershey, Retired, E.I. du Pont de Nemours & Co., Inc.
R. M. Lundberg, Commonwealth Edison Company
Robert L. Pigford, University of California, Berkeley
Elliott J. Roberts, Dorr-Oliver, Incorporated
Thomas K. Sherwood, Retired, Massachusetts Institute of Technology, *Ex Officio*
Jack A. Simon, Illinois State Geological Survey

Staff

R. W. Crozier, *Executive Secretary*, Committees on Pollution Abatement and Control, National Research Council
J. M. Marchello, *Staff Engineer*, Committees on Pollution Abatement and Control, National Research Council
Donnell H. Nicchitta, Administrative Secretary, Committees on Pollution Abatement and Control, National Research Council

Liaison Representative-NAPCA

Paul W. Spaite, Director, Bureau of Engineering and Physical Sciences, National Air Pollution Control Administration, U.S. Department of Health, Education and Welfare

CONTENTS

TABLES

FIGURES

APPENDIXES

I

SUMMARY AND CONCLUSIONS

Controlling and improving the quality of our environmental resources is a growing concern of the nation. National and regional goals and standards for air quality management are being defined. Capital investments of billions of dollars will be required to install processes to meet these standards. Keeping these costs within bounds, while still attaining an acceptable level of control within the shortest practical period of time, will call for the best efforts and most careful planning at all levels from individuals, civic groups, and companies through local, regional, state, and Federal agencies.

The emission of SO_2* from combustion of sulfur-bearing coal and oil, primarily for the generation of electrical energy, is second only to the emission of pollutants from internal combustion engines in quantity of pollutants discharged to the national air environment.

During the next 20 years, the national requirement for electrical energy is expected to more than triple. The supply of natural gas, a low-sulfur fuel, is expected to decrease in about 10 years, and petroleum products may reach their maximum availability in about 30 years. To supply the needed electricity, the use of coal is expected to triple by the year 2000, when it is expected that the use of nuclear energy will about equal the use of coal, after which the requirement for coal will start a downward trend.

The substitution of low-sulfur fuels, the only presently available method for reducing SO_2 emissions, is restricted by the limited availability

---

*The symbol SO_2 is used in this report to designate the sulfur oxides in stack gases (SO_2 plus 1 percent to 2 percent of SO_3).

of natural gas, low-sulfur oil, and low-sulfur coal. More rapid expansion of the application of nuclear energy is constrained by engineering and economic problems, in addition to siting problems, that are of growing concern to all planning of major electricity generating installations. By the late 1980's, new fossil-fueled plants may employ magnetohydrodynamic (MHD) generators followed by conventional steam boilers, or by an advanced gas-turbine/steam-power cycle. The combined energy conversion efficiency of such plants is expected to be in the range of 50 percent to 60 percent compared with about 40 percent for modern conventional plants, which would result in a corresponding decrease in SO_2 emissions. However, the high operating temperature of MHD units may result in increased NO_x emissions.

In addition to improving the energy conversion efficiency, the fast breeder nuclear reactor produces a net gain of fissionable material and thereby reduces the net cost of fuel. The Atomic Energy Commission is planning a 500 MW fast breeder demonstration plant for 1976 and expects the first commercial units to start up about 1985 in the United States.

Therefore, *the reduction of SO_2 emissions from stationary combustion sources, in the next 5 to 20 years, will depend very largely on the development, demonstration, and application of a combination of technologies designed to prevent the sulfur in coal and petroleum products from reaching the atmosphere through the combustion processes.*

The technology for removal of sulfur from oil is being developed by a number of oil companies, and the panel does not believe that NAPCA should contribute significantly to these developments.

Although broader application and refinement of existing technology could increase the quantity of low-sulfur coal available, there are no cleaning or washing processes presently in sight that have the potential for substantially reducing sulfur content below levels presently being achieved. This emphasizes the need for new concepts in engineering and chemical approaches to the desulfurization of coal.

In addition to joint support by groups of utilities, a number of industrial organizations have committed significant funds to research, development, and demonstration of sulfur emission control processes and equipment. An increase in these activities, together with increased support by the Federal Government, is needed.

The panel reviewed the status of United States and foreign sulfur oxide abatement and control processes and firmly concluded that, *contrary to widely held belief, commercially proven technology for control of sulfur oxides from combustion processes does not exist.*

Efforts to force the broad-scale installation of unproven processes would be unwise; the operating risks are too great to justify such action, and there is a real danger that such efforts would, in the end, delay effective SO_2 emission control. *A high level of government support is needed for several years to encourage research, engineering development, and demonstration of a variety of the more promising processes, as may be suited to specific local and regional conditions, to bring these processes to full-scale operating efficiency at the earliest practical date. This can be done most expeditiously if Federal support, in addition to industry commitments, is provided at the appropriate time and in the needed amounts.*

Federal support for the development of the following control approaches is suggested:

1. "Throw-away" processes for removal of SO_2 from stack gases, such as limestone injection, which produce a presently nonmarketable product

2. New combustion concepts, such as fluidized bed combustion (FBC), which fixes the sulfur as a sulfate during combus-

tion and prevents its release as SO_2 to the stack

3. Chemical recovery processes, which produce salable SO_2, sulfuric acid, elemental sulfur, or fertilizers

4. Coal gasification processes, which produce sulfur-free fuels

5. New concepts in engineering and chemical approaches to the desulfurization of coal

The limestone injection processes, with adequate particulate control, should be commercially demonstrated within the next 1 to 3 years and, if successful, can be installed in many existing plants.

Several sulfur-recovery processes appear to be ready for scale-up to commercial demonstration size (100,000 kW or larger boilers). Full-scale demonstration of the industrial reliability of these processes is 3 to 10 years away. Some of them can be installed in a portion of existing plants or engineered into future plants.

New combustion technology may be available for industrial application in 5 to 10 years. Efficient coal gasification processes, which are 5 to 10 years away, have the potential for producing pipeline-quality, low-sulfur gas for supplementing existing supplies of natural gas or for producing a product of less than pipeline-quality, but adequate for power generation. Such fuels seem likely to become increasingly competitive for use in power production as the cost for controlling all pollutants (SO_2, NO_x, and fine particulates) increases the costs for conventional systems.

These time estimates are realistic only if there is dedication and a positive commitment on the part of government agencies, utilities, fuel suppliers, and equipment manufacturers to support the orderly *development and timely application of the more promising processes.*

In recommending a 5-year plan for future work, the panel places special emphasis on the following:

1. Complete development of the limestone process should be given high priority because it is applicable to many existing boilers and is closer than others to demonstrated industrial application.

2. For new power plants and some existing plants, it is expected that sulfur-recovery processes will be necessary to keep costs for future control within reasonable limits.

3. NAPCA should continue to support the development and demonstration of new concepts in combustion technology, sulfur-recovery, and coal-desulfurization processes.

4. Research should be supported on ways to combine the abatement of nitrogen oxide and particulates with sulfur oxide control.

5. Elemental sulfur is a more desirable by-product than sulfuric acid or sulfur dioxide. The conversion of sulfur dioxide to sulfur is not a well established process, and it is important that the technology and costs of this conversion be thoroughly studied.

6. NAPCA should employ a *process engineering and construction firm* to project costs on a *common basis* for all the promising processes at various stages in their development to aid in making scale-up decisions.

II

INTRODUCTION

A. BACKGROUND OF THE STUDY

The concern of Americans for the deterioration of the nation's air resources is reflected in Public Law 90-148 as amended, the Air Quality Act of 1967, enacted by the 90th Congress on November 21, 1967. Responsibility for carrying out the provisions of the law is assigned to the Secretary of the Department of Health, Education, and Welfare.

The purposes of the Act are set forth in Section 101(b) as:

1. to protect and enhance the quality of the nation's air resources so as to promote the public health and welfare and the productive capacity of its population;

2. to initiate and accelerate a national research and development program to achieve the prevention and control of air pollution;

3. to provide technical and financial assistance to State and local governments in connection with the development and execution of their air pollution prevention and control programs; and

4. to encourage and assist the development and operation of regional air pollution control programs.

Special emphasis (Section 104) is given to research and development into new and improved methods for the prevention and control of air pollution resulting from the combustion of fuels. In addition to providing for laboratory and pilot plant testing, Section 104(a)(4) calls upon the Secretary of the Department of Health, Education, and Welfare to "construct, operate, and maintain, or assist in meeting the cost of the construction, operation and maintenance of new or improved demonstration plants or processes which have promise of accomplishing the purposes of this Act."

The Clean Air Act recognizes the regional nature of air pollution problems. One of the functions of the Federal Government under the 1967 legislation is the designation of air quality control regions in all those areas in which air pollution constitutes a serious threat to health and welfare. Once air quality regions are designated, and NAPCA has issued criteria documents describing the harmful effects of specific pollutants, together with documents describing techniques for controlling the pollutants, it becomes the responsibility of the states in the regions to develop air quality standards and plans for enforcing them. In 1969, NAPCA issued criteria on two of the major pollutants--particulate matter and the sulfur oxides--together with the required supporting documents on techniques available for preventing and controlling their emission into the atmosphere. In March 1970, NAPCA issued air quality criteria and recommended control techniques for carbon monoxide, photochemical oxidants, and hydrocarbons.[16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26*]

The Clean Air Act, as amended, states in Section 101(a)(3) "that the prevention and control of air pollution at its source is the primary responsibility of State and local governments," in Section 101 (a)(4) "that Federal financial assistance and leadership is essential for the development of cooperative Federal, State, regional, and local programs to prevent and control air pollution," and, in Section 101 (b)(4), that a major purpose of the Act is "to encourage and assist the development and operation of regional air pollution control programs."

Federal assistance is provided in two major ways--financial and technical. Financial assistance

---

*Refer to numbered items in the bibliography contained in Appendix E of this report.

to air pollution control agencies is authorized under Section 105 of the Act. Under Section 106, financial assistance for planning for air quality standards and implementation plans in interstate air quality control regions is authorized.

The National Air Pollution Control Administration also provides technical assistance in conducting emission inventories, air quality monitoring and data analysis, and diffusion modeling. Diffusion modeling involves combining meteorological and emission data to predict air quality. These services are particularly helpful in attempting to test various emission reduction strategies.

The Air Quality Act of 1967 has created a new role for the Federal Government in air pollution control. The Act states that air quality standards that the states develop for an air quality control region become effective when the Secretary of the Department of Health, Education, and Welfare determines that such standards are "consistent with the air quality criteria," and it states that an implementation plan becomes effective when the Secretary determines "that the plan is consistent with the purposes of the Act insofar as it assures achieving such standards of air quality within a reasonable time."

What may be considered a "reasonable time" for attainment of an air quality standard will depend on a number of factors, including the availability of applicable control techniques and, particularly, the nature and seriousness of the adverse effects of the pollutants involved. Every implementation plan must include a timetable for reaching compliance with the projected requirements for the prevention, abatement, and control of air pollution. This timetable must provide for meaningful increments of progress over relatively short intervals, such as 1-year or 2-year periods, during the total timespan covered by the implementation plan.

B. THE ROLES OF THE NATIONAL ACADEMY OF SCIENCES AND THE NATIONAL ACADEMY OF ENGINEERING

The National Academy of Sciences and the National Academy of Engineering established the Environmental Studies Board in 1967 to coordinate activities of the two Academies in the environmental field. One of the first acts of this board was to create four committees within the Division of Engineering of the National Research Council on air, water, noise, and solid waste management, respectively. These committees have an engineering orientation and are available for advice and assistance to the Congress and to agencies of the executive branch having responsibility for pollution abatement and control. Needed interaction and coordination of the committees are provided through liaison activities of the Environmental Studies Board.

On June 20, 1969, the Department of Health, Education, and Welfare, through the National Air Pollution Control Administration, requested the National Academy of Engineering to make a comprehensive review of present industry and government research and development programs directed toward control of sulfur oxides effluents from stationary sources of combustion. The requested study would include technical and economic potentials, adequacy of scope, proper integration with other similar efforts, and the responsiveness to national needs.

The request was accepted after review and coordination by the Environmental Studies Board with other environmental activities of the National Academy of Engineering and the National Academy of Sciences. The task was assigned to the National Research Council's Committee on Air Quality Management, which in turn requested its *Ad Hoc* Panel on Control of Sulfur Oxide from Stationary Combustion Sources to carry out the study.

Because meeting national energy requirements is only one of man's activities that may result in unacceptable acceleration of environmental degradation, studies of abatement technology for other sources of SO_2 and other air pollutants will be made soon.

C. NATURE OF THE SULFUR OXIDE PROBLEM

At an early meeting of the panel with Dr. John T. Middleton, Commissioner of NAPCA, and subsequent meetings with Mr. Paul W. Spaite, Director of the Buréau of Engineering and Physical Sciences of NAPCA, and other members of the NAPCA staff, the panel was presented data on projected sulfur oxides emission with various levels of control. The panel members considered these data to be realistic, based on authoritative sources, and interpreted rationally and conservatively; and the members were impressed with the magnitude and urgency of the problem of sulfur oxides emission to the atmosphere. *The data and projections gave rise to the conclusion that positive action will be required to prevent the emission of sulfur oxides into the ambient air from more than quadrupling by the year 2000.*

The requirement for electrical power is projected to increase at an annual rate of 6 percent during the next 30 years. It is generally agreed that the generation and distribution of this quantity of electrical energy, using presently available fuels and technology, will result in unacceptable levels of environmental degradation. As previously noted, the use of sulfur-bearing fuels to generate electrical energy is only one of man's activities contributing to the decline in quality of our air resources, but it is a major source of SO_2.

NAPCA chose SO_2 emitted to the atmosphere from electricity generating plants for first attention because: (1) this is the largest man-made source of sulfur oxides; (2) it is widely dispersed nationally, but is largely concentrated in or near urban centers; (3) it is growing at about 6 percent per year; (4) it is intimately related to the national and international flow of energy resources; (5) it is important to regional economic development; and (6) it is critical to continued national well-being, security, and economic growth. Moreover, *while national and regional goals and standards are being defined, the processing methods presently available to attain these goals are inadequate for the task.*

Worldwide emission of sulfur into the atmosphere arises from biological, geological, and industrial activity.[11] Of the man-made sources, coal and oil combustion for electricity generation accounts for about 50 percent, other combustion of coal 16 percent, other combustion of oil 9 percent, primary and secondary smelting 12 percent, petroleum refining 7 percent; and miscellaneous sources including coke and sulfuric acid production, burning coal refuse banks, and refuse incineration 6 percent.

III

ENERGY REQUIREMENTS AND AIR POLLUTION CONTROL

A review of sulfur oxide abatement and control technology gives rise to concern as to the future supply of electricity and the future availability and use of fuels. There are important matters of policy and management regarding future energy conversion and consumption that bear directly and importantly on environmental problems, such as: emission of sulfur oxides, nitrogen oxides, particulates, carbon dioxide, carbon monoxide, and other pollutants from fossil fuels combustion; thermal pollution; siting of generating facilities and distribution systems; fuels policy and availability; radioactive pollution and disposal of radioactive wastes; and technological, political, jurisdictional, and economic limitations and constraints.

Electricity generation, sulfur oxide emission control, and other environmental factors are closely interrelated and require an integrated systems approach. The objective of providing for the nation's growing power needs is subject to the constraints of maintaining environmental quality, fuels availability, and technical developments. Within this framework lie the trade-offs of shifting generation, improved transmission, and the development of control processes. Overriding all of these is the long-term consequence of each alternative.

A. ELECTRICITY GENERATION

The Federal Power Commission now states that the 1970 requirement, including reasonable reserves, for electrical generating capacity is nearly 340 million kW. This requirement is expected to be nearly double by 1980 and to exceed 1 billion kW in 1990.

Figure 1 shows the electricity generation and fuels utilization forecast (assuming early development of the breeder reactor). At present, about 65 percent of the energy for electricity generation comes from coal, with natural gas and oil supplying most of the

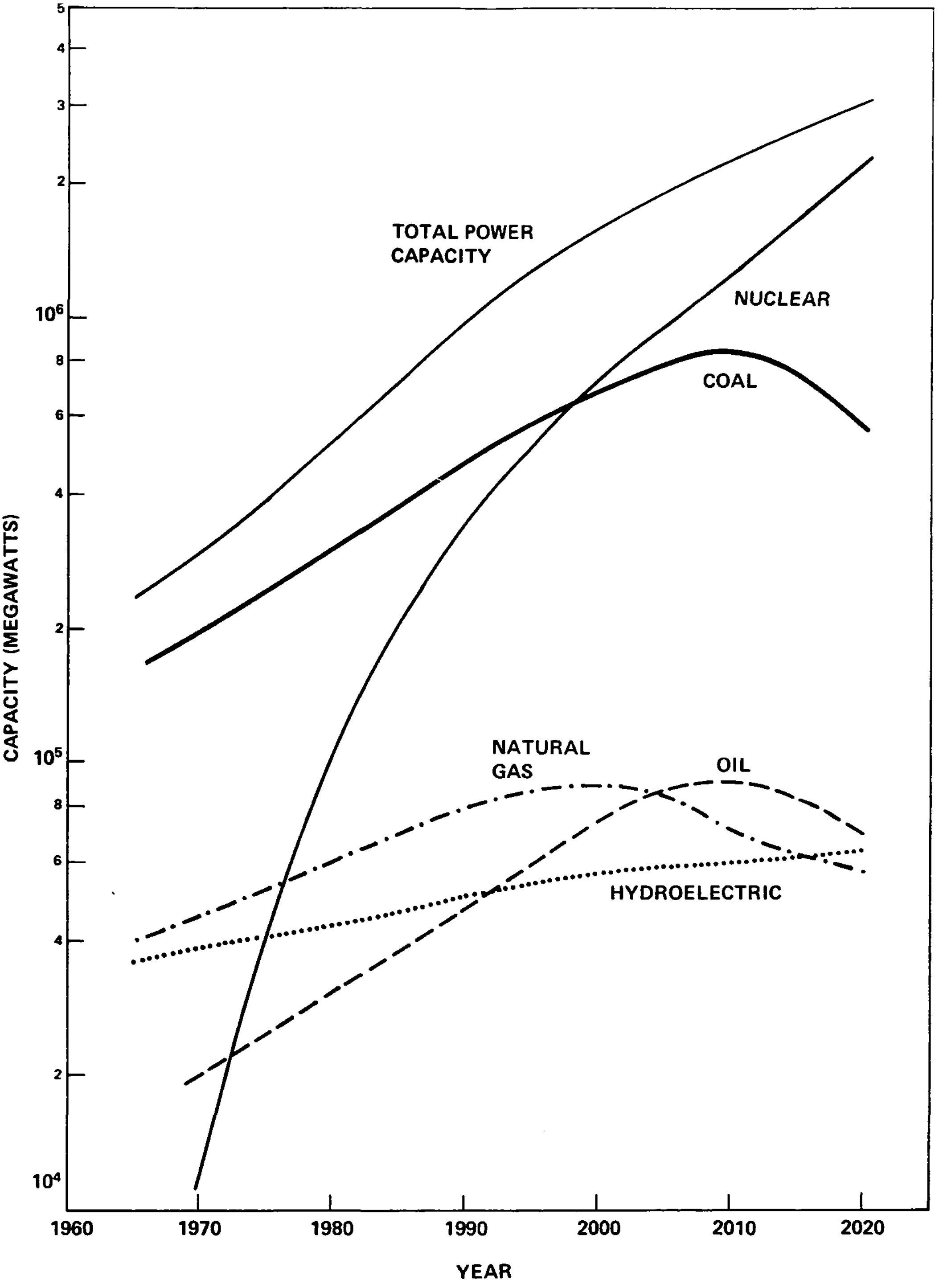

Figure 1. Projected power generating capacity and fuel sources of electric utilities in the United States (with breeder). NAPCA, February 1970.

remainder. It is predicted that the use of nuclear energy will increase rapidly and will exceed coal as an energy source around the year 2000. Because of the need to burn more coal to supply the needed power, sulfur emissions would be expected to increase more than fourfold by the year 2000, unless effective control processes are developed and applied.

Most of the new generating capacity installed between now and 1990 will be provided by some 250 large power plants of greater than 1,000 MW capacity.[2] The siting problem will generally be one of assuring that the relatively small number of large plants are adequately planned and located to meet the goals of providing low-cost, reliable power and minimizing the adverse effects on our environment. With an onsite investment of about $200 million to $400 million each, these new plants will be among the larger industrial establishments in the nation. Including support and auxiliary activities, they will represent approximately $80 billion of capital investment, which will be profoundly affected by the public interest.

B. <u>SULFUR OXIDE EMISSIONS</u>

The demand for electric power is increasing so rapidly that sulfur oxides emissions may increase even allowing for: (1) projected construction of nuclear power plants; (2) substitution of gas or low-sulfur fuel oil at locations where they are available; (3) use of coal of reduced sulfur content to the extent that can be expected; (4) introduction of improved combustion methods; and (5) application of improved stack-gas treatment and sulfur recovery processes.

Even with a national commitment to orderly but urgent plans for application of new technology, the best that can be hoped for through the year 2000 is a total sulfur oxides emission rate from all utilities somewhere near the present level. Near-term improvement in the quality of ambient air at ground level in urban areas may be brought about by resorting to dispersion of facilities, by use of tall stacks, or by load or fuel shifting under adverse meteorological conditions. Sulfur oxides emission data and projections for the United States are shown in Table 1 and Figure 2.

Nuclear power plants emit no SO_2; essentially the same can be said for plants using natural gas. The technology for removal of sulfur from fuel oil appears to be reasonably well in hand. Further development of hydroelectric power will not be a major factor. The import of liquefied petroleum gases will most likely be increased to the limit of economic availability. Despite these factors, the use of coal will steadily increase and is projected to more than triple by the year 2000, before leveling off as large nuclear power stations replace those burning fossil fuels (Figure 1). About 75 percent of the sulfur oxides discharged into the atmosphere from man-made sources comes from the combustion of coal and oil. Gasoline contains almost no sulfur, so emissions from automobiles contribute little SO_2. But the combustion of coal, now averaging about 2.7 percent sulfur and forecast to increase to 3.5 percent by 2000, accounts for 65 percent of the total SO_2. The combustion of heavy fuel oil contributes about 12 percent.

TABLE 1

ESTIMATED POTENTIAL SULFUR DIOXIDE POLLUTION WITHOUT ABATEMENT[a]

UNITED STATES

	Annual Emission of Sulfur Dioxide (Millions of tons)				
	1967	1970	1980	1990	2000
Power plant operation (coal and oil)[b]	15.0	20.0	41.1	62.0	94.5
Other combustion of coal	5.1	4.8	4.0	3.1	1.6
Combustion of petroleum products (excluding power plant oil)	2.8	3.4	3.9	4.3	5.1
Smelting of metallic ores	3.8	4.0	5.3	7.1	9.6
Petroleum refinery operation	2.1	2.4	4.0	6.5	10.5
Miscellaneous sources[c]	2.0	2.0	2.6	3.4	4.5
Total	30.8	36.6	60.9	86.4	125.8

(a) February 1970 estimates by National Air Pollution Control Administration, excluding transportation.
(b) See Figure 2. With breeder reactor.
(c) Includes coke processing, sulfuric acid plants, coal refuse banks, refuse incineration, and pulp and paper manufacturing.

Stack gases from fossil-fueled power plants contain about 1,000 to 3,000 ppm of SO_2, depending on the amount of sulfur in the fuel (1 ppm = 2860 $\mu g/m^3$ at standard conditions). Detrimental effects on vegetation, materials, and human health are first noticed in areas having 0.03 to 0.04 ppm (annual mean) SO_2 concentration.[5,14,15,20] Thus, a 100,000-fold dilution or reduction in concentration is required, on the average, by the time the SO_2 reaches ground level. SO_2 concentrations are near and, in some cases, at times above these levels in several urban areas of the United States.[20]

A number of SO_2 monitoring studies have been made near power plants, and there are various theoretical and computer models for predicting dispersion from stacks and resulting ground-level concentrations for different meteorological and topographic situations. These are intended to show the relation between stack emissions and the permissible concentrations.[20] Such studies have served as the basis for decisions to require use of fuels having lower sulfur content or the use of SO_2 emission control equipment.

The high dilution from stack level to ground level of SO_2 concentration will be required even with development of control devices. The most efficient removal processes can be expected to reduce stack gas concentrations of SO_2 by about 99 percent, which will result in an effluent that could still be above acceptable ground level concentrations. In addition to SO_2 dilution, tall stacks will be needed to disperse carbon dioxide, nitrogen oxide, and water vapor and to provide mixing with air to raise the oxygen content.

In some cases, the 1 percent sulfur limit in fuels has been found to be inadequate, and several regions are considering further reducing the permissible sulfur content. The New York-New Jersey Metropolitan region has set standards limiting sulfur to a maximum of 1.5 percent in fuels that are burned in existing power plants. Other regions are considering similar limits. Bituminous coal containing more than 1.0 percent sulfur cannot now be sold in New Jersey, and the limit will drop to 0.2 percent in October 1971. But the supply of less than 1.0 percent sulfur coal is limited; it appears that it would be impossible to provide the needed fuels if this standard were enforced across the country.

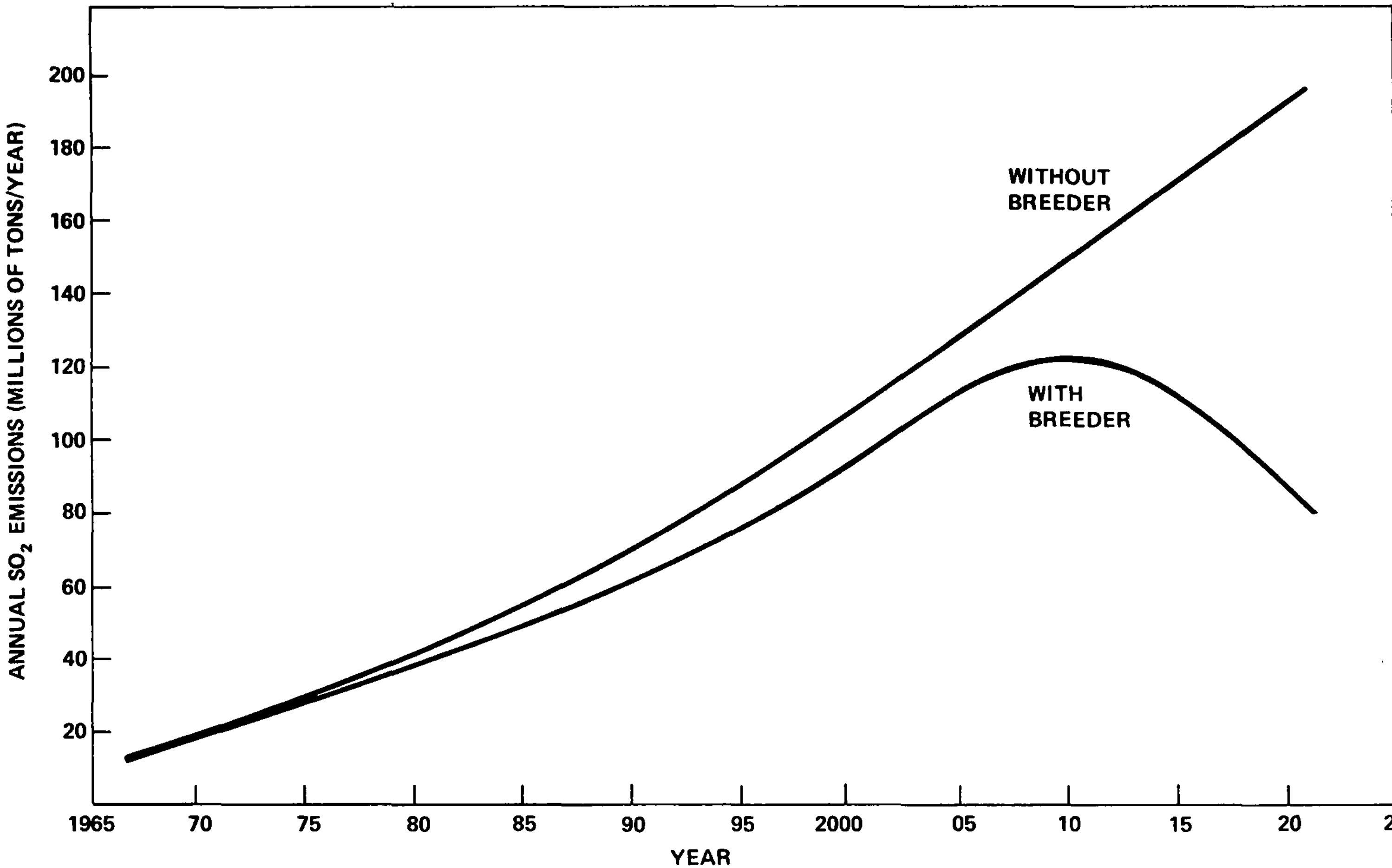

Figure 2. Comparison between projections for total power plant uncontrolled SO_2 emissions. NAPCA, February 1970.

One-third of the coal reserves in the United States are east of the Mississippi and two-thirds west. Large deposits of lower-rank subbituminous coal and lignite, which constitute 83 percent of the relatively low-sulfur reserves, lie in the West and are remote from the large urban markets. The 1 percent sulfur coal produced in the East amounts to about 36 percent of the coal mined. Approximately 26 percent of the low-sulfur coal produced is exported and 49 percent sold for metallurgical use, leaving only 25 percent of present 1.0-percent-sulfur-maximum coal available for general use. This represents only 9 percent of the present total coal production.

Elimination of sulfur from the fuel would be desirable, and considerable progress has been made in the desulfurization of fuel oil. Although the prospects of coal cleaning appear to be limited, increased efforts are warranted to reduce sulfur and ash content in coal to the extent possible. *The preferred use of naturally occurring low-sulfur or cleanable (to low-sulfur levels) coal is in those fuel uses, other than power generation, where flue gas treatment processes to reduce* SO_2 *are not economically feasible.*

The combustion of fossil fuel, particularly coal, in stationary sources creates a number of pollutants, of which sulfur oxides are only one. The panel did not consider the problems of combating all these pollutants, and addressed such questions only incidentally, as when the process being studied might have the potential for removing NO_x or particulates. But, *research on processes with the potential for simultaneous reduction of all pollutants should be encouraged.*

C. SHIFTING GENERATION

Shifting of electricity generation to outlying plants during an incident of serious adverse meteorological conditions appears practical under some circumstances, but only to a limited extent. Chicago, with the Argonne National Laboratory assisting, is developing a future power distribution model for the city. This is a NAPCA-supported activity. It appears possible to shift about 25 percent of the generation within the Chicago service area, without calling on outside service areas. For an eastern seaboard situation this may also be practical, but the panel has no basis for predicting the extent to which this would alleviate a particular situation. Most utilities in a metropolitan region would be able to do a substantial amount of good within their regions. Shifting generation may aid some peak pollution crises in other metropolitan areas. However, there must be idle capacity available beyond the influence of the poor atmospheric conditions if this is to be effective.

A long-term plan for such an operating procedure over the years would require additional investment to provide stronger transmission ties to permit shifting substantial amounts of power, as well as very substantial investment in system reserve generating capacity. Such a mode of operation would incur increased operating costs, because the system would not be operating at its economic optimum.

D. A NATIONAL ELECTRIC TRANSMISSION GRID

A survey of energy reserves in the United States and the status of nuclear reactor development have led to the suggestion that systematic plans be made for the development and utilization of western coal deposits and to a recommendation for a national electric power transmission grid.[12] Since the potential power generation centers based on these fuel sources are distant from the power demand areas, the cost of fuel transportation and energy transmission becomes an important factor in the feasibility of using western coal and oil shale reserves. The argument becomes even stronger when viewed in terms of the many siting problems of large generating stations whether they are coal-, oil-, gas-, or nuclear-fueled.

A national energy transmission grid might consist of a number of highly efficient, primary lines connecting major generating and consuming areas of the country. Secondary tie lines would then branch out from the primary lines much like the existing power-pool transmission lines. Preliminary economic analysis[12] indicates feasibility and additional potential benefits in communication and by-products manufacture. Planning, coordination, and implementation of such a venture must be accomplished at the national level. It is appropriate to note here that transmission lines pose significant environmental problems of their own, which may be solved eventually by placing them underground.

The design, construction, and utilization of a very low resistance (super-conductive) national electric energy transmission system would have many advantages, including: (1) implementation of an effective national fuels and energy policy; (2) management of environmental factors related to energy generation, transmission, and utilization; and, (3) improvement of security and reliability of energy sources, generation, transmission, and utilization.

Long-term, broad-scale planning of this magnitude is important in meeting the problems of environmental quality, energy requirements, economic development, and national security.

E. LONG-TERM ENVIRONMENTAL CONSIDERATIONS

The buildup of CO_2 in the atmosphere has not been an important consideration in most air quality improvement planning, and the *ad hoc* panel was not charged with reporting on the long-term global temperature and ecological effects of increasing concentrations of long-lived air pollutants. But it is appropriate to remark that CO_2 and submicron-size particulates are the only contaminants resulting from combustion and reduction processes that may be of importance to global ecology. A portion of the submicron particles are sulfate aerosols formed by the reaction of SO_2 in the atmosphere.

Combustion of fossil fuels, a major source of SO_2, is also the source of perhaps 50 percent of the atmospheric buildup of CO_2. Because of this relationship to energy requirements and fuels availability, the panel believes that a discussion of SO_2 pollution must also include recognition of the possible long-term effects of increasing levels of CO_2.[10] By the year 2000, it is estimated that there will be a 25 percent increase in CO_2 in the atmosphere, compared to the amount present during the nineteenth century. It is further estimated that this increase may affect the earth's radiation balance causing a corresponding increase in the average temperature near the earth's surface.

However, it has been pointed out[6] that there is also a possible worldwide change in the amount of atmospheric fine particles. In addition to particles rising from the earth's surface, significant quantities may be deposited directly in the stratosphere by supersonic transports when they come into extensive use. An increase in fine particulate materials, some of which are SO_2 decay products, may have the effect of increasing the reflectivity of the earth's atmosphere and reducing the amount of radiation received from the sun.[11] This effect would be the opposite of that caused by an increase in CO_2. It is suggested that the large-scale cooling trend observed in the Northern Hemisphere since about 1955 is due to the disturbance of the radiation balance by fine particles and that this effect has already reversed any warming trend due to CO_2.

Whichever may be the case, *it is clear that considerable uncertainty exists as to the effect of long-lived pollutants on the environment.*

Nuclear power presents several potential air pollution problems.[3] Solid waste from radioactive materials in spent fuel rods appears to be a relatively small air pollution problem but is a significant solid waste disposal problem. There are important questions regarding the effects of small amounts of tritium (half-life of 12.26 years) present in the cooling water. The tritium may enter biological systems and produce radiation effects and damage during its decay. Finally, krypton-85 (half-life of 10.4 years) released at the reactor and the fuel reprocessing plant might accumulate in the atmosphere over an extended period, much like carbon dioxide. At some time it may become necessary to collect the tritium and krypton for storage rather than release to the environment.

IV

ENERGY RESEARCH

The National Air Pollution Control Administration has been designated the Federal "lead agency" to provide objectivity, coordination, emphasis, and support to the national efforts to restore and control the quality of our air environment, including:

1. Accumulation, interpretation, and dissemination of all pertinent information

2. Coordination of short-, medium-, and long-range planning of research, development, and demonstration activities of Federal groups such as the Atomic Energy Commission, Tennessee Valley Authority, Federal Power Commission, Bureau of Mines, Office of Coal Research; and state, regional, and local agencies as they relate to air quality factors resulting from extraction, processing, transportation, and utilization of energy resources

3. Planning, initiation, coordination, and funding of research, development, and demonstration of broadly acceptable systems, subsystems, and components as required to reduce air pollution to acceptable levels

Accomplishment of these objectives will require a high level of planning and coordination between the several governmental, research, legislative, industrial, and civic groups involved to: (1) evaluate feasible and acceptable alternative courses of action, (2) determine present and future consequences of specific action or inaction, (3) evaluate the impact of changes on one or another element of the system, (4) determine priorities and funding levels, and (5) select the most broadly acceptable courses of action.

The complexities of the national energy-generation and energy-utilization system will increase with time. However, careful planning and coordination of national and regional efforts, not only for SO_2 control, but also for control of other air, water, thermal, visual, and solid waste pollutants, will minimize future problems related to environmental degradation associated with plant siting, transmission systems, fuels utilization, engineering feasibility, economics, and public acceptability. Planning and coordination activities of this magnitude present a major national challenge to keep pace with the 6 percent projected annual increase in electricity requirements and still maintain an acceptable environment.

Each year the Federal Government supports research and development to improve methods for producing, converting, and transmitting the primary energy sources--petroleum, gas, coal, oil shale, uranium, and water power. Table 2[1] provides an accounting, by primary energy source, of Federal research and development funds currently being devoted to the task of assuring an abundant supply of energy at reasonable costs to meet the nation's future needs, with minimum impairment of the quality of the environment.

In addition, industry spends hundreds of millions of dollars annually for research and development, with the petroleum industry accounting for a substantial portion of the private expenditures in the energy field. Substantial amounts are spent by utilities and manufacturers on electric power generation and transmission equipment and nuclear fission as part of their facilities development. However, industrial research and development expenditures on coal, oil shale, hydroelectric power, and controlled fusion are but a fraction of the Federal program in this area.

The important bases for viewing research and development expenditures in Table 2 are the energy generation patterns in 1980 and 1990 (Figure 1), and these, in turn, are influenced by the success of present research and development. The relative stage of development of each form of energy conversion must also be considered, since the costs of developing a new technology, such as nuclear fission or fusion, are

TABLE 2

FEDERAL RESEARCH AND DEVELOPMENT EXPENDITURES BY PRIMARY ENERGY SOURCE
(Excludes programs less than $500,000)

		In Millions by Fiscal Year		
		1968	1969	1970 Est.
Uranium and Thorium				
AEC	Fast Breeder Reactors	82	102	122
	Other Breeders and Converters	82	62	50
	General Reactor Technology and Safety	91	97	104
	Total	255	261	276
Coal				
Interior	Bureau of Mines	9	9	11
	Office of Coal Research	12	14	13
	Total	21	23	24
Petroleum and Natural Gas				
Interior	Bureau of Mines	3	3	3
Oil Shale				
Interior	Bureau of Mines	1	2	2
Thermonuclear Fusion				
AEC		27	29	34
	Total	31	34	39
General R&D				
AEC	Plowshare Underground Engineering	3	1	1
HEW	Air Pollution	8	12	15
Interior	Explosives Research	1	1	1
NSF	Energetics Engineering	3	3	3
TVA		1	1	1
	Total	16	18	21
	Over-all Total	323	336	360

greater than those for improving existing systems involving other forms of energy.

The energy conversion efficiency of fossil-fueled power plants appears to have stabilized after gradually increasing over the years. New fossil-fueled steam power plants currently have efficiencies of about 40 percent in converting the fuel combustion energy into electrical energy. Present commercial nuclear power plants range from about 30 to 35 percent in conversion efficiency, and breeder reactors are expected to reach about 40 percent efficiency. Combined cycle systems, are, in principle, more efficient energy conversion facilities. For magnetohydrodynamic generation using fossil fuels, with a steam plant to utilize the energy contained in the hot gases leaving the magnetohydrodynamic unit, the combined efficiency is projected to be on the order of 50 to 60 percent.[12] The high temperature required will cause increased nitrogen oxides formation. Improved efficiency reduces the amount of fuel required and the amount of heat rejected to the environment to meet a given demand. For sulfur-bearing fuels, the SO_2 emission would be correspondingly reduced.

V

FACTORS OF FUELS UTILIZATION

Fuel use patterns are dependent upon supply (availability) and on certain technical developments in fuel production, energy conversion, and energy transmission. Projections indicate maximum production of natural gas in the United States within 10 years and of petroleum products within 30 years. [8]

The Atomic Energy Commission estimates that in the year 2000 nuclear energy will supply about 44 percent of the national electricity generating capacity, coal about 41 percent, and gas, oil, and hydroelectric power about 15 percent. Present fuel sources for electricity generation are: nuclear, 1 percent; coal, 65 percent; and gas, oil, and hydroelectric, 34 percent. Serious delays in construction schedules of several nuclear power plants have occurred during the past year, and the cost estimates per installed kW have risen from about $130 in 1967 to about $200 in 1970.[13] Cost for fossil-fueled plants were about $110 to $130 per kW in 1967, and are $120 to $160 per kW in 1970. These costs include particulate-control devices, but do not include equipment for SO_2 or NO_x control. *Recently, a number of orders for fossil-fueled plants, with shorter lead time and lower capital costs, have been placed by utilities to meet power requirements that nuclear plants might have met under earlier construction schedules.*

These factors indicate a greatly expanded use of coal as an energy source during the next 30 to 40 years (Figure 1). The United States has an assured reserve of coal and oil shale to meet its energy needs for hundreds of years to come. Some changes in the schedule are dependent upon the development of:

1. Early resolutions to siting, environment, and economic problems related to present and future power plant development

2. Processes for more effective coal desulfurization

3. Processes for conversion of coal to "clean" gaseous or liquid fuels

4. The fast breeder nuclear reactor, which will reduce nuclear fission fuels costs and extend nuclear fuel resources

5. Various combined cycles such as magnetohydrodynamic generators, which are potentially more efficient than steam turbine generators

6. Industrially efficient processes for the extraction of oil and gas products from oil shale

7. The controlled nuclear fusion reactor, which would make large amounts of energy available

Difficulties with equipment delivery and plant siting have already seriously delayed the construction of generating capacity in parts of the United States. The Federal Power Commission states that 39 of 181 major systems have reserves of less than 10 percent of peak load. There is a real possibility of power shortages and "brown-outs" in some power pool areas during peak-load periods of the next several years.

At many inland sites, river water and ground water are no longer available in sufficient quantity to be used for once-through cooling; hence, evaporative cooling towers have come into fairly common use. At several locations, in the eastern as well as far western parts of the country, even the demand for make-up water for cooling towers (about 2 to 3 percent of the once-through rate) exceeds the amounts available from rivers and existing wells without endangering the river flow or the water table. In England, this situation has resulted in installation of closed-cycle cooling systems that exchange heat to the air through finned heat exchangers.[2] Costs, of course, increase substantially with the transition from once-through to closed-cycle cooling systems.

There is also some thought that man's future needs may be better served if substantial reserves of coal, petroleum, natural gas, and oil shale are set aside for the rapidly growing requirement for chemical industry feed stocks. Such a reserve will, of course, depend largely on the beneficial application of developing nuclear technology. Thus, the critical need for development and application of technology to control pollution resulting from fossil fuel (particularly coal) combustion may well occur between now and 1985 or 1990.

In view of these consideration, it is evident that SO_2 problems that are generally restricted to coal use (and in a smaller way to ore smelting and petroleum use) will grow until SO_2 control processes or other energy sources are developed. Thus, *the SO_2 abatement problem fits into the larger problems of fuel policy and management.*

VI

TIME PHASES OF TECHNICAL DEVELOPMENTS

Successful development and application of several control processes and the breeder reactor are crucial in the abatement of sulfur oxide emission to the atmosphere. As shown in Figure 2, assuming the breeder reactor comes into wide application after the year 2000, coal consumption and sulfur emission would peak and decrease rapidly even without emission control.

Research on fast breeder nuclear reactors is proceeding rapidly in several countries. The British 60 MW pilot breeder reactor at Dounreay, Scotland, went critical in 1959 and has operated continuously except for a 1-year shutdown during 1968-69 to repair a leak. The United States 150 MW "Fermi" breeder reactor in Monroe, Michigan, first went critical in 1963. It was shut down in October 1966 due to a subassembly meltdown and is scheduled to start up again in 1970. The Atomic Energy Commission is now selecting a site for a 500 MW demonstration breeder power reactor to start in 1976. Projections call for the first commercial breeder reactors of the 1,000 MW size to start up about 1985 in the United States.

Fuel substitution has already begun to be practiced but is restricted by the limited availability of low-sulfur oil, coal, and natural gas. More intensive cleaning of coal to remove pyrite may make a contribution to sulfur-emission control comparable to fuel substitution as it comes into wider use in the next few years. Although limestone processes for the removal of SO_2 from stack gases--which do not produce a marketable product--should be commercially proven in the next 1 to 3 years, broad application of these processes will require several more years. Several product-producing processes for SO_2 removal should be commercially available in the mid-1970's or early 1980's and should find wide application in the new coal-fired plants. With adequate funding and experimental success, new combustion technology should be available in 5 to 8 years.

As with the breeder reactor, there is no assurance that the control processes will be developed as predicted. *The time estimates are realistic only if there is a positive commitment on an urgent basis by government agencies, utilities, fuel suppliers, and equipment manufacturers to support the orderly development and timely application of these processes.*

The sequence of technical developments must be coordinated with the plans for compliance with air pollution control regulations and the availability and use patterns of various fuels. As the national air quality control regions implement their criteria and emission control schemes to improve the quality of the air, there will be a growing need for the different kinds of technology and a shifting in types of fuel used.

For example, in the Washington, D.C., area, plans are being developed for the National Capital Interstate Air Quality Control Region.[7] In addition to a reduction in suspended particulate matter, it is proposed that all fuels burned in the region must contain 1 percent or less sulfur. It is also proposed that, after July 1, 1971, distillate fuel oils (ASTM No. 1 and No. 2) should contain 0.3 percent or less sulfur. Fuels containing in excess of 1 percent sulfur could be burned, provided control equipment to desulfurize stack gases had been installed or other methods were used that would produce results equivalent to the burning of fuel containing 1 percent or less sulfur.

All fuel-burning installations constructed and all fuel-burning installations altered or modified for use of a different fuel having a maximum heat input of less than 250 million Btu's per hour would be required to burn gaseous fuels, provided that distillate fuel oils could be used for not more than 30 days in any calendar year. However, liquid and solid fuels could be burned, provided it were demonstrated that sulfur oxides, particulate matter, and nitrogen oxides emissions would be equal to or less than would result from burning gaseous fuels to accomplish the same heating objective

At this time, the complete substitution of gas, or low-sulfur oil, for coal in Washington, D.C., appears to be the only possible way, short of establishing an all-electric city, to achieve the long-term goals that are being considered.[7] Other proposed actions include control of open burning and tighter limits on emissions of particulates and sulfur oxides from incinerators and industrial operations. These suggestions, of course, are not to be taken as courses of action recommended by the panel.

To meet such goals in other cities, it would be necessary for industrial plants to install more efficient particulate control on all stacks, and SO_2 scrubbers on many processes. Heating systems would have to convert to gas, low-sulfur oil, or electricity, depending upon fuel availability. Existing power plants would need to convert to oil or gas or add stack removal of SO_2, and new plants would use nuclear energy, gas, or perhaps something like fluidized bed combustion of coal.

Such shifting would require the expansion of gas and oil supply systems. Since natural gas reserves are limited, both coal gasification and importing of liquefied natural gas would probably be necessary to meet the increased demand.

There is a possibility that a number of the newly created air quality control regions will adopt plans such as those described above in the next few years. *Care must be exercised at the local, regional, and national levels to assure that realistic criteria and plans are adopted which can be implemented in concert with the development of technology and the systematic use of our energy resources.*

There is a real danger that the public may be led to expect environmental improvements at a rate that cannot be realized. This is not to say that high goals should not be established, but rather that realistic and coordinated implementation plans must be adopted.

VII

SUPPORT OF TECHNOLOGICAL PROGRESS

The objective of support of technological progress in SO_2 emissions control is to advance the state of the art with all deliberate urgency consistent with prudent engineering and economic judgment and national needs.

The Federal effort to achieve the necessary sulfur oxide control should be in partnership with the electric-power industry, equipment manufacturers, and the fuels industry. Eventually, sulfur oxide control may create a market that will offer some industrial incentives. Meanwhile, implementation of SO_2 control plans is a major national problem that will require large expenditures by the utilities and large costs to consumers, unless technology is developed that will minimize these costs.

In seeking suggestions for enlisting the private sector in support and augmentation of the Federal effort, the panel found that in recent years many companies have spent up to several million dollars developing their processes to the pilot scale and beyond (Chapter VIII). Other companies, some with interesting technological approaches, do not have adequate funds even for bench-scale work. Within industry, the competition for research and development money is such that the expenditure of \$5 million to \$10 million of a company's funds on commercial demonstration of one process may be a poor research and development risk when compared with alternative projects of corporate interest.

A. COAL INDUSTRY

The coal industry is not process-research oriented and its air-pollution research and development has been fragmented. To date, the industry's effort has been limited to a few modest projects that have been conducted by several major companies and with sponsorship by Bituminous Coal Research, Incorporated

(BCR). Work within individual companies has been largely concentrated on methods for removing ash and sulfur from coal. The work at BCR, which is supported broadly by the industry, has been devoted to stack gas cleaning processes and coal cleaning, with the predominant emphasis on the latter.

B. EQUIPMENT MANUFACTURERS

The panel learned that the equipment suppliers see no immediate profit potential in the research and development of new SO_2 control equipment under present accounting and taxing policies. What the equipment manufacturers do develop can seldom be protected from use by competition, because very little of such equipment is proprietary or subject to patents that cannot be circumvented. A manufacturer may invest his money and develop a sulfur control process using equipment that he manufactures, only to find that similar equipment is available from many manufacturers, and the utility applying the process may seek competitive bids. Consequently, patents on equipment of this type are regarded as relatively worthless. Patents on a process may be valuable, but the overall situation is such that little acceleration of the research effort can be expected to follow automatically in the private sector, even when sulfur control regulations become more stringent.

Despite these considerations, equipment manufacturers are developing new equipment for air pollution control applications and have participated in a number of joint pilot, demonstration, and feasibility studies.

C. UTILITY COMPANIES

As regulated monopolies, electrical utility companies are subject to the control of various governmental bodies, Federal, state, and local. Consequently, funds spent by utilities for development and application of pollution control processes may not be readily included in their capital structure, which is the basis for establishing consumer rates.

The utility companies, however, are supporting sulfur oxide emission control studies individually and jointly. Over 25 utilities are participating in research, development, and demonstration work on several promising processes (Chapter VIII). The panel agreed on the following points with respect to support by the utility companies of research, development, and demonstration (R,D,&D).

1. Funds spent for development and application of pollution control processes may not have the potential of self-liquidation under present rate-making policies.

2. Many utilities located in urban areas are making determined efforts to secure reliable sources of low-sulfur fuels and installing equipment for multiple fuels capability.

3. The costs of developing and applying control processes will be high; the utilities are neither equipped nor staffed to do the kind of process development and demonstration that is needed. Because of the expense and time involved, it is probably not realistic to expect individual companies to carry out impressive internal R,D,&D programs.

4. The technological risk of applying processes that are inadequately demonstrated is too great to force acceptance and installation of these processes. The most likely effect of legislative pressure will be to force the use of the limited supplies of available low-sulfur fuels. Therefore, until reliable processes are adequately demonstrated, the effectiveness of legislative pressures will be limited.

5. It might be possible for utilities to do more cooperative R,D,&D. Regulatory and taxing agencies might consider adjusting their policies to encourage such activity.

D. FEDERAL GOVERNMENT

Even if additional cooperative funding by the coal industry, equipment manufacturers, utility companies, and process developers can be arranged, government support will be needed for many years to encourage development, demonstration, and application of sulfur oxide control technology. *Unless the necessary technology becomes available, the country may have to choose between clean air and electricity.*

The crux of the problem is its urgency with respect to lead time and degree of applicability of any single process. The schedule for abatement of the emission of sulfur oxides reduces the lead time to a very short period. In order to demonstrate a variety of processes which might be applicable to specific conditions, *the reduction of lead time and the diversity of processes required demand an intensive and concerted effort substantially greater than normal industrial process development.*

Although no control process has yet reached the stage of demonstrated full-scale application in a power plant, several methods that may be suited to particular sets of conditions are under development and should be brought to a stage of industrial efficiency with all deliberate speed. *This can be accomplished most expeditiously by adequate funding of NAPCA in its role as Federal "lead agency" to assure significant progress in an acceptable period of time.*

There are three stages of process development at which Federal support and encouragement are justified:

The first stage is in unrestricted broad-ranging investigations. Such pioneering investigations should normally be restricted to bench-scale work and are worth supporting on a continuing basis.

The second stage involves pilot-plant trials of new processes that appear to be promising.

The third stage comes after pilot-plant trials have been concluded, and when the most promising processes are considered ready for demonstration on a scale that would provide engineering and economic data that could be projected with confidence to large operating units. Such large-scale demonstrations are necessary and will be quite expensive, running into several million dollars for each process selected. This is a critical point in the application of new technology. National needs will be most effectively accomplished by a full partnership (financial and technical) between government agencies, utilities, equipment manufacturers, process developers, and fuel suppliers.

In addition to support of research and development, governmental assistance may be provided through changes in tax and patent policies and provisions for Federal funding of "risk capital." The proposed Tax Reform Act allows accelerated amortization of pollution control equipment. The prospect of profitable patents is an incentive for further research by industry. Several government agencies are reviewing patent policy at this time to determine what changes might be made to encourage research, development, and application of processes designed for pollution control. The Patent Office has recently announced its intention to accelerate the handling of applications dealing with pollution control inventions.

In addition, the Subcommittee on Air and Water Pollution of the Senate Committee on Public Works has heard testimony in recent hearings on S.2005--The Resource Recovery Act of 1969, S.3469--The Wastes Reclamation and Recycling Act of 1970, and the Amendment to S.2005, cited as the National Materials Policy Act of 1969. Federal provision for "risk capital" was one of a variety of subjects discussed. Other approaches of financing of research, development, demonstration, and application of processes and facilities designed to control various types of pollution are being considered at the Federal executive and legislative level.

VIII

PRESENT STATUS OF RESEARCH AND TECHNOLOGY

A. AVAILABILITY OF TECHNOLOGY

Although the panel is optimistic that acceptable sulfur oxides control technology will be developed, it concludes that this technology is not yet commercially proven. Moreover, a rapid pace must be maintained in pursuit of the technical objectives, if only to prevent conditions from getting worse. Even when the expected technology becomes available, it will be too late to prevent a significant rise in total sulfur emissions during the next several years.

Five general approaches might be made to sulfur oxides control problems:

1. Undertake a crash program to build nuclear power plants

2. Remove sulfur from fuels before they are burned

3. Remove sulfur from fuels during the combustion process

4. Remove the SO_2 from the combustion gases before emission to the atmosphere

5. Employ very high stacks and remote siting so that the gases are dispersed and diluted to an acceptable level

The first approach is impractical because of the prohibitive expense and inability to meet even present construction commitments. Some combination of the second, third, and fourth approaches offers the best promise in the United States. However, the processes to accomplish sulfur removal from coals before and during combustion, and from combustion gases, are not adequately developed, and are not immediately acceptable for wide application. Tall stacks and remote siting, the fifth approach, are being promoted in England and to some extent in the United States.

Sulfur is readily removed from distillate oils, and the technology is well established. Residual fuel oils are more difficult to treat, because they contain metals that deposit on the solid catalysts employed. The petroleum industry has invested heavily in the development of ways to desulfurize fuel oil, and there is no doubt that some of these methods will work. The plants required are costly, and the added refining step of reducing the residual fuel oil from an average of 2.6 percent to less than 1.0 percent sulfur will probably increase the price to the power station by 50 to 80 cents per barrel. This represents an increase in fuel cost of 20 to 35 percent. Fifty cents per barrel of oil is equivalent to an increase of about 0.7 mills per kWh in power costs.

Sulfur in coal is present principally as the mineral pyrite and in complex organic compounds; in these two forms, it exists in widely varying ratios. With some coals, pyrite can be largely removed by grinding and washing, but, on the average, only about half can be removed, using existing coal cleaning technology. It appears that organic sulfur may be removed only by hydrogenation, liquefication and gasification processes.

Preliminary results of NAPCA's survey of naturally occurring low-sulfur coals and washability characterization tests of coals available for uses other than for metallurgical coke production suggest that of the steam-coal production: 8 percent has 1 percent or less sulfur as mined and could be cleaned further; 11 percent is coal with over 1 percent sulfur that is easily cleaned; and 6 percent is coal with over 1 percent sulfur that is cleanable at a higher cost. Thus, perhaps, 25 percent of the steam-coal production is capable of being cleaned to produce coal with a maximum of 1 percent sulfur.

NAPCA further estimates that refinement and broader application of coal cleaning technology might result in an average reduction in sulfur content of the remaining 75 percent of steam coals by as much as 40 percent.

Coal washing costs may range from 25 to 75 cents per ton of cleaned product.

Where fuel desulfurization is practical, it offers the most obvious and direct method to reduce SO_2 pollution from combustion. Several processes are under development for the production of liquid and gaseous fuels from coal, and liquid fuels from oil shale, and will perhaps be demonstrated to be industrially feasible within a decade. Meanwhile, most of the needed coal cannot be desulfurized to a maximum of 1 percent sulfur by use of presently available technology.

At least two processes offer hope for removal of sulfur during combustion: (1) "fluidized bed" combustion, and (2) "molten iron bath" combustion. Optimistically, the perfection of these techniques as commerical processes is 3 to 8 years away, and there is some question that either can be retrofitted into existing plants. If successful processes can be developed, their major application will be in plants that are engineered and constructed after the processes are determined to be applicable on a commercial scale.

Many ways of removing SO_2 from stack gases are being actively investigated--all involving some means of contacting the gas with a substance that removes SO_2. At least 25 such processes are under development in this country by industry and by NAPCA (Appendix C), and others are under development in Japan and Europe (Appendix D). Most are bench-scale laboratory projects, but several have reached the pilot-plant stage (10- to 25-MW equivalent gas streams). Only the limestone-wet scrubbing process has been installed in sizable operating power plants. Several of these processes will probably be technological successes, but the efficiencies are not yet well established for even the most advanced. Projected costs range up to 1 mill per kWh and, in some cases, higher, depending upon method of financing.

Although SO_2 emissions are not decreased by remote siting and tall stacks, these measures help reduce ground-level SO_2 concentrations in urban areas. As previously discussed, even with application of sulfur removal processes, tall stacks will continue to be necessary for large power stations to disperse and dilute all remaining emissions, including carbon dioxide, nitrogen oxide, and water vapor.

It should also be noted that the possiblity of establishing one national air quality control region and broader international and even global cooperation in environmental quality management may require national emission standards.

The future of sulfur control is not hard to predict in general terms. The country is committed to reducing air pollution, and increasingly stringent standards regarding sulfur concentrations in the ambient air are being established. Users of high-sulfur fuels will attempt to switch to natural gas, desulfurized fuel oils, or low-sulfur coals, all of which are in limited supply. These will command a premium price over present fuels. Where practical, the coal industry will find more intensive treatment of steam coals profitable. Where possible, new mines in known low-sulfur coal deposits will also be opened. It normally takes about 3 years to bring a new mine into full production.

Because these developments will not meet the total requirements of low-sulfur fuels necessary to control the continuing increase in sulfur emissions, many presently operating utilities will have no near-term alternative except to install facilities to remove sulfur from stack gases. Probably, the simpler methods, which produce "throw-away" by-products, will be the first to be adopted by many existing plants. The more complicated processes, which produce sulfuric acid, SO_2, or elemental sulfur, may be demonstrated in 3 to 10 years.

By perhaps 1980 or 1985, sulfur emissions stemming from smelters and the combustion of fossil fuels will be under fairly good control, although total sulfur emissions will have risen substantially over those at the present time. By 1975 to 1985, there may be ways to burn coal, such as by fluidized-bed combustion in the presence of lime, to fix the sulfur so it is not carried by the stack gases.

B. THE NEED FOR COMMERCIAL DEMONSTRATION

It is important to note that industrially proven technology for the control of sulfur oxides resulting from fossil fuel combustion does not now exist. Only one of the several processes under development has been installed in 100-MW or larger boilers, and it has operated only intermittently.

Data on processing variables accumulated during each stage of process development are evaluated to determine the feasibility of scale-up to the next stage. If feasibility at the bench and pilot scale has been established, prototype industrial scale operation for a minimum of 1 year is necessary to secure sufficient knowledge of the process to establish control parameters, operating reliability and efficiency, maintenance requirements, adequacy of materials and engineering, and ability of the process to meet air quality objectives.

Consequently, *there is an urgent need for commercial demonstration of the more promising processes, to make reliable engineering and economic data available to engineers who are designing full-scale facilities to meet specific local and regional conditions.* The panel's definition of proven industrial-scale reliability is satisfactory operation on a 100-MW or larger unit for more than 1 year. Also, technical and economic data developed must be adequate for confident projection to full commercial scale. Pilot scale refers to investigation using flue gas in the capacity range of 10 to 25 MW. Smaller sizes and studies using synthetic gas mixtures are considered to be bench scale.

Estimates of industrial-scale feasibility and adequacy of a process based on paper studies or bench-scale projections are, by their very nature, too speculative to be reliable in making large-scale economic or engineering choices between alternative processes. Such estimates do, however, provide a basis for decisions related to the next level of scale-up. The estimates of installed cost per kilowatt range from $4 to $40 for the processes under development. If the figure were $10, the cost to install control equipment in existing coal-fired power plants would be about $2.2 billion. Total operating costs may be of the order of 0.5 mill per kWh. These are not reliable estimates of the ultimate cost to the consumer of electricity, but they do serve to indicate the magnitude of the problem of SO_2 control.

Even though the technical feasibility of a process were indicated on a pilot-plant scale, industry would be understandably hesitant to fund a large installation prior to full-scale evaluation. For a utility, the risks of failure to meet air quality objectives--as well as operational objectives--are great. For the nation, the possibility of delaying effective SO_2 control by installing equipment that does not do an adequate job is also great. When national objectives call for accelerated construction of high-risk, expensive facilities using unproven processes, it is proper for the government to share in the risks by participation in those portions of the project that are first-of-a-kind engineering demonstration units.

The development of several of the processes for removal of sulfur from stack gases is well advanced. Pilot plants of up to 25 MW have demonstrated to varying degrees the technical feasibility of at least three of these developments. The diversity of the schemes being developed is gratifying, because quite different technical solutions will be required to meet the wide variety of situations in which sulfur control is necessary.

The panel believes that it would be appropriate and very much in the national interest for NAPCA, *under Section 104(a)(4) of the Clear Air Act of 1967, to provide support of several million dollars, in partnership with industry, to expedite the first commercial demonstration installation of each of several promising processes for* SO_2 *control.*

C. BACK-FITTING EXISTING PLANTS

The dry- and wet-limestone processes could probably be used by many existing plants. These are by no means the final solution, and other processes involving by-product recovery should be developed.

Many stations have limited areas in which they can dispose of the ash, and would have to haul it away. For some older plants in crowded areas, very little space is available; forcing them to utilize large quantities of limestone could result in their conversion from coal to a low-sulfur oil. Sometimes, simply upgrading the electrostatic precipitator for the dry-limestone process would cost more than to convert from coal to an oil-fired unit utilizing low-sulfur oil. In addition, for a given precipitator efficiency, a threefold increase in fly ash will nearly triple the particulate emission.

The existing smaller power plants have the other alternatives of obtaining low-sulfur coal, oil, or gas, if supplies of these fuels are available. These alternatives are also available to large plants, but the panel believes that, *from a national point of view, the most logical use for the low-sulfur coal is in commercial and industrial plants, small power plants, space heating, and for production of metallurgical coke.*

The forward-looking utilities are providing space in new plants, in anticipation of the necessity of installing corrective measures for flue gas treatment. They are allocating space or buying enough land to enable them to fit in the technology more easily when it is available. One restriction of this policy is that it provides only for the type of process that would take gases at the usual discharge temperature of 300°F. It would not easily permit installation of a process that requires use of the high-temperature part of the boiler. The plan is to minimize the back-fitting cost on a 300°F process. Those processes that are designed to operate at 600°F to 900°F will require about 3 years' lead time, and the back-fitting will cost much more than if control technology were available and could be incorporated in the initial design.

D. CENTRAL RECOVERY FACILITY

Utilities may find product-producing processes more attractive if a central chemical processing plant can be employed to collect and regenerate the absorbents or adsorbents from several installations. This appears to be an interesting possibility in connection with several of the schemes that produce salable chemicals.

The suggestion has been made that the chemical industry be brought into partnership with the electric power industry. It is feasible to have a separate chemical operation that would serve a number of utilities. The attractiveness of this scheme depends on the distance and the transportation involved and the method of financing. It would probably have to be a facility financed by the electric power industry and operated by the chemical industry under a contractual arrangement. It is possible that the utility could pay enough for the return of the absorbing medium to make it attractive for the chemical company.

A central facility is attractive for several reasons:

1. The utilities evidently prefer not to get into the chemical business.

2. The recovery operation in many of these processes requires facilities and space comparable to the boiler plant.

3. The economy of scale for a central unit would be better than that of a single

utility plant, in which the installation of a chemical plant of uneconomic size would not be feasible.

4. The central processing facility could operate at a higher and more uniform rate than one located at, and dependent on, a single power station operating on a varying load factor.

It has been suggested that the ultimate control facility might be a combination major power plant, petrochemical, and sulfur-chemical complex. Coal chemicals are presently produced in quantity during coke manufacture by the steel industry. These organic chemicals are used as feed stocks for petrochemical processes in competition with petroleum refinery products. A similar activity may evolve from the utility companies as they strive to reduce pollutant emissions from coal and other fossil fuels used in power generation.

E. RESEARCH PLANNING

From a national point of view, the research strategy should be to have several processes in commercial operation at the earliest possible date. Primary emphasis should be placed on achieving industrial feasibility for the processes that can be readily incorporated into existing power plants, even though some of them may produce only nonsalable or throw-away byproducts. Successful development of these processes would do most to alleviate air pollution in the shortest possible time.

Besides development of throw-away processes, development of product-producing processes must be continued. For the new installation, improved processes, including steps to recover some value from the sulfur, will be necessary to keep costs for future control within reasonable limits. Installation of many of these processes in existing plants would require major changes. Consequently, they are unlikely to be found broadly applicable to plants now in existence. Compliance with the standards that may be promulgated within the next year or two will be extremely difficult at best, and may be impossible, even with the development and installation of the throw-away processes that appear to be nearly ready for installation.

The limestone injection processes expected to be available in 1 to 3 years will probably not be adequate for the long-term requirements, and NAPCA should continue to support the development of sulfur-recovery processes.

Coal cleaning should be studied further, at least on a small scale, until its sulfur reduction potential is clearly defined. Imaginative new methods for removal of both pyritic and organic sulfur from coal should be encouraged.

The panel places special emphasis on the following:

1. Complete development of the limestone process should be given high priority because it seems applicable to existing boilers. At the same time, NAPCA should support long-range research on processes that industry will be slow to develop. Fluidized bed combustion, which has potentially attractive antipollution features, is such a process.

2. Coal cleaning processes should be refined to their maximum potential. Promising new concepts in coal desulfurization should be supported.

3. Processes for desulfurization of fuel oil are being developed by several petroleum companies. It is believed that NAPCA cannot, nor should it, contribute significantly to these developments.

4. Probably, much of the NO_x will have to be removed from stack gases or combustion temperatures controlled to reduce its

generation. Only two of the SO_2 processes under development appear to be potentially effective in removing oxides of nitrogen. *Research on ways to combine SO_2, NO_x and particulate abatement should be supported.*

5. NAPCA should employ a *process engineering and construction firm* to project costs on a *common basis* for all of the promising processes at various stages in their development. This not only would provide more reliable estimates of the ultimate cost of sulfur control, but also would provide NAPCA with a valuable guide in contract allocation and scale-up decisions.

6. Recovery of sulfur in the elemental form is desirable for storing and handling. Though acid-producing processes will find application in special marketing situations, acid sales will generally be limited by shipping costs.

7. Most of the processes using regenerable absorbents or adsorbents produce SO_2. The conversion of SO_2 to elemental sulfur is not a common industrial process, and it is important that the technology of this conversion be thoroughly studied.

8. The following general considerations should be kept in mind in choosing processes for development:

    a. Insertion of equipment ahead of the air preheater is a radical change in power plant design that may find slow acceptance in the power industry.

    b. Parallel absorber-regenerators, which require shifting the gas flow from one vessel to another, will necessitate large investments in dampers or other flow control apparatus.

c. Solid absorbents are subject to attrition and to chemical deterioration.

d. Finely divided solid adsorbents are difficult to recover completely from the gas stream.

e. Processes that involve flow of the stack gas through all the equipment, both for absorption and regeneration (or other type of product recovery), have relatively high capital cost.

f. High absorbent loading and good mass transfer and sorption kinetics are important in keeping equipment size at a minimum.

g. Gas reheating, while expensive, may be needed to take care of the loss of buoyancy of stack gas in some treatment processes.

h. Impurities will accumulate and cause trouble in absorbent-recycle processes.

i. The disposition of sulfate formed is a major problem in any absorption process.

j. Processes that lead to fertilizer products may be desirable under some circumstances, because much of the recovered sulfur can be used by the fertilizer industry.

F. PROCESS DEVELOPMENT

1. General Considerations of Individual Processes

Brief commentaries on each class of the processes reviewed by the panel are presented here with special emphasis on the general process considerations. In each of the descriptions, the current level of knowledge about the process is reflected in the state of process development (bench, pilot, or demonstration level).

Generally speaking, bench-scale work may proceed for several years, depending upon what is already known about each of the individual steps of the process. Pilot-plant design and construction may take from a few months to more than a year following completion of bench-level work. Normally, the pilot plant would be operated for about 1 year. Scale-up, together with design and construction of a demonstration plant, following successful pilot-plant studies, takes from 1 to 2 years. Demonstration work will take 1 to 3 years to provide adequate information about the process. Thus, a process for which bench-scale studies have been completed is generally at least 4 1/2 years away from industrial feasibility, assuming success in subsequent studies. The schematic in Figure 3 summarizes the time scale for process development.

The panel was impressed by the readiness with which full information concerning the several proprietary processes was disclosed and has no reason to suspect that there is a major domestic effort on SO_2 control that has not been reported because of proprietary reasons.

A wide variety of processes are being considered in the United States (Appendix C) and in foreign countries (Appendix D). A number of these are reviewed here--particularly those that are receiving the most attention in the United States. In most cases, the developers are seeking funds from industry or Federal agencies, or some combination of the two to supplement corporate funds in expediting

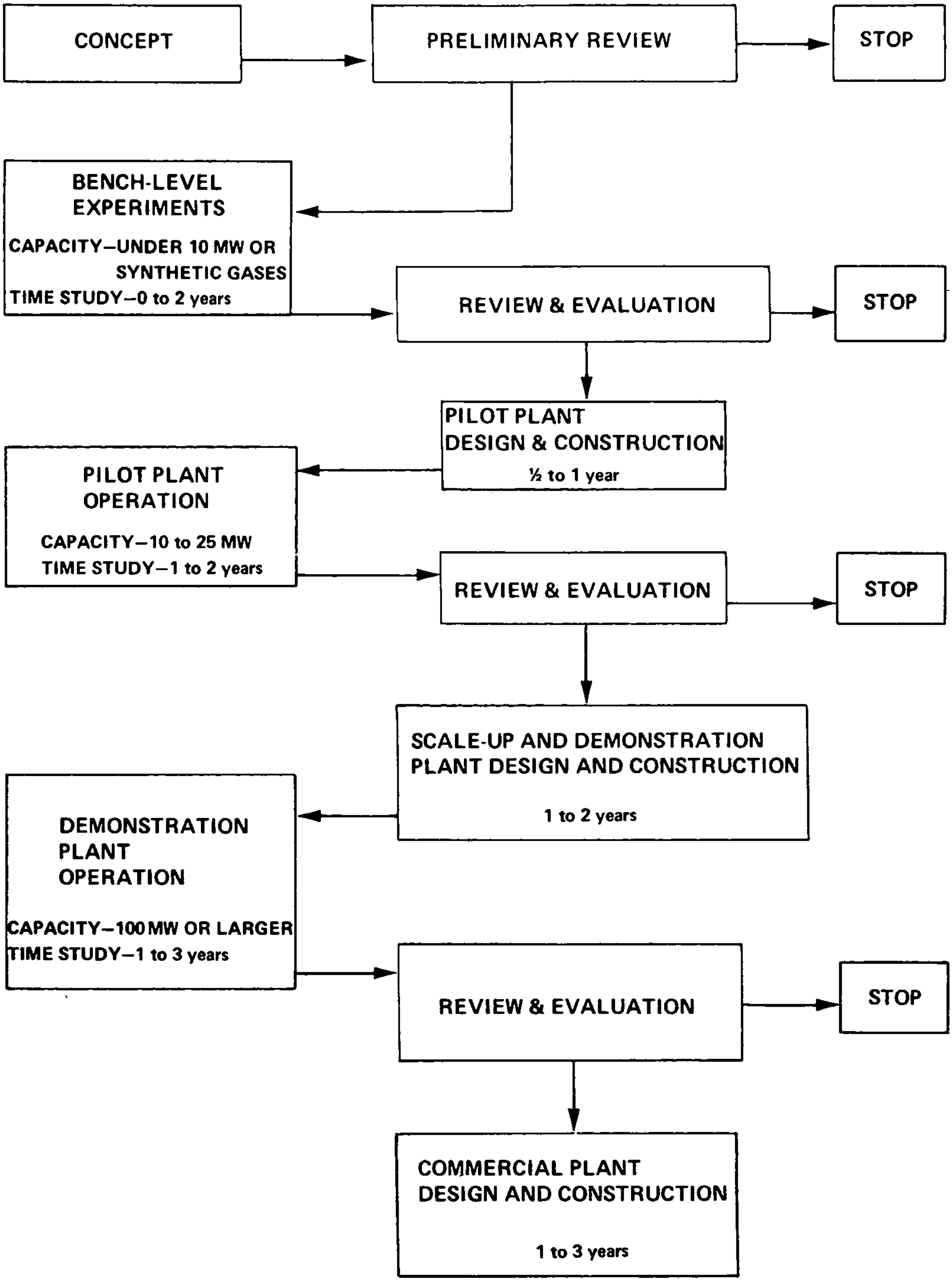

Figure 3. Time scale for process development.

the next level of feasibility investigation and reducing the time required for full-scale demonstration.

2. Precombustion Processes

Coal cleaning and coal gasification are processes that attempt to overcome the sulfur oxide emission problem prior to combustion. The processes have the potential advantage of removing the sulfur at higher concentrations than are present in the stack gas. They also provide for the recovery of sulfur or pyrite and would contribute to the conservation of this resource.

a. Coal Cleaning

Coal washing or beneficiation by present methods is limited to reduction of pyritic sulfur and can be expected to yield only a moderate increase in the supplies of low-sulfur coals. In some cases, sulfur emissions may be controlled by combining coal washing with sulfur removal from stack gases by the dry-limestone or other relatively inexpensive processes.

Coal beneficiation to reduce ash content has been a regular practice of the industry for years. Some pyrite is also removed, but only in the past few years has specific attention been directed toward sulfur removal by this procedure. The sulfur in many coals is present in about equal parts as pyrite and organic substances. Differences in the specific gravity of coal and pyrite are the basis for accomplishing sulfur removal; however, only part of the pyrite sulfur can be removed by gravity cleaning methods. The pyrite is present as nodules on cleat faces, and as disseminated small veins and crystals. In some coals, the larger pyrite particles may be partially freed by crushing and grinding the coal. Some types of coal are more easily cleaned than others, depending upon the manner and form in which the pyrite is present. Experiments with organic solvents, such as hexane, to remove the organic sulfur indicate that prohibitive costs would be involved.

The coal cleaning process produces a pyrite-rich reject as well as the cleaned coal. The reject stream may be further separated into a concentrated pyrite and a high-sulfur fuel. These may be used, respectively, for sulfuric acid manufacture and in a combustion unit with flue gas scrubbing or some other means of SO_2 control.

The Bureau of Mines and Bituminous Coal Research have had active programs in air cleaning and coal preparation for years. Pilot tests on air and water classification and other means of removing pyrite from coal have been made. Studies include the technology of pyrite separation, washability tests, evaluation of standard coal cleaning equipment, in addition to flue gas processing.

b. Coal Gasification

Present projections indicate that the cost of generating electricity from low-sulfur gas produced from coal will be greater than the cost of obtaining the same energy directly from coal. Coal gasification's potential will depend greatly on the availability of natural gas and on the cost of alternative methods for SO_2 control. Because gasification is potentially an alternative method of reducing SO_2 emissions to the atmosphere, the panel suggests that consideration be given to less sophisticated and possibly less costly gasification processes that would produce a relatively clean lower-heating-value gas, suitable for onsite use, but not of pipeline quality.

The Office of Coal Research has an active program for the development of pipeline gas and liquids from coal. While the manufacture of pipeline-quality gas from coal is not competitive at present, it appears that it may become so, as gas demand increases, natural gas reserves decline, and the technology of gasification processes improves in the next 5 to 10 years.

At present at least four processes are being considered:

1. Hydrogasification--Institute of Gas Technology

2. CO_2 Acceptor--Consolidation Coal Company

3. Two-Stage Super-Pressure Gasification--Bituminous Coal Research

4. Molten Salt Process--Kellogg Company

These processes require preliminary grinding, and those using lignite require drying. For coal hydrogasification, a mild air-oxidation pretreatment is used to avoid agglomeration in the hydrogasifier. The BCR process uses high pressure combustion to provide heat in the gasifier; the Kellogg process circulates hot molten salt to the gasifier; and the CO_2 Acceptor process employs the reaction of calcined dolomite with CO_2. Hydrogen is obtained by reacting char and steam. All processes require purification plus methanation to upgrade the gasifier effluent to gas of pipeline quality. During the purification step, sulfur is removed as an H_2S feed for a Claus plant.

The Institute of Gas Technology Hygas process is the nearest to commercialization and, assuming success in the pilot studies, will be commercially available in the late 1970's. IGT is starting up a 5-ton-per-day pilot plant, funded by the Department of the Interior Office of Coal Research, in Chicago for further study of the Hygas process. Only recently has attention been given by IGT to production of gas of less than pipeline quality for power plant fuel.

In addition to the research being supported by the Office of Coal Research, several companies are developing coal gasification processes of their own to produce either pipeline or sub-pipeline quality gas. It should be noted that low-heating value gasification processes will require sulfur removal from volumetric flows only slightly smaller than stack gas rates, thereby reducing the advantage of easier sulfur removal resulting from the higher concentrations.

3. Combustion Processes

The new combustion processes remove the sulfur during burning by methods that do not require extensive stack gas cleanup. Some of the more promising processes that offer the possibility of being brought to commercial acceptability in the later 1970's are discussed below. These processes also offer the possibility of sulfur recovery and the corresponding conservation of sulfur resources.

The combustion processes proposed for sulfur oxide control require new concepts of boiler design. The manufacturers and utilities have standardized boiler design to the extent that few major changes have been made in recent years. Additional effort will be required to obtain acceptance of these processes by industry since changes in manufacturing procedures and in operation will be necessary. The processes offer some of the more logical approaches to sulfur oxide emission control and deserve the extra level of support that will ensure their full consideration.

a. Fluidized Bed Combustion (FBC) is a new concept in boiler design and would be applicable only to new plants. The burning fuel is contacted with a fluidized bed of limestone particles which react with the sulfur. A portion of the bed is continuously removed and replaced with fresh limestone. Several FBC systems are being studied in England. The (British) National Coal Board is conducting research on atmospheric and pressurized systems. Esso Research Ltd. has been developing a two-stage FBC unit in which high-sulfur residual fuel oil is burned and sulfur values recovered. In the United States, the firm of Pope, Evans, and Robbins (under sponsorship of the Office of Coal Research and the National Air Pollution Control Administration) has conducted pilot plant work and studied the applicability of fluid bed combustion to industrial boiler systems. The National Coal Board projects that scale-up, from current laboratory testing, to a 20- to 30-MW single-stage atmospheric pilot unit can be completed by 1972.

b. The Black, Sivalls, and Bryson Combustion Process is a new concept in boiler design, in which sulfur oxide formation is prevented by the submerged partial combustion of coal in a bath of molten iron. The resulting carbon monoxide is burned above the molten bath. The sulfur is removed with the ash-slag and is subsequently recovered as sulfur. Black, Sivalls, and Bryson are conducting feasibility studies and have begun pilot plant design.

4. Limestone Processes

The limestone processes for sulfur oxide removal should be given priority in terms of research money and encouragement, because sufficient work has been done on these processes to suggest that they may become commercially acceptable sooner than any of the processes that produce salable products. Moreover, it appears that, for some applications, the net cost of throw-away processes may be less than for a recovery process. This is particularly true of a station that has been in operation for some time, since amortization of the cost of the control equipment would be over the remaining life of the plant, and the load factor of the plant would be lower in its later years.

Problems may arise with limestone because of limitations on the space available for disposal of waste products. In some locations, this could be expensive and tip the balance toward a recovery process. On the other hand, the dry-limestone process can be used intermittently for incident control, and thereby reduce the amount of material handled. This could be done in certain areas of high pollution levels where local control at specific times is needed.

The possibility that the limestone-based processes may solve an air pollution problem but create a water pollution problem is one reason that the panel endorsed NAPCA's plan to install plant-scale test facilities at TVA, where full consideration will be given to various ways of handling air and water pollution and solid wastes. The government effort has merit because the plans are to study the situation not only for dry-limestone but also for scrubber design alternatives; this would expand the applicability of the limestone processes. In addition, the technology developed for SO_2 removal by limestone-wet scrubbing will contribute to the general knowledge of wet scrubbers, and this will be useful in other wet scrubbing processes.

The panel does not favor the dry- or wet-limestone processes exclusively, but merely as a stopgap or a first line of defense. There are other processes that will have to be developed to provide more adequate control of emissions. Limestone injection technology seems nearest to industrial application and therefore deserves priority in the near term.

The limestone processes appear to be applicable to many existing power plants. Because they do not produce a salable product, the limestone processes should appeal to utilities not wishing to get into the chemical business. The lower capital costs make these processes attractive to the older plants operating with low-load factors. There is added cost for the additional fly ash removal, and there is a probable increase in particulate emissions resulting from the increased precipitator load for the dry removal process.

While the limestone processes are generally thought of as not producing a salable product, there is the possibility of recovering sulfur dioxide by heating the calcium sulfite portion of the recovered solids. With control of oxidation to sulfate, this could provide for recovery of most of the sulfur dioxide and reuse of the limestone. This area will also be covered in the TVA study.

a. Limestone-Wet Scrubbing was originally studied at Battersea in London, England, and at the Tir John Power Plant in Swansea, Wales, during the 1930's. In this early work 90 percent removal of SO_2 was obtained [26] confirming the technical capability of the process. However, the work also identified specific problems of low reliability, high maintenance and operating costs, corrosion, abrasion, scale deposit, solid waste disposal and loss of plume buoyancy.

Current studies in the United States and other countries are attempting to overcome these problems through improved process and equipment design, closer control of operating parameters, improved materials, systems optimization, and reliability.

Limestone-wet scrubbing may be added to existing plants without significant boiler modification. Limestone may be injected into the boiler as well as added to the scrubbing liquor. Solids disposal will be several times the normal fly ash disposal rate. The Combustion Engineering Company has recently built two full-scale units at the Meramec Plant of the Union Electric Company in St. Louis and at the Lawrence Plant of the Kansas Power and Light Company. Each unit is designed to handle all the flue gas from a 125-MW boiler. Both plants have had start-up troubles but are expected eventually to meet the design objectives of 83 percent sulfur removal and 98 percent particulate removal. However, Kansas Power and Light Company is proceeding with plans for a 430-MW power plant, using the limestone-wet scrubbing process. Problems of scrubber optimization and waste disposal may require several years of additional study and are further discussed at the end of this chapter.

b. Limestone-Dry Removal uses an electrostatic precipitator. The process may be added to existing plants. Reaction time and temperature requirements are such that the process may not be applicable to cyclone-fired boilers. Solids disposal problems will be several times the normal fly ash disposal rate. The Tennessee Valley Authority is installing a 175-MW demonstration unit at its Shawnee plant near Paducah, Kentucky.

5. Processes for Sulfur Recovery from Stack Gases

Several processes for recovering sulfur from the stack gas following combustion are at or near the demonstration level. These processes will recover the sulfur oxide and convert it into products for the chemical industry, such as sulfuric acid, hydrogen sulfide, sulfur oxides, and elemental sulfur.

Domestic reserves of sulfur are limited, and consideration should be given to their conservation. It would be desirable to *conduct a study of the long-range supply and demand situation with regard to the several alternative by-products to aid in establishing priorities for support of control and abatement technology*. Most of the processes reviewed rely on relatively straightforward chemical reactions and processing equipment. The major technical problems are related to the low concentration of SO_2 in large volumes of flue gas containing a variety of corrosive materials.

a. The Cat-Ox Process of Monsanto Company is a direct translation of the contact sulfuric acid process. Boiler modifications are needed as the converter uses gas at temperatures of 700° F to 900° F. The process has been successfully piloted (15-MW equivalent) at the Portland, Pennsylvania, station of Metropolitan Edison Company. Monsanto has proposed the pilot unit as a modular alternative to commercial-scale demonstration. It is especially applicable to high-sulfur fuels, such as coal-cleaning middlings and ore smelting. This process could be commercially demonstrated by 1973.

b. The Wellman-Lord Process is an add-on process and does not require boiler modifications. Sulfur dioxide is recovered from the stack gas by scrubbing and reprocessing the scrubbing solution. During 1969, a 25-MW pilot study was conducted at the Crane Station of the Baltimore Gas and Electric Company. W. R. Grace Company, the Bechtel Corporation, Potomac Electric Power Company, Delmarva Power and Light Company, and Potomac Edison Company also participated in this study. A commercial Wellman-Lord recovery plant is being installed to recover SO_2 from the stack gas of a contact sulfuric acid plant of the Olin Mathieson Chemical Corporation at Paulsboro, New Jersey.

c. The Esso-Babcock and Wilcox Dry Adsorbent Process requires boiler modification to provide 900° F gas. Regeneration of the adsorbent produces sulfur dioxide for a sulfuric acid plant. A 2,000 CFM bench-scale unit is in operation, and a 25-MW pilot plant is planned. If this is successful, a demonstration unit costing approximately $7.5 million is planned, with the objective of developing a commercial process by 1973. Sixteen utilities in the midwest and eastern United States and Canada are cooperatively funding the project.

d. Magnesium Oxide Scrubbing is an add-on process in which the scrubber removes both sulfur oxides and particulates. Chemico proposes a central recovery plant to remove sulfur dioxide and recycle the magnesium oxide to the power plants. Chemico and Basic Chemicals are conducting pilot studies of the process.

e. The Formate Scrubbing Process is an add-on process in which the reprocessing of the scrubbing solution yields a feed gas for a Claus plant for sulfur recovery. Bench-scale studies have been conducted by Consolidation Coal Company.

f. Ammonia Scrubbing of stack gases can be done as an add-on process without boiler changes. Sulfur dioxide can be stripped from the scrubbing liquid, using heat, or the solution can be acidified with nitric, sulfuric, and phosphoric acids to produce various fertilizers. Bench-scale studies were made some years ago. The renewed interest in the process lies mainly in the decrease in the price of ammonia in recent years.

g. The Westvaco Char Process is an add-on process. A source of hydrogen is needed for regeneration of the adsorbent/catalyst char and to produce a feed stream for a Claus sulfur recovery plant. Pilot-level studies are being conducted by Westvaco.

h. The Molten Carbonate Process is intended mainly for new plants with modified boilers to provide the gas at 900° F. Reprocessing of the scrubbing melt produces a feed gas for a Claus sulfur recovery plant. Bench-scale studies have been made by Atomics International.

i. Sodium Bicarbonate Adsorption is an add-on process that removes both sulfur oxide and fly ash. Pilot-level studies have been conducted by Dow Chemical Company.

j. The Modified Claus Process is an add-on process and is an extension of the conventional Claus sulfur process. A source of hydrogen (natural gas) is needed for the process to recover sulfur. Princeton Chemical Research has conducted bench-scale studies of the process.

k. The Catalytic Chamber Process is a modification of the old lead chamber process and removes both sulfur and nitrogen oxides and produces sulfuric acid. It is an add-on process that requires some additional space. Bench-scale studies have been conducted by Tyco Laboratories.

l. The Ionics/Stone & Webster Process uses a scrubber and an electrolytic cell system to recover sulfur dioxide for subsequent sulfuric acid production. It is an add-on process that requires a significant amount of power. Pilot-level studies have been conducted by Ionics and Stone & Webster.

m. The Alkalized Alumina Process has received significant attention. Attrition of the alkalized alumina has been a continuing problem. Recent detailed engineering and cost analysis (by M. W. Kellogg) suggests that further work on this process is unjustified.

6. Scrubber Development

There is a wide variety of SO_2 removal processes that use scrubbers as the principal chemical contactor. Some, such as the lime scrubbing process, employ reactants that may cause scaling and plugging of equipment because of the precipitation of solids, while others, such as sodium salt scrubbers, use clear liquids containing no solids. Nearly all scrubber applications require corroision studies and materials evaluation. The problem is not simply a matter of finding a single best scrubber for all applications, but to develop a scrubber technology for a variety of applications. Consequently, NAPCA plans to look at several scrubber types on a small scale in an effort to characterize process chemistry combinations and generate the background data necessary to select the best scrubber for the specific process. In this way scale-up would not be repeated for every promising process.

The proposal for work to be done by the TVA on the wet-limestone process involves a large development and testing effort on scrubbers. This same installation could conceivably be utilized with some modification to test other wet scrubber sulfur recovery processes, when technology reaches the stage at which testing on this scale is justified.

APPENDIX A

LIST OF PRESENTERS

The following organizations made presentations to the Panel on Control of SO_2 from Stationary Combustion Sources:

Babcock & Wilcox
Bituminous Coal Research, Inc.
Black, Sivalls, & Bryson, Inc.
Chemical Construction Corporation
Combustion Engineering, Inc.
Continental Oil Company
  (Consolidation Coal Company, Inc.)
The Dow Chemical Company
ESSO Research and Engineering Company
Institute of Gas Technology
Ionics Incorporated/Stone & Webster
The M. W. Kellogg Company
McNally Pittsburg Manufacturing Corporation
Monsanto Company
National Air Pollution Control Administration
North American Rockwell Corporation
  (Atomics International Division)
Office of Coal Research
Pope, Evans and Robbins
Princeton Chemical Research Company
Roberts & Schaefer Company
Tennessee Valley Authority
Tyco Laboratories, Inc.
Wellman-Lord, Inc.
Westvaco

APPENDIX B

LIST OF CORRESPONDENTS

The following companies sent in material to the panel describing their activities and experience on control of SO_2 from stationary combustion sources:

Abcor, Inc.
The Air Preheater Company, Inc.
Air Products and Chemicals, Inc.
American Petroleum Institute
Basic Chemicals
The Carborundum Company
The Detroit Edison Company
Edison Electric Institute
Institute of Gas Technology
Joy Manufacturing Company
(Western Precipitation Division)
Kaiser Aluminum & Chemical Corporation
(Kaiser Chemicals Division)
The Kansas Power and Light Company
Nalco Chemical Company
Pennsylvania Electric Company
Precipitair Pollution Control, Inc.
Research-Cottrell, Inc.
Reynolds Metals Company
Reynolds, Smith and Hills
Slick Industrial Company
(Pulverizing Machinery Division)
Union Electric Company
United International Research, Inc.
Universal Oil Products Company
(Air Correction Division)
The Wheelabrator Corporation

APPENDIX C

UNITED STATES SO_2 POLLUTION CONTROL RESEARCH AND DEVELOPMENT*

Company	Type of Work
Abcor, Inc.	Aqueous absorption systems for SO_2
Air Products and Chemicals, Inc.	Dry process for SO_2 removal
American Iron and Steel Institute	Studies of sulfur pollution control from various iron and steel manufacturing steps
Argonne National Laboratory	Reduction of atmospheric pollution by the application of fluidized bed combustion
Babcock & Wilcox	Magnesium oxide scrubbing system and other SO_2 removal processes
Basic Chemicals	Magnesium slurry scrubbing (in conjunction with Chemico)
Bituminous Coal Research, Inc.	Use of limestone or dolomite for SO_2 removal from coal-burning boiler flue gases
Bituminous Coal Research, Inc.	Removal of pyritic sulfur from coal
Black, Sivalls, & Bryson, Inc.	Coal gasification in molten iron; sulfur removal in slag
The Carborundum Company	Limestone injection with wet scrubbing or bag filtration
Chemical Construction Corporation	Various projects for SO_2 control from sulfuric acid plants and power plants
Combustion Engineering, Inc.	Limestone injection-wet scrubbing process

*Compiled by NAPCA, March 1970.

Company	Type of Work
(Kansas Power and Light Company)	Demonstration of Combustion Engineering limestone injection-scrubbing process
(Union Electric Company)	Demonstration of Combustion Engineering limestone injection-scrubbing process
Consolidation Coal Company, Inc.	Flue gas scrubbing, fluidized combustion in a lime bed, and pyrite removal from coal
The Detroit Edison Company	Limestone scrubbing, ammonia injection
The Dow Chemical Company	Gas-phase removal of SO_2 with solid alkaline materials
Edison Electric Institute	Dispersion characteristics of stack effluents, development of a formula for stack design
Esso Research and Engineering Company	B&W-Esso proprietary process for SO_2 removal
General American Transportation Corporation	Catalytic reduction of SO_2 to sulfur
Hydrocarbon Research, Incorporated	Catalytic hydrogenation of fossil fuels
Illinois Institute of Technology Research Institute	Oxidation and reduction catalysts
Institute of Gas Technology	Coal Gasification
Ionics Incorporated/ Stone & Webster	Regenerable aqueous scrubbing system for SO_2 removal and recovery (Stone & Webster-Ionics process)
Kaiser Chemicals	Improved dry sorbent for SO_2 removal
The M. W. Kellogg Company	Undisclosed process for power plant SO_2 removal
Monsanto Company	Catalytic oxidation of SO_2 with recovery of sulfuric acid
(Pennsylvania Electric Company) (Air Preheater Company) (Research-Cottrell)	Development of Monsanto catalytic oxidation process

Company	Type of Work
Nalco Chemical Company	Dry sorbent for SO_2
Petroleum Industry (Source: API)	Industry-wide R&D for sulfur oxides control
Pope, Evans & Robbins	Control of gaseous emissions from coal-fired fluidized-bed boilers
Precipitair Pollution Control, Inc.	Gas-phase removal of SO_2 with solid alkaline materials, and collection with fabric filters (cooperative work with Southern California Edison)
Pulp and Paper Industry (Source: NCASI)	Sulfur oxides control from sulfite and kraft pulping processes
Research-Cottrell, Inc.	Scrubbing equipment development
Reynolds Metals Company	Dry sorbents for SO_2 removal
Reynolds, Smith, and Hills	Scrubbing process for flue gas SO_2 removal
Slick Industrial Company	Dry SO_2 sorbent development
Southern California Edison Company	Gas-phase removal of SO_2 with solid alkaline materials, and collection with fabric filters
Stone & Webster	Regenerable aqueous scrubbing system for SO_2 removal and recovery (S&W-Ionics process)
United International Research, Incorporated	Regenerable scrubbing process removal; SO_2 converted to H_2SO_4
U.S. Bureau of Mines-Morgantown	Study of corrosion/erosion and of coal type during fluidized bed combustion
U.S. Stoneware Company	Process for SO_2 control from sulfuric acid plants
Universal Oil Products	Dolomite slurry scrubbing; catalytic hydrogenation of fuels

Company	Type of Work
Wellman-Lord, Incorporated	R&D of regenerable wet scrubbing process at Lakeland, Florida, and Tampa Electric, plus direct reduction of SO_2 to sulfur
Tampa Electric Company	Pilot study of Wellman-Lord process, contributed to Stone & Webster
(Bechtel Corporation)	Demonstration plant of Wellman-Lord process at Baltimore Gas and Electric power station
(Baltimore Gas and Electric Company) (Potomac Electric Power Company) (Delmarva Power and Light Company) (Potomac Edison Company)	Demonstration plant of Wellman-Lord process at BG&E power station in Baltimore
Western Precipitation Group (Joy Manufacturing Company)	Scrubbing equipment development
Westinghouse R&D Center	Evaluation of the fluidized bed combustion process
Westvaco	Adsorption of SO_2 by activated carbon
The Wheelabrator Company	Scrubbing equipment development
Wisconsin Electric Power	Lime scrubbing, other aqueous scrubbing systems

APPENDIX D

FOREIGN SO_2 POLLUTION CONTROL RESEARCH AND DEVELOPMENT*

Company	Type of Work
Australia	
Commonwealth Science Industrial Research Organization	Fluidized bed combustion
Czechoslovakia	
Research Institute of Inorganic Chemistry	Ammonia scrubbing of SO_2 effluent
Czech acid plant scrubbing	Ammonia scrubbing on H_2SO_4 plant tail gas
Fuel Research Institute	Fluidized bed combustion
Institute of Mines	Desulfurization of coal
England	
Esso Research Center	Fluidized bed combustion of oil
National Coal Board Coal Research Establishment BCURA Industrial Labs	Fluidized bed combustion of coal
LHF Patented Process Esso Research	Desulfurization of coal
Bankside and Battersea Process	Alkaline water scrubbing on Thames River
France	
Societe Nationale Des Petroles D'Aquatane (joint project with Halder Topsoe of Denmark)	Catalytic oxidation of flue gas
Ugine Kuhlmann-Weirtam Process	Ammonia scrubbing of flue gas
Societe Anonyme Activit	Fluidized bed combustion
Neyric	Desulfurization of coal

*Compiled by NAPCA, March 1970.

Company	Type of Work
Germany	
Bayer Double Contact Process	Two-stage catalytic oxidation of H_2SO_4 tail gas
Bischoff Process	Lime/Limestone scrubbing of flue gas
Lurgi Sulfacid Process	Wet char sorption of SO_2 from effluent
Activated Carbon Adsorption Bergbau-Forschung	Wet char sorption of SO_2 from effluent
Activated Char Sorption Bergbau-Forschung	Dry char sorption of SO_2 from gaseous effluent
Grillo Process	Sorption by proprietary mixture of metal oxides
Siemens-Schuchert Process	Sorption on iron oxides in silica gels
Holland	
Shell CuO process	Sorption on proprietary mixture of copper based metal oxides
NVCP (Nederlandsch Verkoopkantoor voor Chemische Producten N.V.)	Hydro desulfurization of oil
Italy	
University of Cagliari	Desulfurization of coal
Japan	
Kiyoura Ammonium Sulfate Process	Catalytic oxidation of flue gas
Nippon Kokan Ltd.	Lime/Limestone scrubbing of flue gas
Japan Engineering and Construction Co. (JECCO)	Lime/Limestone scrubbing of flue gas
Showa-Denko Process	Ammonia scrubbing
Hitachi Activated Carbon Process	Wet char sorption of SO_2 from effluent
Central Research Institute of the Electric Power Industry	Dry limestone injection for SO_2 control of flue gas
Resources Research Institute	Dry limestone injection for SO_2 control of flue gas
Mitsubishi DAP-Manganese Process	Manganese oxide sorption
Kanagawa	Aqueous scrubbing

Company	Type of Work
Poland	
Dry Ammonia Injection	Injection of gaseous ammonia into flue gas
Sweden	
BAHCO Lime-scrubbing Process	Lime/Limestone scrubbing of flue gas
U.S.S.R.	
Wet Limestone scrubbing at Kusnetsk Abagur Plant	Lime/Limestone scrubbing
Ammonia and sodium carbonate scrubbing-Voskresenskij Chemical Industry	Ammonia scrubbing
I.M. Gubkin Institute of Petroleum and Others	Fluidized bed combustion
Academy of Science	Desulfurization of coal
Lensovet Technological Institute	Desulfurization of oil
Yugoslavia	
Institute of Mines	Desulfurization of coal

APPENDIX E

BIBLIOGRAPHY

1. Executive Office of the President. Office of Science and Technology. Energy Policy Staff. *Federal Research and Development for Civilian Energy Production, Conversion and Transmission.* Washington: Office of Science and Technology, September 8, 1969. 9 p.

2. ______. *Considerations Affecting Steam Power Plant Site Selection.* Washington: Office of Science and Technology, December 1968. 133 p.

3. Holcomb, R. W. *Power Generation: The Next 30 Years.* Science, 167: 159-160, January 9, 1970.

4. Institute of Gas Technology. *LNG: A Sulfur-Free Fuel for Power Generation.* Springfield, Virginia: Clearinghouse for Federal Scientific and Technical Information, May 1969. (various pagings). (PB 184 353)

5. Linzon, S. N. *The Influence of Smelter Fumes on the Growth of White Pine in the Sudbury Region.* Toronto: Ontario Department of Lands and Forest, Ontario Department of Mines, 1958. 45 p.

6. McCormick, Robert A. and John H. Ludwig. *Climate Modification by Atmospheric Aerosols.* Science, 156(3780): 1358-1359, June 9, 1967.

7. *Minutes of the Air Quality Control Advisory Council.* January 28, 1970. Baltimore: State of Maryland, Department of Health, Air Quality Control Division.

8. National Academy of Sciences-National Research Council. Committee on Resources and Man. *Resources and Man.* San Francisco: W. H. Freeman and Company, 1969. 259 p.

9. *Operating Characteristics of a High Temperature Electrostatic Precipitator.* Report RI 7276. Washington: U. S. Bureau of Mines, July 1969. 45 p.

10. President's Science Advisory Committee. Environmental Pollution Panel. *Restoring the Quality of Our Environment.* Washington: U. S. Government Printing Office, 1965. 317 p.

11. Robinson, E., and R. C. Robbins. *Sources, Abundance, and Fate of Gaseous Atmospheric Pollutants.* SRI Project PR-6755. New York: American Petroleum Institute, February 1968. 123 p.

12. Steinberg, M., J. Powell, and B. Manowitz. *The Western Coal Deposits: A National Source of Power.* Preprint of Report BNL 50187 (T-542). Upton, New York: Brookhaven National Laboratory, June 1969. 54 p.

13. U. S. Atomic Energy Commission. Division of Industrial Participation. *The Nuclear Industry--1969.* Washington: U. S. Government Printing Office, 1969. 338 p.

14. Upham, J. B. *Atmospheric Corrosion Studies in Two Metropolitan Areas.* J. Air Pollution Control Association, *17:* 393-402, June 1967.

15. Wicken, A. J., and S. F. Buck. *Report on a Study of Environmental Factors Associated with Lung Cancer and Bronchitis Mortality in Areas of North East England.* London: Tobacco Research Council, 1964. (Research Paper 8)

16. U. S. Department of Health, Education, and Welfare. Public Health Service. Consumer Protection and Environmental Health Service. National Air Pollution Control Administration. *Air Quality Criteria for Carbon Monoxide.* Washington: National Air Pollution Control Administration. (NAPCA Publication AP-62)

17. ______. *Air Quality Criteria for Hydrocarbons.* Washington: National Air Pollution Control Administration. (NAPCA Publication AP-64)

18. ______. *Air Quality Criteria for Particulate Matter.* Washington: National Air Pollution Control Administration, January 1969. (NAPCA Publication AP-49) 211 p.

19. ______. *Air Quality Criteria for Photochemical Oxidants.* Washington: National Air Pollution Control Administration. (NAPCA Publication AP-63)

20. ______. *Air Quality Criteria for Sulfur Oxides.* Washington: National Air Pollution Control Administration, January 1969. (NAPCA Publication AP-50) 178 p.

21. ______. *Control Techniques for Carbon Monoxide Emissions from Stationary Sources.* Washington: National Air Pollution Control Administration. (NAPCA Publication AP-65)

22. ______. *Control Techniques for Carbon Monoxide, Nitrogen Oxides, and Hydrocarbon Emissions from Mobile Sources.* Washington: National Air Pollution Control Administration. (NAPCA Publication AP-66)

23. ______. *Control Techniques for Hydrocarbons and Organic Solvent Emissions from Stationary Sources.* Washington: National Air Pollution Control Administration. (NAPCA Publication AP-68)

24. ______. *Control Techniques for Nitrogen Oxides Emissions from Stationary Sources.* Washington: National Air Pollution Control Administration. (NAPCA Publication AP-67)

25. ______. *Control Techniques for Particulate Air Pollutants.* Washington: National Air Pollution Control Administration, January 1969. (NAPCA Publication AP-51) 215 p.

26. _____. *Control Techniques for Sulfur Oxide Air Pollutants*. Washington: National Air Pollution Control Administration, January 1969. (NAPCA Publication AP-52) 122 p.

27. _____. *The Climate of Cities: A Survey of Recent Literature*, by James T. Peterson. Washington: U. S. Government Printing Office, October 1969. (NAPCA Publication AP-59) 48 p.