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A Summary Report of the Automotive Power Systems Contractors Coordination Meeting

Ann Arbor, Michigan

May 13-16, 1974

ALTERNATIVE AUTOMOTIVE POWER SYSTEMS DIVISION

U. S. ENVIRONMENTAL PROTECTION AGENCY

FOREWORD

ABOUT THE MEETING

In an effort to stimulate and promote the maximum rate of technical progress toward the country's clean air objectives, the Alternative Automotive Power Systems Division holds periodic coordination and progress meetings with all of its contractors, staff, consultants, prospective contractors, and selected guests. The meetings focus attention on the status of the programs and provides an opportunity for interaction between the participants on problem areas of mutual interest.

This report summarizes the presentations and discussions at the seventh such meeting held on May 13-16, 1974, in Ann Arbor, Michigan. Documentation such as this is believed to be both an effective and timely means of providing a full and up-to-date accounting of the AAPS Program progress in the U. S.

This document includes:

- The key issues under consideration in the AAPS Division

- Gas Turbine Engine Program

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- Rankine Cycle Engine Programs
- Diesel Engine Study, Alternative Fuel Investigations, Combustion Studies, Electric Vehicle Impact Study, and Hydrogen Storage Investigations.

Each of these presentations is summarized along with the pertinent questions, comments and items of discussion. Wherever possible specific data, principle conclusions, and key illustrations are included.

Additional supplementary material contained in the appendices include explanatory notes on the AAPS Division in the EPA organization (Appendix A); a list of attendees and representatives (Appendix B); a review of the background and evolution of the new EPA Highway Test Cycle (Appendix C); a final report on the health hazards of nickel oxide regenerator seal materials (Appendix D) and a bibliography of AAPSD reports released through May 1974 (Appendix E).

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I. SPECIAL SESSION ON KEY ISSUES UNDER CONSIDERATION BY EPA, AAPS DIVISION, TO ACHIEVE A BALANCED PROGRAM, BY JOHN J. BROGAN, DIVISION DIRECTOR

A. Objective of Special Session

The Alternative Automotive Power Systems Division is in the process of planning an expanded program of automotive research and technology development. This program is an integral part of the $10 billion, 5-year program of energy related Research & Development announced in January this year.

By outlining the background and current thoughts on the general direction which this program might take, it is hoped to stimulate subsequent reactions, comments, and suggestions from the broad sector of the technical community represented at this conference.

B. Orientation and Background of AAPS Division Within the Environmental Protection Agency

The AAPS Division reports to the Office of Mobile Source Air Pollution Control, under Eric Stork, Deputy Assistant Administrator. He in turn reports to the EPA Administrator, Russell Train, through Roger Strelow, Assistant Administrator for Air and Waste Management. (A somewhat more detailed description of the organization is shown in Appendix A.)

The AAPS Division is comprised of two branches, Power Systems Development Branch, under George Thur, and Alternative Systems Analysis Branch, under Graham Hagey (Fig. 1).

The Power Systems Development Branch focuses on development of component and system hardware, such as: the work on turbo compounding, transmissions and the Rankine and Brayton cycle engine development projects. The Power Systems Analysis Branch focuses on assessment and evaluation of available engine and fuel technologies, and assessment of the impacts associated with the use of alternative fuels and battery powered electric cars. One branch develops; the other branch studies.

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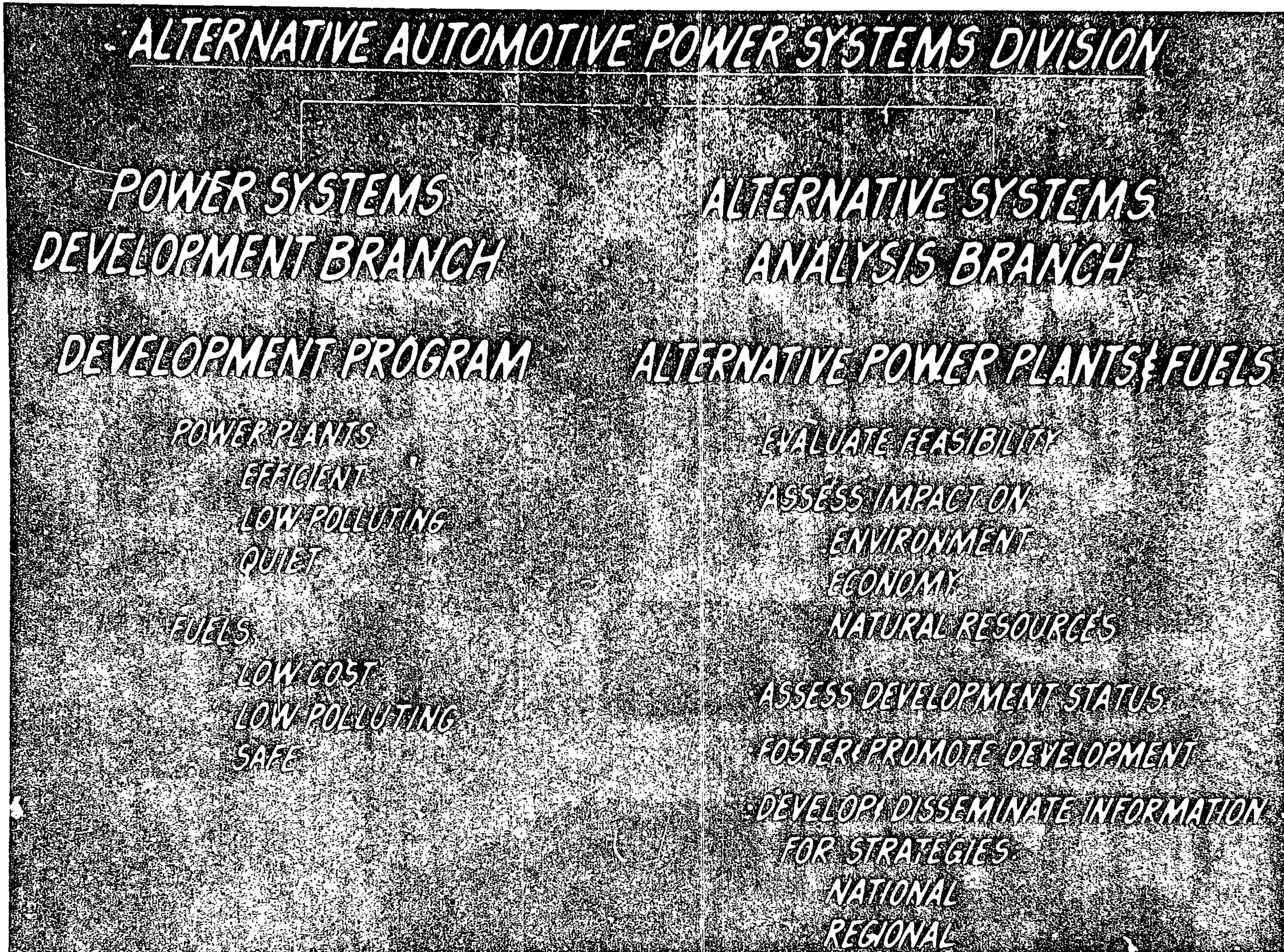


Fig. 1 Alternative Automotive Power Systems Division

The need for an alternative power system development program was identified in late 1969. The Office of Science and Technology, then headed by Dr. Lee DuBridge, expressed concern to the President about:

- the automobile's significant contribution to our nation's deteriorating ambient air quality
- the exhaust emissions standards required in future years - through the end of this century - might have to be so stringent that the conventional engine might not be capable of being clean enough
- the technologies needed to produce alternative power systems should at least be available to the nation if needed
- the auto industry had no serious alternative engine development programs underway and none were planned.

As a result, a Federal program was recommended to serve as a stimulus to industry and to provide this base of technology. The President announced the program in his Message on The Environment early in 1970. The program is managed by the Environmental Protection Agency AAPS Division in Ann Arbor, Michigan.

C. The Purpose, Approach and Evolution of AAPS Program

The purpose of the program is to evaluate powerplant alternatives to the conventional engine. In some cases the evaluations did not require development of new hardware systems; however, for some powerplants development has been necessary. The program was focused initially on power systems that offered the potential of being inherently clean compared to the conventional engine. In 1972 the program scope was broadened to include studies of alternative fuels and battery powered systems; energy efficiency was elevated to share equal importance with low emissions in the hardware development program. The Rankine cycle and gas turbine systems are the two technologies currently in various hardware stages in this program.

Until a year ago the AAPS Division assisted in funding the Army program on stratified charge engine development. The AAPS Division charter permits development to the end of the Advanced Development phase where engineering prototypes can be tested in motor vehicles. The Army program, having different constraints, is carrying the stratified charge engine into the next phase, Engineering Development in which soft tooling is to be provided.

On December 1, 1973 the Chairman of the Atomic Energy Commission (AEC) presented the President with a 5-year, $10 billion-total, energy R&D package which included a new program that emphasized automotive energy R&D. The EPA is responsible for a portion of this new program. Basically the ongoing AAPS program and the new energy oriented program overlap by about one year starting in Fiscal Year 1975. The new program basically broadens the scope of the ongoing program in that additional types of power systems will be developed through to demonstration of engineering prototypes in motor vehicles. This expanded scope may permit a next generation of hardware development beyond that originally contemplated - for the gas turbine, for example.

D. Key Issues Include: Fuel Economy, Emissions, Cost and Critical Materials

The automobile is deeply entwined in modern economy and life style. In the U.S. it is relied upon more than any other mode of transportation. The following data from 1971 and 1972 attempt to place the automobile in its nationwide perspective. Automobiles represent:

- 82% of total U.S. registered automotive ground transportation vehicles
- 71% of total U.S. automotive transport fuel use
- 20.5% of total U.S. energy use (Includes fuel consumed by automobiles and the energy used in manufacturing them.)
- 30.1% of total U.S. petroleum use
- 10% of total U.S. steel and aluminum use
- 5 to 40% of total U.S. use of critical materials
- 14% of total U.S. imports (percent of dollar value of imported automotive products - new cars, engines, fuel)
- 27.5% of total U.S. pollution toxicity

It is clear that the automobile is a major factor which impacts on national issues of: energy, pollution, natural resources and on the economy of the country. The drop in Gross National Product in the first quarter of 1974 was in large measure due to the drop in sales and manufacture of automobiles and components. The nation's balance of payments deficits will be relatively large now that imported petroleum has tripled in price - another illustration of the importance of the automobile to the national economy.

The issues facing the automobile industry have traditionally included achievement of low initial cost. This remains an important issue. Since the 1960's emissions have become another important issue and, more recently, fuel economy has been recognized as far more important than it had been in the past. These issues and others have influenced engine and vehicle systems design and will continue to do so because, once exposed, they never disappear completely.

Because a program is being planned that must somehow relate to these past and current issues it is also important to anticipate other potential issues that have not yet surfaced. Dwindling domestic natural resources is expected to be the next critical issue.

Consideration of these various issues emphasizes the need for a balanced program both in its technical content and its timing (Fig. 2).

E. Key Issues To Be Incorporated in Balanced AAPS Program

The automobile caused pollution issue has been faced by the industry, and significant reductions in CO, unburned hydrocarbons, and NOx have been achieved; however, it should be remembered that in any Federally sponsored program on new engines and/or fuels that the same or even more stringent standards must be met if the gains already made on the emissions issue are to be retained. If impact on the fuel or energy problem is achieved by exceeding the emission standards, then a step backward would have been taken.

Consider the automobile and its relationship to petroleum consumption. Figure 3 shows this for four different scenarios. Taking the known domestic petroleum reserves and assuming that through intensive exploration etc. that these

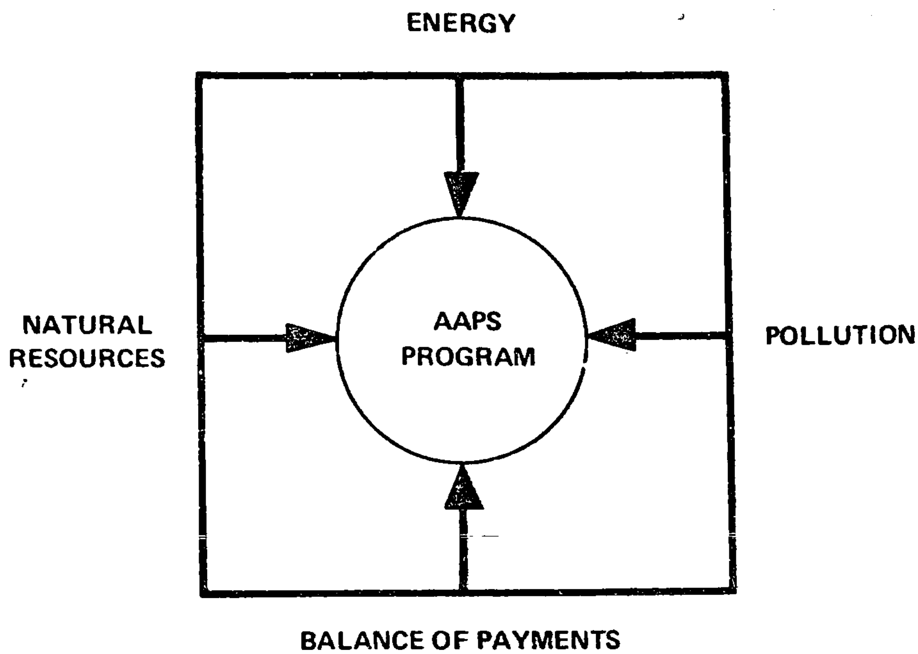


Fig. 2 A Balanced AAPS Program

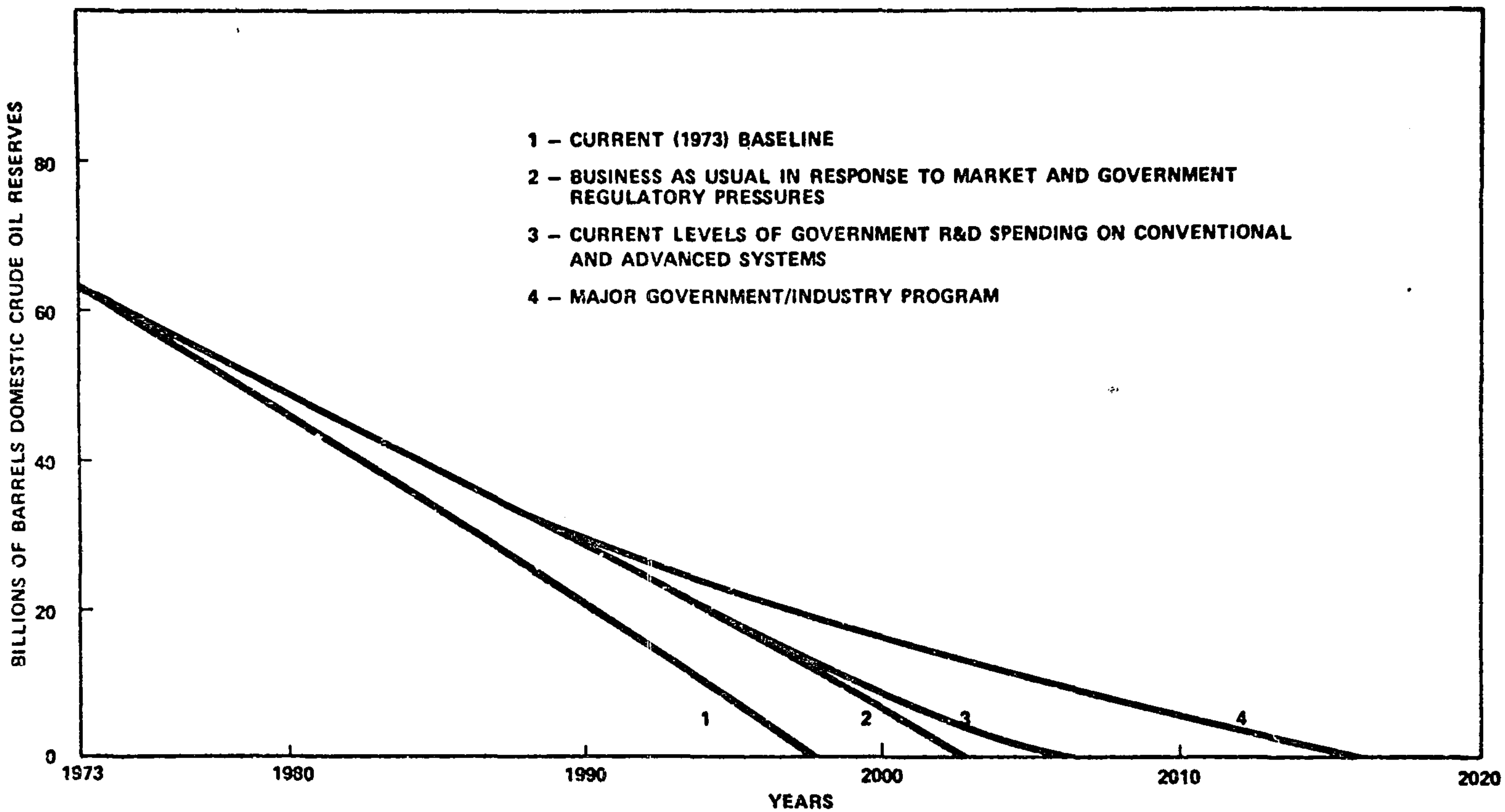


Fig. 3 Depletion of "Auto Share" of Domestic Oil Reserves

reserves somehow could be increased by a factor of 5 (Ref: Meadows and the Club of Rome Report), and assuming that the automobile's share of these total resources remains fixed, then Curve 1 applies where the current nationwide average fuel economy of 13.6 mpg remains fixed for all cars on the road with projected growth in numbers of vehicles assumed. Under these extreme circumstances we would be out of domestic petroleum before the year 2000.

Curve 2 assumes introduction into the marketplace of 10 million new vehicles yearly starting in 1975 and getting an average of 30% improvement overall in fuel economy perhaps due to lower power/weight, rear axle ratio change, increase in smaller size car mix, etc. This kind of improvement (if it could be achieved) would increase the 'run-out' point by about 5 years.

Curve 3 continues with the Curve 2 scenario, but additionally considers introduction into the marketplace by 1980 and after, of automobiles with a 100% improvement (doubling) in fuel economy (to 28 mpg). This would result in an extra 3 years. If Curve 3 is achievable, it may be so with use of completely different engines and vehicular system concepts than those available today.

Finally Curve 4 is similar to Curve 2 and 3 until 1985 where 40 mpg overall average for new automobiles would be introduced and would continue thereafter. To achieve 40 mpg may well require a major industry/government R&D effort. If successful that would give us an additional 20 years over the baseline, Curve 1. Under crisis conditions that could be significant.

Although it is not necessary to agree now on the practicability of achieving these fuel economy levels at least the trends are apparent:

1. If no one does anything - either the public, industry, or the Government - and petroleum is considered in the future as unconstrained as in the past, then the petroleum would be gone by 2000.

2. If a business as usual stance is adopted, an extra couple of years may be achieved.

3. If Federally sponsored research focuses only on energy conversion efficiency improvements with only long range impact, the effects will be insignificant.

4. A major government/industry effort to improve efficiency of energy conversion in automobiles may still gain only about 20 years on this basis.

This does not say that working on improvements in energy conversion efficiency are wasted effort. However, it is only one area where research is needed; research is also needed in conjunction with other parallel development activities.

When it comes to measures that may have short term impact, increasing cost to the consumer is frequently mentioned as a natural means to reduce consumption. This could take the form of a tax for example; however, it probably would take an enormous increase in gasoline cost to have an appreciable effect on consumption. In Europe, since lifting the embargo, even higher gasoline prices than shown in Fig. 4, have hardly made a dent in total consumption rates. Other so-called institutional measures would include modal shifts, carpooling and even regulatory measures. Institutional changes then do offer the possibility of near-term impact. What is needed here is knowledge - knowledge of what can and cannot be accomplished on current engine and vehicle systems.

Other means considered to reduce petroleum energy consumption include use of alternative fuels. Figure 5 applies to the total petroleum consumption (not just to autos) because it is a more straightforward illustration than one made up only for automobiles. The shaded dots through 1972 are historical data; the dots for later years are from Shell estimates. Using the best estimates available to us on realistic growth of availability of either methanol from coal, gasoline-like fuel from coal or gasoline-like fuel from shale, the projected impact is shown. It is apparent that if alternative fuels come as currently expected, they cannot have significant impact until the 1990 time period. It should be noted that the President's Project Independence aims at moving these curves back to 1.0.

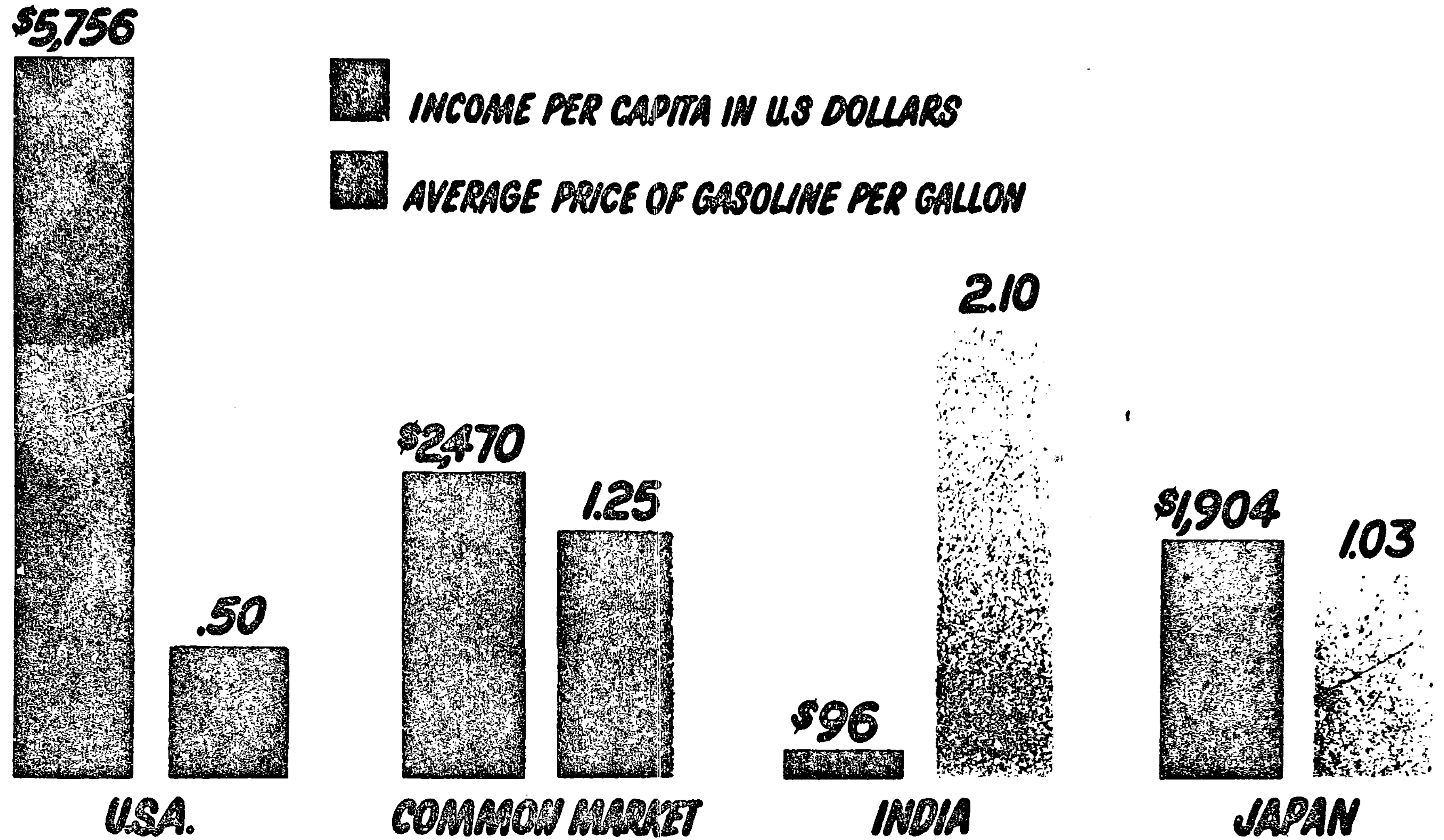


Fig. 4 The Price of Gasoline in Relation to Income

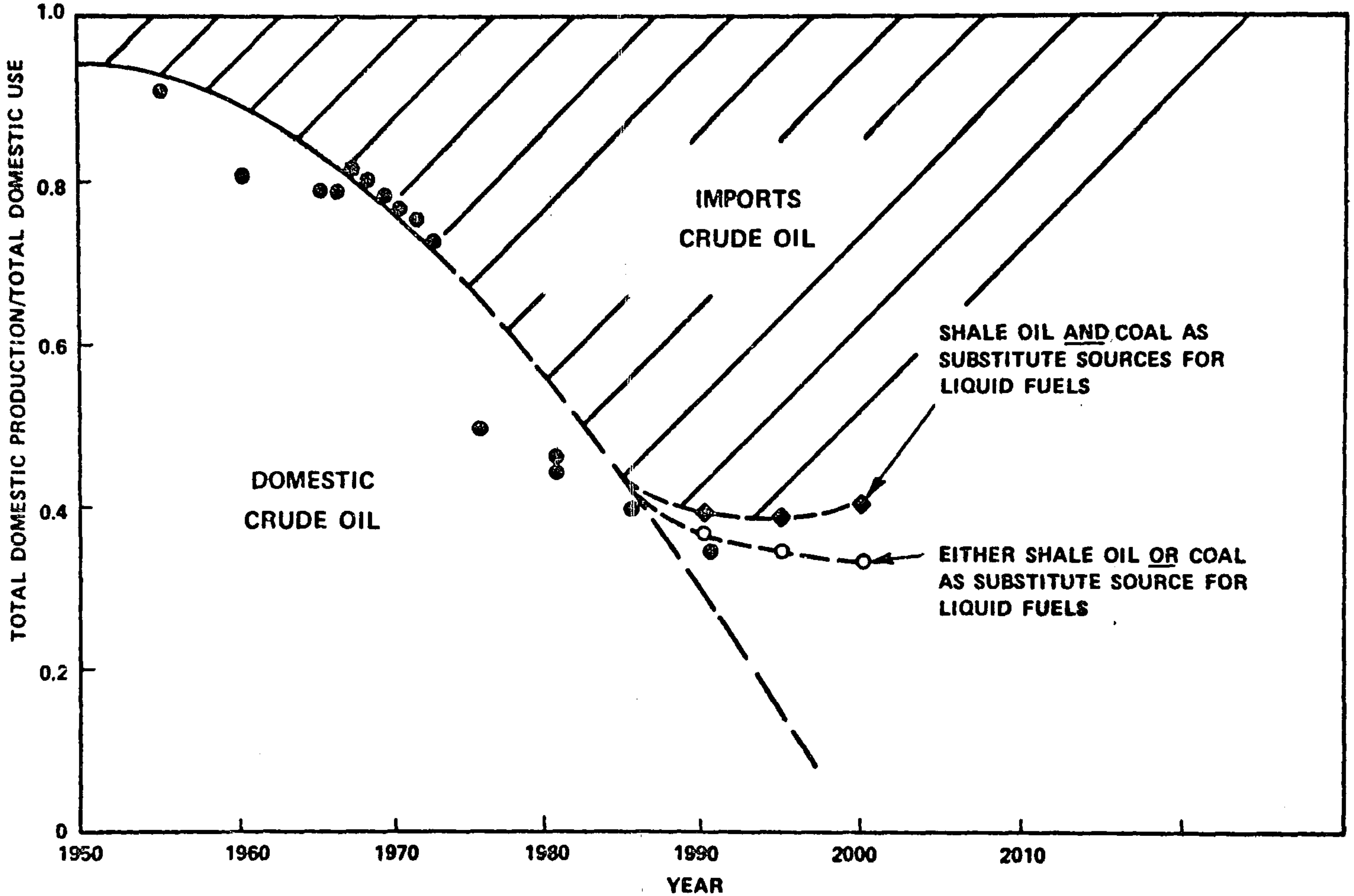


Fig. 5 Alternate Fuel Sources

The separate effects of higher energy conversion efficiency, alternative fuels, and institutional changes on a baseline petroleum consumption curve have been discussed. Each by itself can contribute somewhat toward changing the slope of the consumption curve. This is the impact we seek, but when applied together, the combined impact can be appreciable. Hence, to effect needed reductions in consumption, a balanced technology program is one of the important factors needed.

By standing back and looking to the past and future regarding energy sources for transportation it is recognized that all of the fossil fuel sources are finite. Also, changes in demand or consumption merely lengthen the time to ultimate depletion; therefore, although we expect certain alternative fuels will come along, current planning should consider how to make effective use of the virtually unlimited nuclear and solar sources of energy (Fig. 6).

Looking at these future energy sources and how they can be used for transportation fuel gives further guidance for directions of effort. As illustrated in Fig. 7 the primary energy source must go through some intermediate form and then through a conversion device to provide motive power for the transportation vehicle. Crude oil (or shale oil) or coal are compatible with internal and external conversion devices either in their conventional or somewhat advanced form. When the intermediate energy form is heat or electrical power (or is used for hydrogen generation) new transportation conversion systems will be needed. Probably these will be either electric or heat storage driven, or completely new hydrogen propulsion systems. New fuel distribution and handling systems also will be needed.

Now consider natural resources. The issue anticipated in the near future is the limitation of our mineral resources and the demands on our reserves of natural resources for the automobile. Tabulated in Fig. 8 are the amounts of various materials found in a typical 1970 car (4100 lbs). We have shown the weights of material used directly in the manufactured auto and the amounts of material needed in the after-market to keep the vehicle on the road for its average 10-year life. It is seen that the automobile accounts for significant percentages of the total U.S. use of many of these materials.

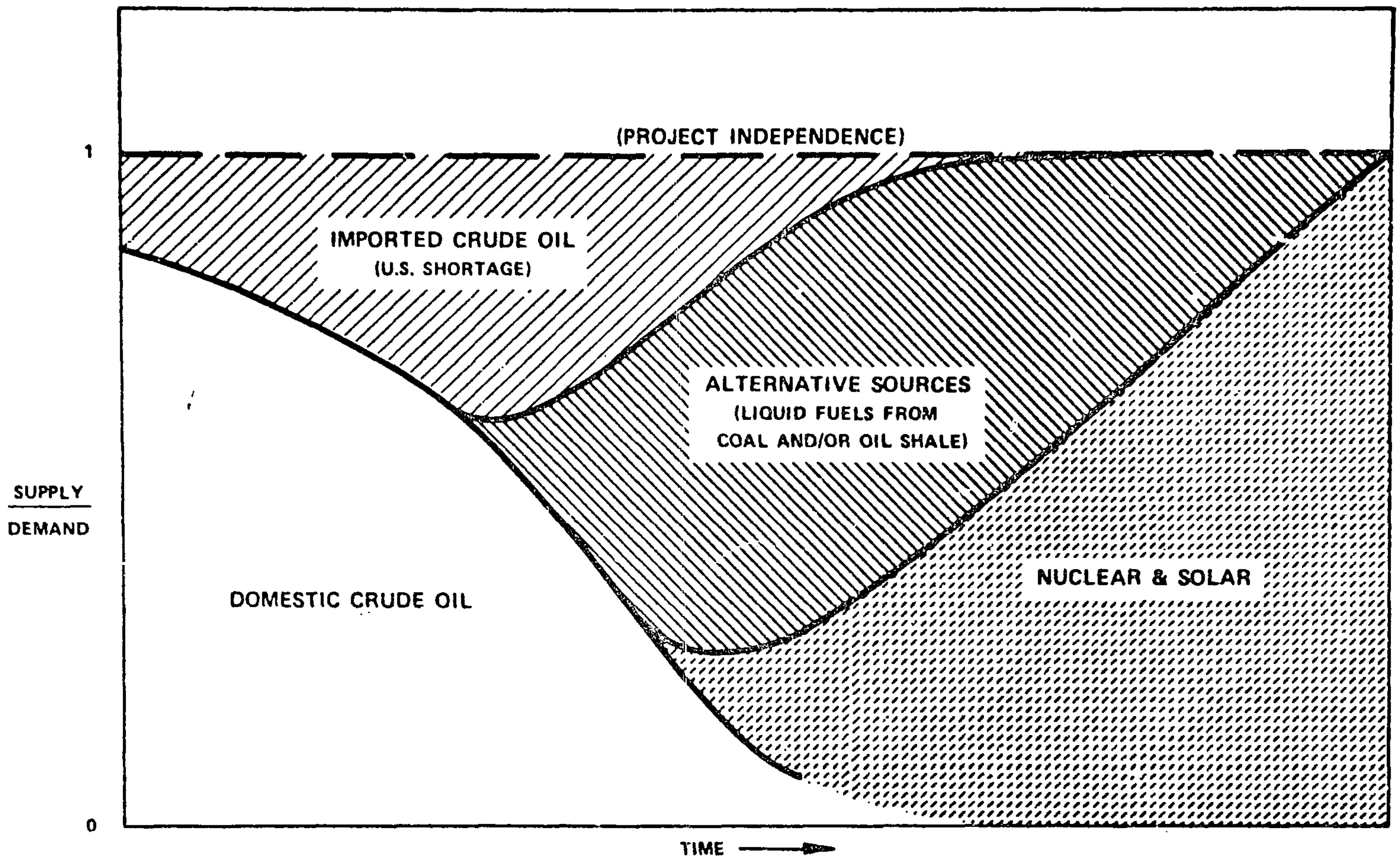


Fig. 6 Future Projection of Energy Sources for Transportation Fuels

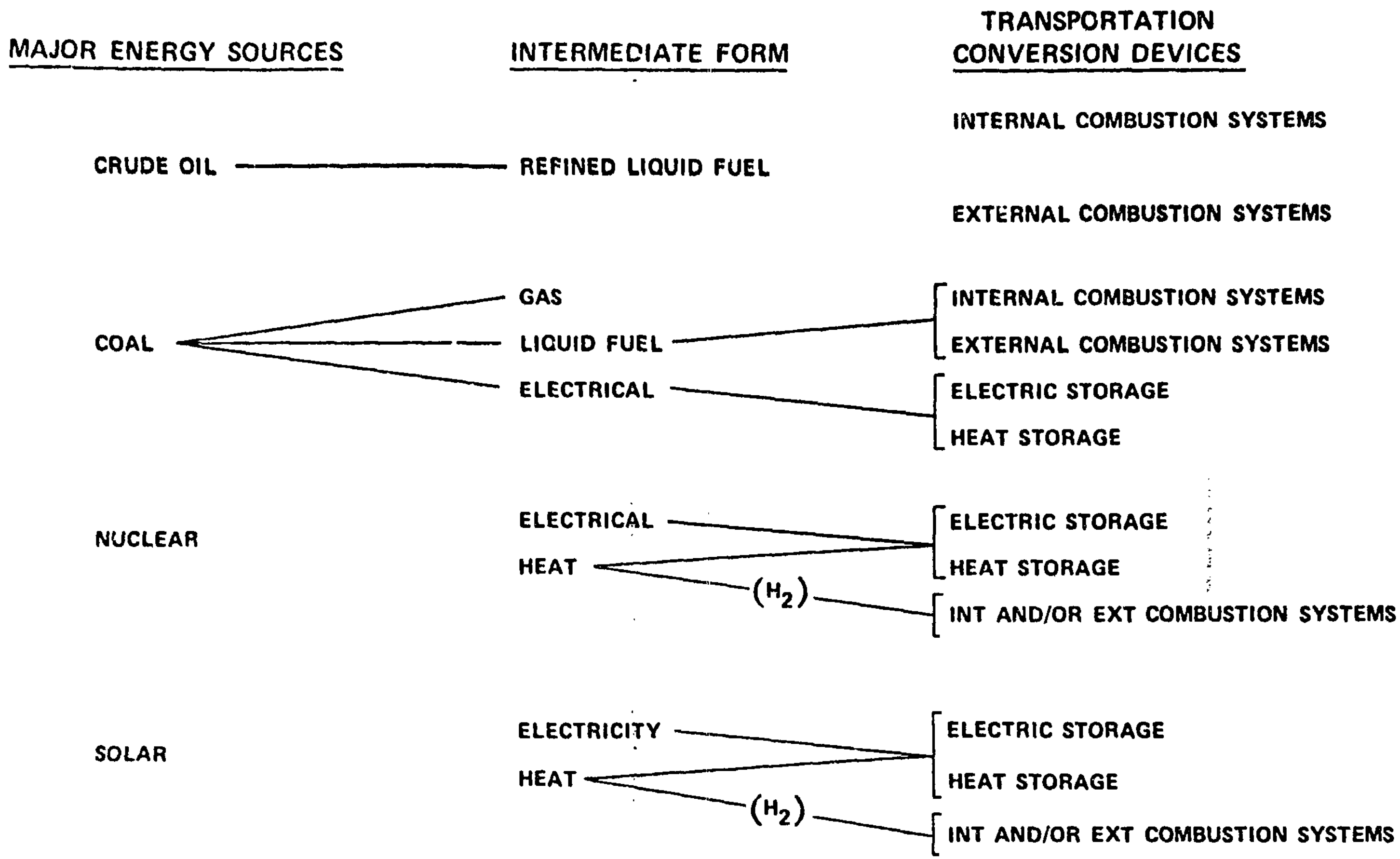


Fig. 7 Using Future Energy Sources for Transportation Fuel

METAL	DIRECT	AFTER MARKET	TOTAL AUTO USE 1973	TOTAL U.S. USE 1970	PERCENT USED IN U.S. AUTOS (1950 - 1970 AVG.)
	(POUNDS/AUTO)		(MILLIONS OF POUNDS)		
IRON	3,500	496	38,633	324,000	10
ALUMINUM	65	17.7	799.5	7,835	9
LEAD	28	99.3	1,230.7	2,710	40
COPPER	30	7.9	366.4	4,370	7.3
ZINC	65	12.2	746.4	2,300	28.4
NICKEL	4.5	.35	46.9	311	13.7
CHROMIUM	8	.23	79.6	684	9.1
MOLYBDENUM	.5	–	4.8	76	5.6
MANGANESE	12	3.5	149.9	2,296	5.7
TIN	2	.04	19.7	164	10.5

Fig. 8 Auto Metal Consumption

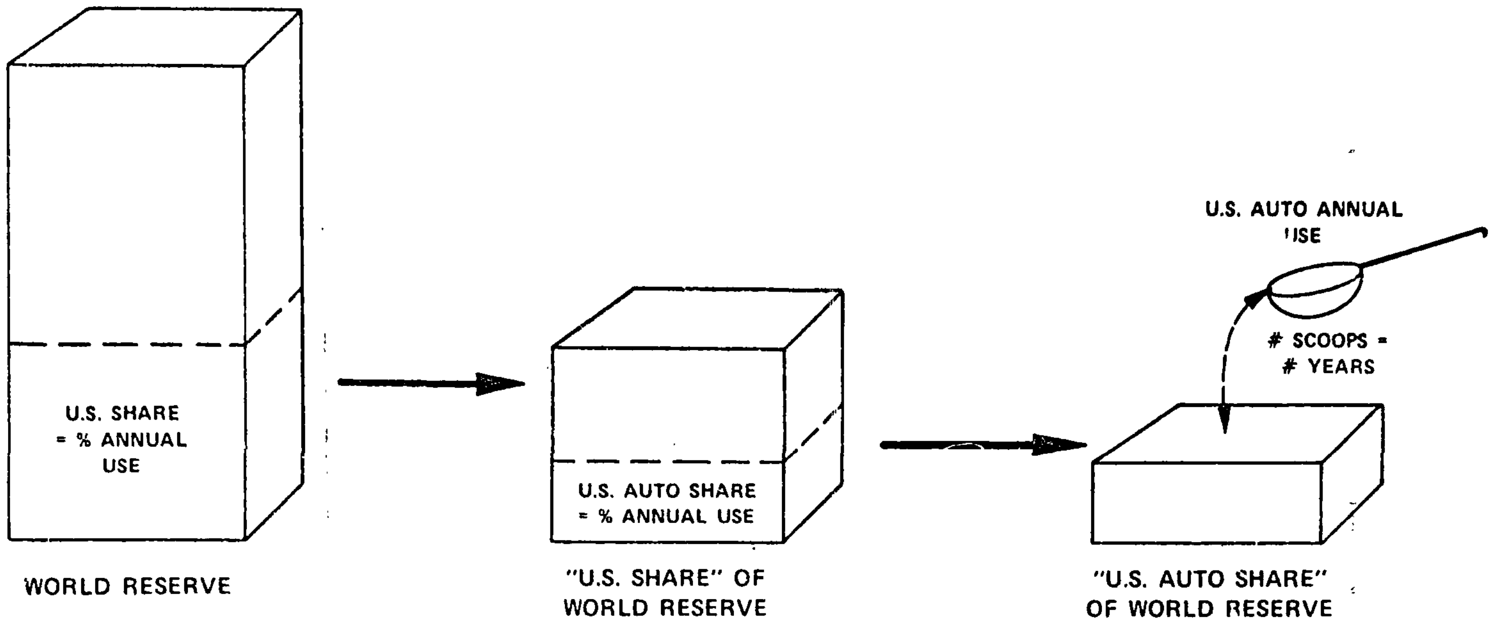
Figure 9 shows the methodology used to obtain years of supply remaining which appear in Fig. 10. Considered are: total world reserve of each metal, total U.S. annual consumption of the metal as well as the fraction of the annual U.S. consumption of the metal needed for automobiles. Assuming that this 'share' remains fixed, an estimate can be made of the years until depletion of the world reserve.

Obviously this will change if the average car weight changes and also as the mix of materials in the car changes. A 2500 lb. vehicle and a 4100 lb. vehicle were studied. Also, it is unlikely that the U.S. will continue to get as large a share of the world use as other countries develop. New reserves may also be found that will change the picture somewhat - but at least some perspective can be obtained from these data. It is added that the recycling situation today has been considered with each material and has been factored into the results shown. For example, lead has a 60% recycle rate, iron 47%, tin 5%, etc. (Based on Dept. of Interior Data)

Thus, serious problems lie ahead if materials like lead, zinc and tin continue to be used at current rates. The trend toward lower car weights will help somewhat, but the major influences will be the net balance between increasing demand for these materials from the rest of the world and the discovery of new supplies. The true picture is not easy to pin down since the actual reserves are often masked by economic and trade policies and even by the tax laws.

This area needs much more intensive study, particularly when looking ahead to possibilities like the electric car and battery storage. Basically, natural resources are finite, and as new solutions to shortages of energy are sought, blind alleys involving other resources should be avoided. The path must be carefully chosen and consideration given to how much of the needed critical materials can be recycled.

Another aspect of natural resources is the impact on balance of payments. Figure 11 shows how the amount of certain materials used in the automobile compares with the total percent of those materials imported by the U.S. It is seen that if the content of certain materials in the car, like copper,



Data Source — U.S. Bureau of Mines, "Mineral Facts and Problems," 1970

Fig. 9 Methodology for Determining Years of Supply Remaining for Critical Materials (All Data Static at 1970)

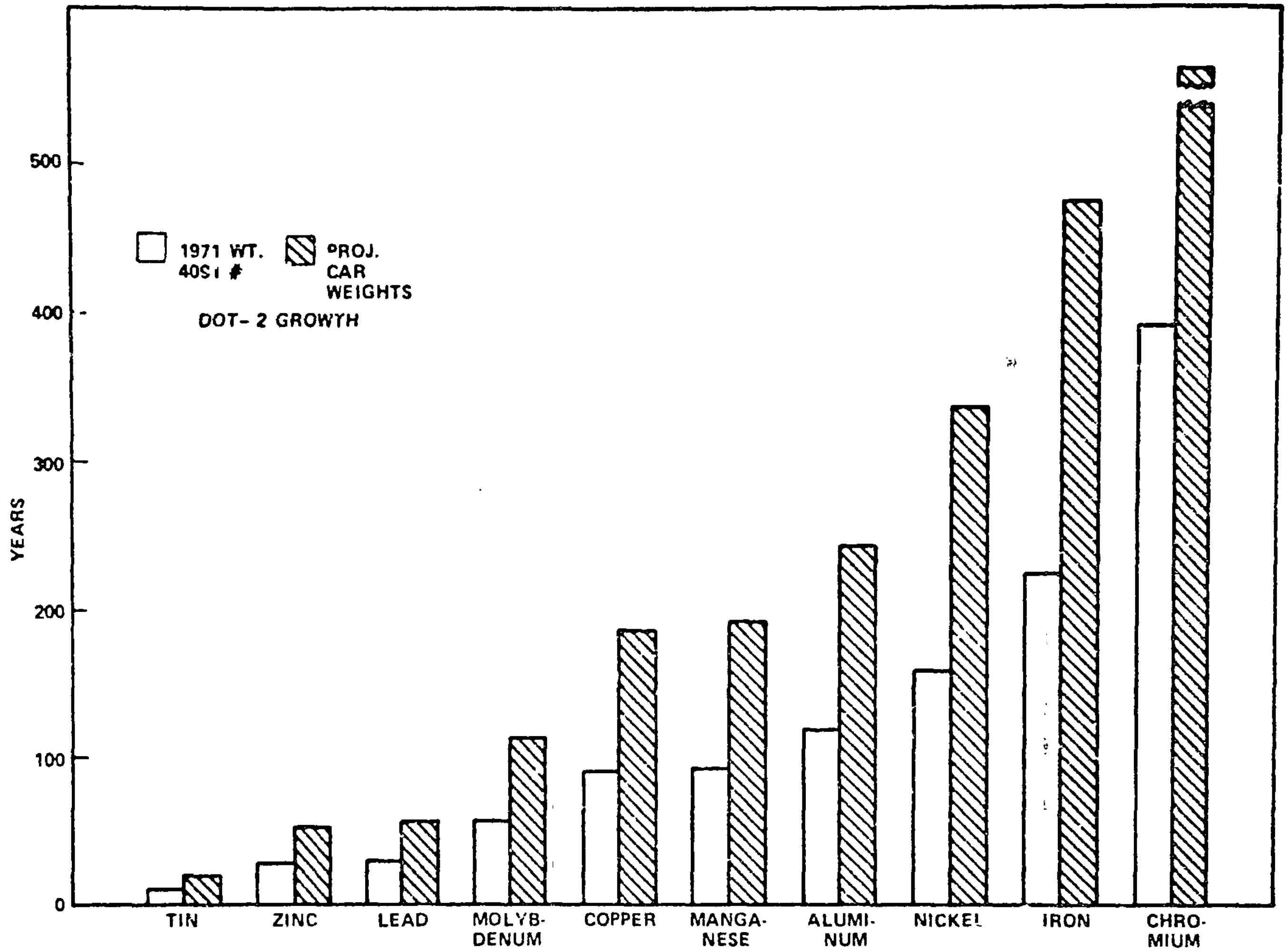


Fig. 10 Years to Depletion of U. S. Auto Reserve - Materials

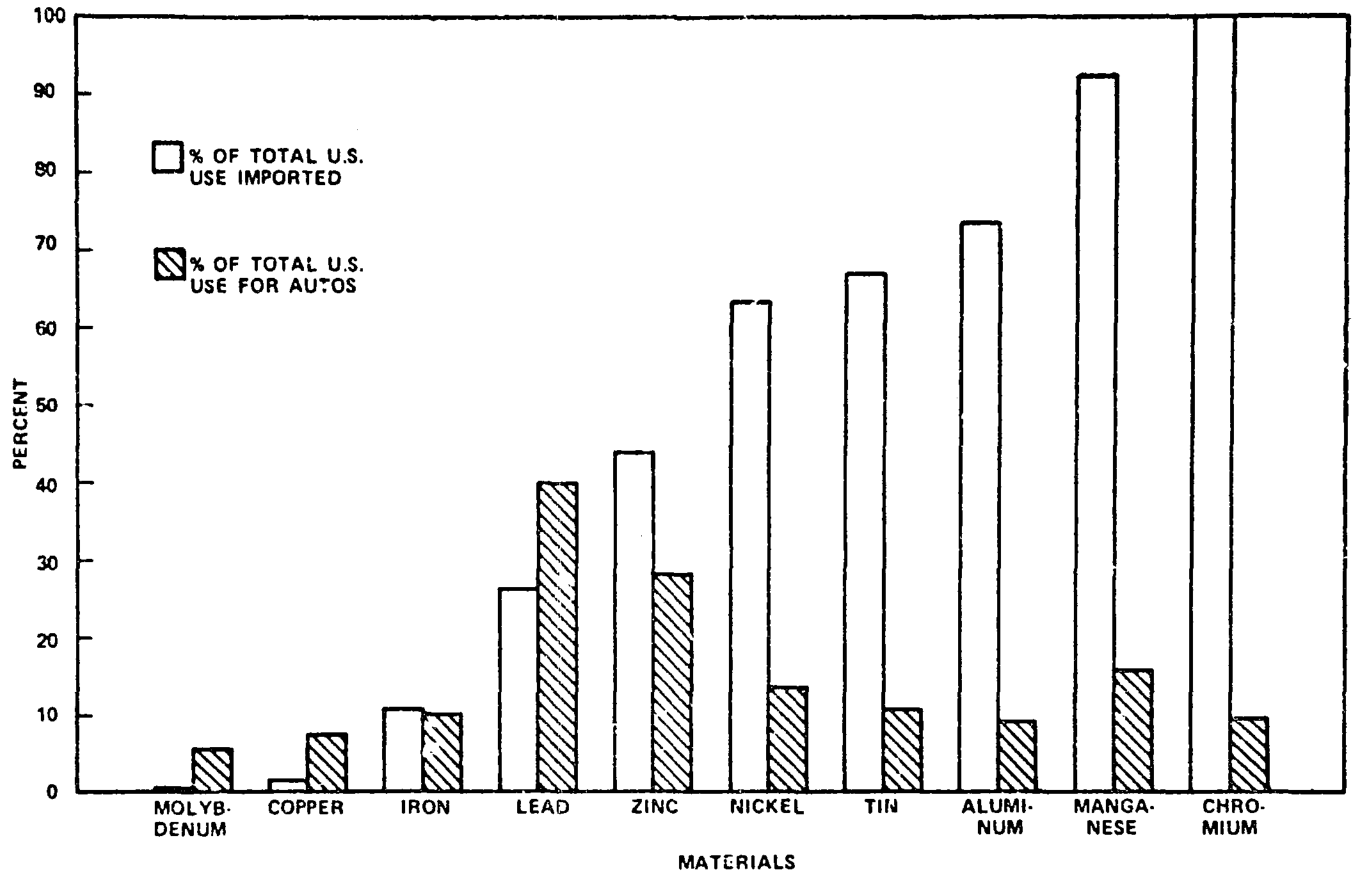


Fig. 11 Natural Resources - Auto Use and Imports (1970)

lead, iron and zinc, could be reduced, there could probably be an immediate benefit from reduced imports.

F. Preliminary Conclusions, Directions and Criteria for New Programs

Integration of the above data and observations has lead to the following primary conclusions:

- Alternative fuels appear required to achieve "Project Independence".
- Major improvements in conventional and alternative propulsion systems will:
  - a) extend depletion time of domestic oil reserves
  - b) reduce the magnitude of the import peak
  - c) accelerate achievement of Project Independence
- Future energy sources, such as solar and nuclear, will require different propulsion systems than will petroleum and its substitutes.
- Major national programs are required to achieve impact.

Some of the secondary conclusions are:

- Small early improvements may have far more impact on the major issues in the long run than big improvements that take a long time to achieve.
- The trend to small cars must be encouraged, with the objective for even smaller utilitarian design in the future.
- Future automobiles must be considered as part of the "Transportation System" to optimize impact on the issues. Strategy and auto design have to get together.
- Efforts to improve energy or resource conservation by increasing vehicle useful life must be planned carefully. The inertia of the system increases with vehicle life and introduction time for changes.

Based on these conclusions, three broad areas have been selected for program direction; specific projects are being selected in each area; feedback from this meeting will weigh heavily in the selection of projects:

- Improved Energy Conversion System Development
- Alternative Fuel and Fuel Systems Development
- Advanced Energy Systems Development

The primary criteria being used in selecting the projects are:

- Lead time to impact
- Impact potential
  - Energy
  - Fuel
  - Materials
  - Pollution
- Public acceptance
  - Safety
  - Performance
  - Cost
- Industry acceptance

It is anticipated that discussion and feedback from this meeting will assist in quantifying the above criteria. It is recognized that industry acceptance of any new technology developed by the Government is imperative. Without it, innovations will not be implemented and will not reach the market place; the impact on national issues will be zero.

Consequently, the proposed objective and specific goals for the new program are:

GOAL

IMPLEMENT A BALANCED PROGRAM IN AUTOMOTIVE GROUND TRANSPORTATION THAT PROVIDES TECHNOLOGY FOR INDUSTRY AND GOVERNMENT TO IMPACT ON NATIONAL ISSUES SUCH AS ENERGY, NATURAL RESOURCES, POLLUTION AND BALANCE OF PAYMENTS.

OBJECTIVES

- CONSERVATION OF ENERGY

  - CONVENTIONAL FUEL

    DEMONSTRATE AND EVALUATE IN A VEHICLE AN AUTOMOTIVE PROPULSION SYSTEM TO DOUBLE THE FUEL ECONOMY OF CURRENT (1974) AUTOMOBILES WHILE MEETING 1977 EMISSION STANDARDS.

  - UNCONVENTIONAL FUEL

    DEMONSTRATE AND EVALUATE IN A VEHICLE AN ADVANCED AUTOMOTIVE PROPULSION SYSTEM WHICH IS CONSTRUCTED OF NONCRITICAL MATERIALS AND WHICH OPERATES ON PLENTIFUL NONPETROLEUM FUELS WHILE MEETING 1977 EMISSION STANDARDS.

- CONSERVATION OF NATURAL RESOURCES

  - MATERIALS

    DEMONSTRATE AND EVALUATE IN A VEHICLE AN ADVANCED AUTOMOTIVE POWER SYSTEM USING NONCRITICAL MATERIALS, INCLUDING NONMETALLIC MATERIALS, WHICH WILL MEET 1977 EMISSION STANDARDS AND HAVE HIGH FUEL ECONOMY.

  - MATERIALS AND ENERGY

    DEMONSTRATE AND EVALUATE IN A VEHICLE AN ADVANCED AUTOMOTIVE POWER SYSTEM WHOSE LIFE AND DURABILITY ARE DOUBLE THAT OF PRESENT SYSTEMS WHILE MEETING FUEL ECONOMY AND EMISSION STANDARDS.

Questions and Comments

Question (Mr. Scully, U.S. Army Tank Automotive Command): It is understood that if hydrogen were economically available, present technology engines and machines could be used with little modification and no sacrifice in emission performance or life style. What progress is being made toward this possible solution to the fuel problem?

Answer: No practical approach to the key problem of on-board storage of hydrogen has been identified. If this, and economical production problems can be solved, hydrogen may become a promising alternative fuel.

A recent Request For Proposal to a large sector of the technical community, soliciting new approaches to the problem, had disappointing results. Three small programs on storing hydrogen in other forms are being considered. No practical cryogenic system was suggested. Another RFP is expected to be issued in about 6 months.

Projections in the ESSO, Alternative Fuel Study (See Section V-C) indicate that hydrogen will not be available in quantities sufficient to supply any significant percentage of the requirements until after the year 2000.

Comment (Walter Stewart, Los Alamos Scientific Laboratory): Los Alamos has under development a liquid hydrogen storage and re-fueling system for automotive applications.

Question (Dr. Brown, University of Rhode Island): In trying to develop a program for a new Diesel engine, with some half dozen agencies, it was apparent that no one group or agency is coordinating automotive propulsion research and development at the national level. Is this situation being corrected? Also, the current AAPS Program seems primarily concerned with demonstration and evaluation of concepts which are nominally within five years of engineering or production prototypes. This does not seem to allow for the growth and development of newer, more advanced concepts which often require more than five years of research and development.

Answer: The confusion in coordinating Government automotive research and development is recognized, both in and outside the Government, particularly since the Office of Science and Technology was dropped. It is anticipated that the new Energy Research and Development Agency will be the vehicle which will correct this situation. It should also be recognized that the AAPS program constitutes a new situation for the Government. Heretofore, development of consumer oriented hardware was left entirely to industry. But, as pointed out earlier, the automobile has a broad impact on our economy, environment, and resources justifying limited activity on critical problems. Consequently, the AAPS program has evolved with the care and caution which a new situation in Government activity warrants. As the needs and requirements of the Nation are more clearly defined, it is expected that a longer term, better funded program will emerge.

Answer: A representative from DOT pointed out that R&D in the automotive area is coordinated once a year. Agencies are kept informed of each others activities. Each Agency submits a budget to the Office of Management and Budget. Congress decides what is to be done. Past policy has left near term R&D in this area to industry; whereas, long term effort has been supported by the Government.

Question (Mr. Huber, Consultant): In considering the automotive issues over the years; i.e., cost (1900-1965), emissions (1965), energy (1974), and natural resources (anticipated in 1975), no mention was made of the initial issue which started the whole sequence--the desire for a personal transportation system. Now, since the more widely dispersed urban population centers are heavily dependent on frequently available autos and trucks, contemplated changes in propulsion systems must take into consideration the effect on the ability of the car to meet present socio-economic needs for basic transportation. For example, the near term electric car will not have the cruising radius, it will have poorer performance, and it may use more, not less, resources since a lot of lead is required in lead-acid batteries. And now, two cars are needed to meet all demands whereas, heretofore, one was adequate. So, the electric car for emissions might not be a real cure when the other issues are considered. Are these basic transportation requirements being considered?

Answer: Because of low cost, wide availability of the automobile, many segments of our earlier transportation system in major cities such as streetcars, trains, and busses have deteriorated or stopped. Industry and population centers have dispersed. As a result of current issues, the transportation system is even now in the process of being reconstructed to meet the needs of the people. A big problem has evolved; significant action and changes are required to solve the problem.

The Department of Transportation has been addressing this problem. The annual budget went from 2 million dollars this year to 6 million dollars for the next fiscal year. This effort is directed to discerning the facts, evaluating approaches and understanding the needs, secondary costs and ramifications of various potential solutions. It is to provide information on which to base policy.

Question (R. W. Hurn, Bureau of Mines): It was mentioned that any relaxation of emission standards would constitute a loss of progress. It is suggested that required emission levels be considered from the technical viewpoint of the trade-offs involved with the cost of energy and environmental control.

In considering hydrogen as a future fuel, it was pointed out that all of the current alternative fuels are hydrogen deficient unless they are to be used as solid fuels. A very big problem is where will enough hydrogen be found to convert the solid fuels?

Answer: The National Academy of Science is examining the trade-offs between emission levels and energy cost; they will be making recommendations to Congress probably this summer. It is expected that these recommendations will reflect the results of these studies and may or may not be the same as present legislated standards.

Question (Dr. W. Hryniszak, Clarke Chapman): Regarding Fig. 3, what is the basis of assuming a factor of 5 for increased recoverable oil reserves? It sounds high compared to the 2 or 3 which has been mentioned in England.

Answer: The intent of the chart in Fig. 3 is to determine, qualitatively, the relative impact of an early versus a late entry of our advanced transportation system on the depletion of recoverable world oil reserves. So a more accurate basis, other than that used by Meadows, for estimating new discoveries was not warranted. The values used were 40 billion barrels of crude--present reserves--times 5 for future discovery gives 200 billion barrels. It was assumed that 30 percent of this would be used for surface transportation.

Question (Don Lapedes, Aerospace Corporation): The lead time from concept to mass production in the automotive industry can be 15 to 20 years, so impact or effect of current research on new concepts is necessarily far off. What are the prospects for reducing this lead time, so that needed effect or impact can be realized sooner?

Answer: The most likely place to reduce lead time is in the R&D phases to reduce the time required to reach the production engineering stage. Parallel effort on several candidate approaches and concepts can compress the time required for the R&D phases, but it must be accepted that a much larger Government/Industry investment will be required to bring this about. Current and past efforts have been more of the series type because of the limited money available for R&D.

Question (John Stone, Mitre Corporation): One approach to conservation of energy and resources is to reduce the demand for individual transportation systems. Is the Government investigating such plausible substitutes as telecommunications?

Answer (Bob Husted, DOT): Such factors as telecommunications, aimed at reducing the vehicle miles traveled, have been studied and are being planned for future programs.

Question (Carl Bachle, Consultant): What is the total amount of money being spent by the Government on R&D in this area; how much should be spent?

Answer: In FY '74 about 20 million dollars were budgeted; in FY '75 about 32 million dollars are budgeted. This includes in-house salaries, paper studies, hardware, etc. being spent in AEC, NSF, EPA, DOD, DOT and NASA. This indicates how splintered the effort is. The amount which should be spent will depend on the top level leadership in assessing the gravity of the energy crisis and establishing the specific goals to be reached. With established goals, requirements can be identified and costs estimated.

Question (Carl Bachle, Consultant): With the apparent need for short term improvement in fuel economy, why is so little effort and emphasis being given to the Diesel engine?

Answer: Considerable attention is being given to the Diesel engine; however, due to planning and procurement lead time in the Government, very little about this effort has been released as yet.

Question (Dr. J. E. Davoud, D-Cycle Power Systems): Has serious consideration been given to chemicals which can be produced from crops (such as methanol, ethanol, acetone, etc.) as alternative fuels?

Answer: Two contractors are studying all of the alternative fuels available from domestic sources. Methanol derived from coal is a leading contender. These programs are reviewed and discussed in Section V-B and C.

Comment (Commander E. Tyrrel, Department of Trade and Industry - London): Many people in England believe that the advantages of liquid hydrocarbons as a fuel for transportation vehicles are so great as compared to other uses that in the short term perhaps they should be conserved and used only for that purpose.

Answer: There seems to be general agreement in the U.S. that liquid hydrocarbons will be used in automobiles at least through the end of this century. Pressure will be on stationary power systems to use substitute fuels.

Question: What are the AAPS funding plans for the automotive R&D, particularly regarding increased effort?

Answer: The AAPS Division budget started FY '74 at 7 million dollars. During the year, it was increased to 12 million dollars. The budget submitted for FY '75 is 17 million dollars. It is not known how this will change during the next year (FY-75). Current plans call for approximately 6 million dollars for the continuation of the current gas turbine and Rankine engine programs; 11 million dollars will be devoted to the other aspects of the AAPS effort including: use of alternate fuels, electric propulsion system studies, investigations of new concepts and in-house overhead.

Comment (Paul Vickers, General Motors Research): Some of the solutions to the energy crisis might ultimately limit the individual's freedom of mobility. Care should be taken to make sure realistic emission standards are set in view of all of the surrounding priorities and circumstances.

Comment (Ernest Petrick, U.S. Army Tank Automotive Command): Concerning the proposed goals above, it is imperative that the specific duty cycle of the vehicle be specified along with the method and instrumentation for measuring the fuel economy. On this basis, numerical values for fuel economy of current (1974) automobiles should be established and the numerical goals set for future vehicles to achieve within a specified time frame.

It is suggested that the non-critical materials element be eliminated from the "unconventional fuel" goal; it is really part of the "conservation of natural resources" goal.

It seems that a basic decision should be made as to whether to develop the fuel to satisfy the current engine/vehicle requirements, or to develop the engine to satisfy the fuel requirements.

Questions (Dr. Sternlicht, M.T.I.): Because the American economy is definitely tied to the automobile as well as housing and other items, because the national issues identified are major, and because potential pay-off of the AAPS program is very big, the following three questions are important to the future development of the AAPS program:

- How does the AAPS Program get a balanced share of Government attention, so that it gets commensurate funding and priority?
- How do you motivate people in the technical community to participate and contribute to the program?
- How is the time reduced which is required to transfer the technology to the industry at large, and into meaningful production activity; i.e., early achievement of Project Independence, higher living standards, and increased automotive exports?

Answer: Strong industrial support and endorsement of the AAPS program through their representatives in Washington would be very helpful in getting a balanced share of attention and an appropriate priority level established.

It seems that the technical community is getting motivated; perhaps the problem is how to accelerate the motivation.

The AAPS Coordination Meeting is one means of disseminating information and getting direct response from knowledgeable people in the industry.

Comment (A. F. Underwood, Consultant): At the recent SAE Meeting in Los Angeles, three standard vehicles were operating which provided 30-40 mpg with "Standard" car performance. These cars, with a form of Diesel engine, are in production not in the U.S.; 70-100 mpg are projected. (No other information was available.)

Stratified charge engines and Stirling engines have the same potential fuel economy with low emissions and should be getting AAPS attention in the 1980's.

Question: In typical free enterprise systems, the communication link and lead time between the consumer in the market place and the provider (industry) is generally short and relatively direct. Lead time for feedback is of the order of one year. In a situation such as the energy crisis where lead times are longer - 10 years or more - and there is broad impact on the public, wherein lies the responsibility for alerting and informing the public, so that industry can get appropriate feedback in time to pursue the needed product development? Is this a Government responsibility of should industry handle it?

Answer: No answer presently exists.

II. SUMMARY OF CURRENT STATUS, PLANS, AND ACCOMPLISHMENTS ON AAPS PROGRAMS, BY GEORGE M. THUR, CHIEF, POWER SYSTEMS DEVELOPMENT BRANCH

AAPS Division activities have encompassed the following avenues of approach to alternate power systems:

- Gas Turbine Engines
- Rankine Cycle Engines
- Stratified Charge Engines (Further engineering development now completely under Army support)
- Diesel Engines (Supplemental budget increase during FY '74 now permits support of needed programs on Diesel engines. These are being implemented.)
- Rotary Otto Cycle Engines
- Stirling Cycle Engines
- Hybrid Engines (Heat Engine/Battery; Heat Engine/Flywheel)
- Electric Vehicles
- Alternative Fuels
- Improvements in Conventional Systems

To date, emphasis has been on the gas turbine and Rankine engines. Work is in its early stages on alternative fuels and electrics. These are discussed in more detail below along with a summary of the general AAPS status and accomplishments.

A. Gas Turbines

The gas turbine programs are structured to focus on the prime problem areas associated with gas turbines:

- Emissions - high NOx particularly
- High manufacturing cost
- Low part-load fuel economy

The original Brayton Power Systems Development Team is shown in Fig. 12. Under an inter-agency agreement, NASA (Lewis Research Center) has been testing and characterizing Chrysler's Baseline Engine since September 1973. Current attention is focused on identification of all of the various losses, particularly heat loss. This information constitutes important input and guidance for design of the next generation engine. Of the eight different combustor technology contractors, the Solar approach was selected for adaptation to the Baseline Engine. Work continues on recuperators and regenerators. A program is being implemented with Ford Motor Company to concentrate on the known problems of the ceramic regenerator. Pratt & Whitney has recently achieved very promising results on the low cost turbine wheel manufacturing program. There were a number of studies (reported at previous meetings) on cost and economics. Work continues on the major gas turbine program at Chrysler on component and system improvements as well as the gas turbine upgrading program.

Since the last AAPS Coordination Meeting, an important decision was made to redirect the program from an intermediate size automobile to a compact car. This has involved major changes and modification of the effort at both Chrysler and NASA. Preliminary design has been started on an upgraded engine for compact car requirements.

In-house effort at EPA has concentrated on vehicle tests including emission and particulate measurements and evaluation of test procedures. The objective is to use the technology evolving from the Baseline Engine Program and the advanced technology programs, and to demonstrate a gas turbine vehicle with good fuel economy and low emissions in calendar year 1976.

NASA is also looking at the technology for applications beyond 1976 including such items as ceramics, gas bearings, advanced aerodynamic designs and cooling concepts. With these elements, it may be possible to have a 20 mpg gas turbine vehicle on the road within 10 years.

B. Rankine Engines

The Rankine Program has concentrated on the following problem areas:

- Emissions (problem now considered under control)
- Condenser size and weight

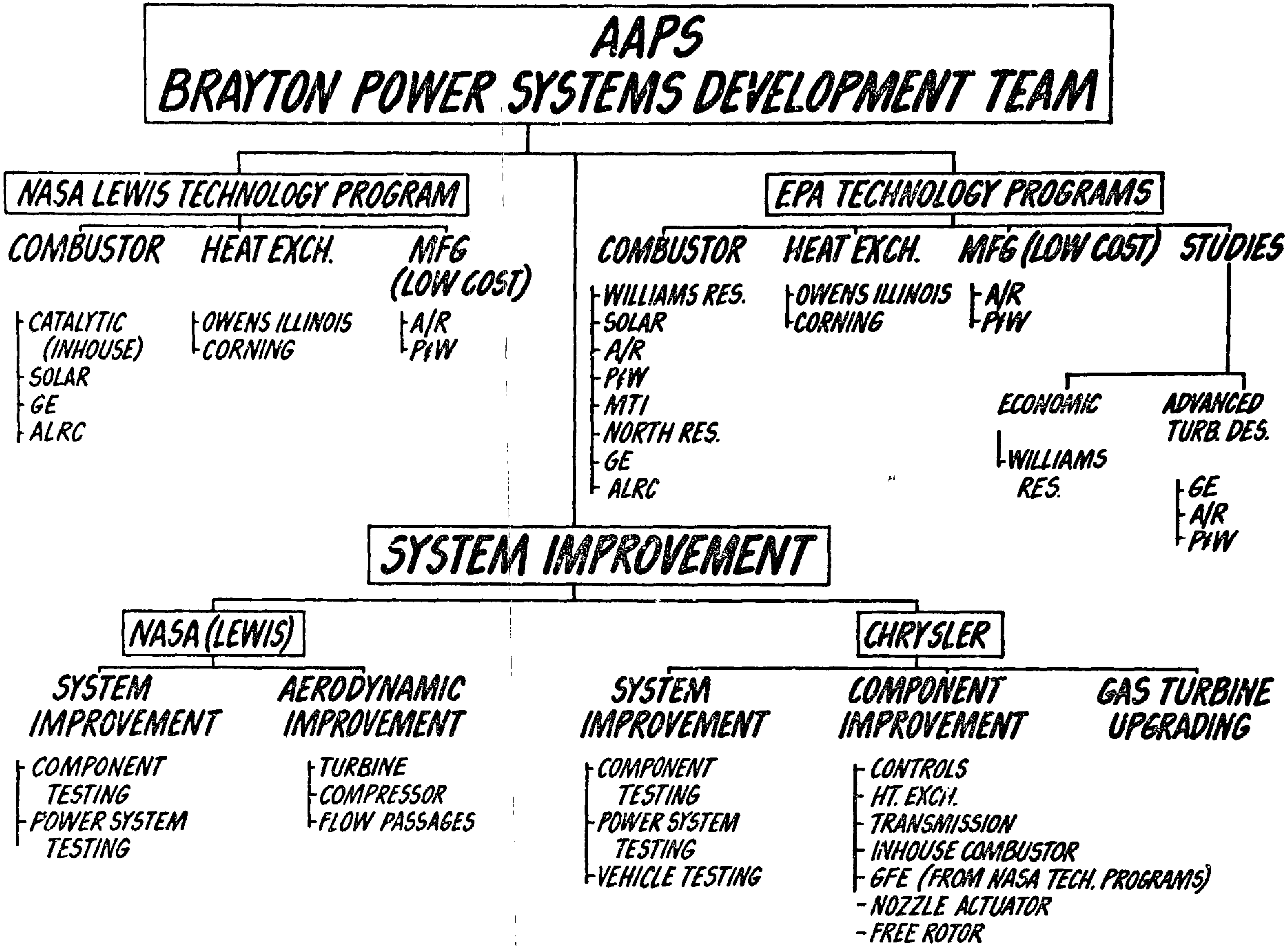


Fig. 12 AAPS Brayton Power Systems Development Team

- Control complexity
- Freezing (when using water as the working fluid)
- Thermal degradation problem (when using organic fluids)
- Lubrication problem of reciprocating systems
- Valve design problems of reciprocating systems
- Boiler size and weight

Initially, technology programs and four different engine developments were pursued: reciprocating organic and steam systems; and rotary (turbine) organic and steam systems. The reciprocating steam engine of Scientific Energy Systems, Inc. was selected at the end of 1973 for further development through the prototype stage; the Thermo Electron organic reciprocating engine is continuing at a reduced level of effort as a back-up system.

The implications of switching to a compact car with the SES engine are being assessed. This means that the demonstration in a car originally scheduled for late 1975 will have to be re-scheduled in 1976.

C. Alternative Fuels Program

The objective of the Alternative Fuels Program is to evaluate the impact of using other fuels in automotiles and trucks on the national economy, environment and resources. These fuels include: methanol, gasoline and distillates from coal, shale and hydrogen. Research is being conducted on these fuels to characterize their use in current and projected automotive engines.

The present feasibility studies on the above fuels are to be completed in July 1974. The impact study is to begin in July 1974. Combustion research on methanol, gasoline and distillates was started in May 1974; research programs on hydrogen storage in metal hydrides and chemical carriers are in progress.

D. Electric Vehicles

The objective is to evaluate the potential impact of electric cars on the nation's economy, environment, and natural resources. Applicable critical technology is to be developed. The impact study for Los Angeles is to be completed in November 1974. Studies for Philadelphia and St. Louis are to begin in July 1974.

E. Overall AAPS Status and Accomplishments

The 12 million dollar AAPS Division budget for FY 1974 is broken down according to the type of effort and purpose of the effort in Fig. 13. This and the preceeding effort since inception of the AAPS program in 1970 have resulted in a number of accomplishments:

Management Accomplishments

- Established working relationship with automotive industry
- Principal Government group conducting automotive R&D
- Established and maintained technology transfer process
- Identified need for new transportation criteria
- Involved other governmental agencies
- Developed understanding of automotive engineering practices
- In 1972 established action plan to impact national need

Technical Accomplishments - Gas Turbine

- Achieved 1977 emission levels under steady-state conditions
- Completed 3500 hours durability test
- Developed unconventional combustion concepts

Technical Accomplishments - Rankine

- Bettered 1977 emission standards by 50%
- Achieved peak steady-state fuel economy of 16 mpg on preprototype system
- Packaging feasibility demonstrated without vehicle modification
- Component sizes and weights reduced
- Characterization of organic fluids and lubricants
- Generation of computer system design tools
- Developed unconventional combustion concepts

Technology Spin-Off - Gas Turbine

Much of the technology developed for the AAPS program has promise for commercial use in other sectors of the economy as follows:

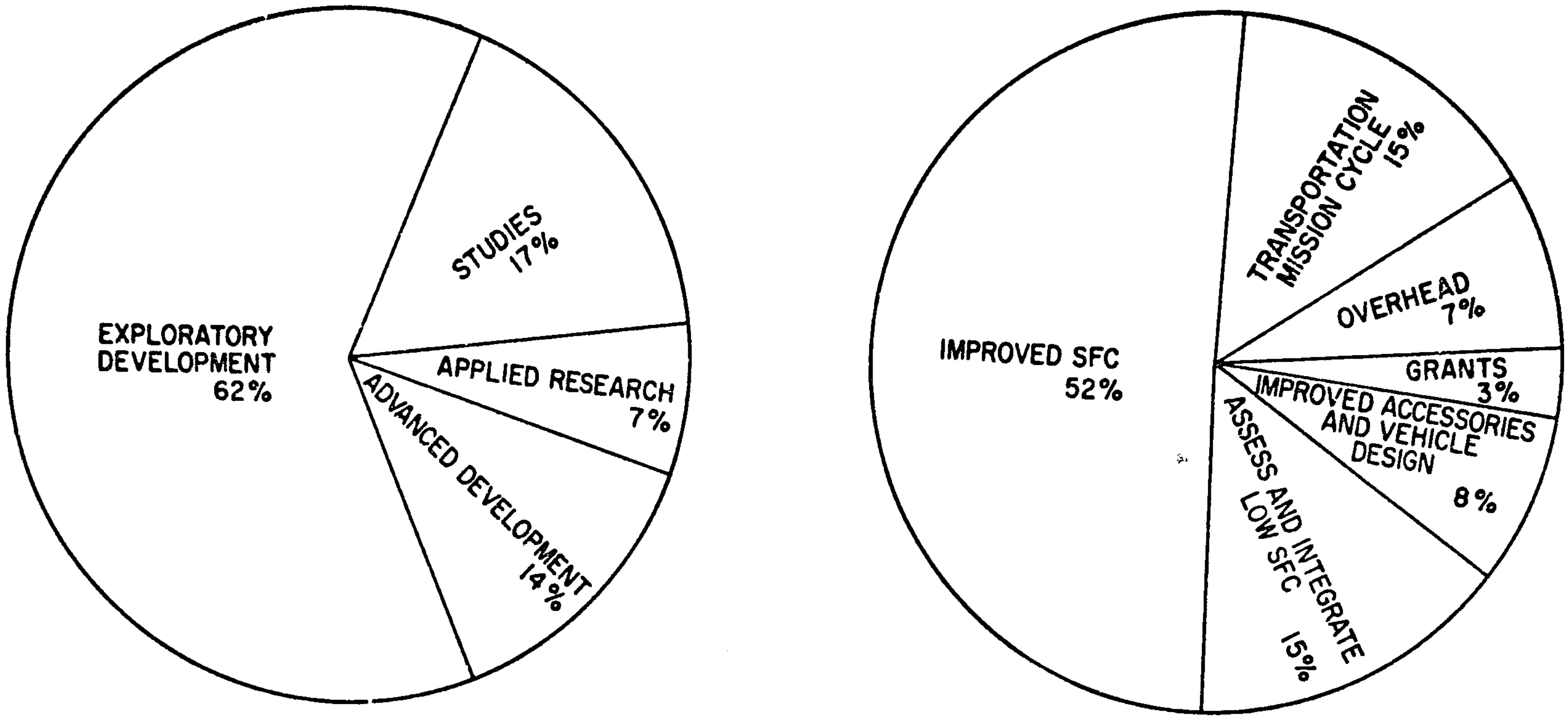


Fig. 13 FY '74 Budget - $12,000,000

• Low Emission Combustor	—	Land Gas Turbines, Aircraft, Total Energy Systems
• Ceramic Heat Exchangers	—	Exhaust Heat Recovery for Heating Units, Power Systems
• Improved Manufacturing Process for Turbine Wheels	—	Low Cost Turbine Wheels for Turbo Charging Units, Aircraft and Land Gas Turbine Units

<u>Technology Spin-Off - Rankine</u>

• Organic Rankine	—	Indoor Personnel Carriers
	—	Bottoming Cycle for Ship and Stationary Powerplants
• High Temp Lubricant	—	Special Purpose Engines
• Efficient - High Pressure Water Pumps	—	Quick Auto Wash Industry
	—	Home Water Heating Systems
• Low Emissions Burner and Compact Boiler	—	Home Furnace (Stationary and Mobile)
	—	Water Heaters
	—	Total Energy Systems
• Improved Heat Exchanger Surfaces	—	Air Conditioning and Refrigeration
	—	Auto Radiators

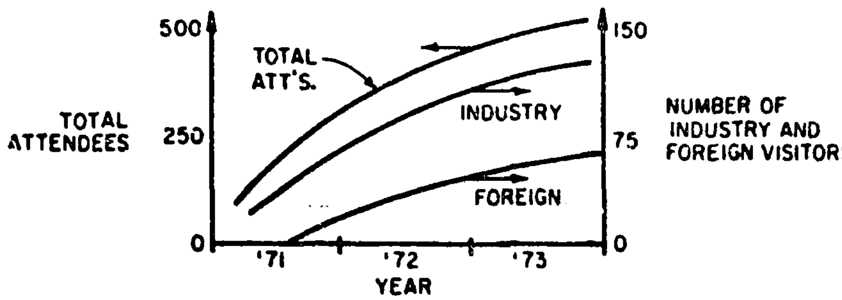
<u>Technology Transfer</u>

Communication and transfer of the technology developed on the AAPS program is being accomplished through the following media·

- Interaction through Government contracts and Government agencies
  - 37 Contracts issued
  - 3 Government interagency agreements (NASA, DOD, DOT)
- Technical Reports
  - Over 60 technical reports issued

• Meetings

— Seven AAPS coordination meetings to date (every 4-5 months)



— Status Review Meetings

— GM - 2 meetings/year

— Ford - 4 meetings/year

— Chrysler - 2 meetings/year

Questions and Comments

Question (Dr. D. Walzer, Volkswagen): What horsepower range is being considered for the gas turbine in the compact car in 1976-1979?

Answer: The present Chrysler program is considering 100 hp unaugmented and 122 hp augmented. No projections have been made for 1979.

III. GAS TURBINE ENGINE PROGRAM

A. Baseline Engine Project by C. E. Wagner, T. D. Nogle, R. C. Pampreen, and J. I. Gumaer, Chrysler Corp.

Objective and Overall Status: The basic program objective is to show that the gas turbine is a credible alternate automotive powerplant. Using Chrysler's sixth generation engine as a state-of-the-art baseline engine, improvement programs are being conducted as a basis for designing, building and demonstrating an upgraded state-of-the-art engine.

Specifically, the final program goal is to demonstrate the Upgraded Engine powered vehicle which:

- Uses significantly less fuel than a comparably powered spark ignition reciprocating engine.
- Meets the original 1976 emission standards.
- Has the potential for being mass produced and marketed competitively.

Delivery to the program of 7 Baseline Engines and 3 Baseline Vehicles has been accomplished, baseline improvement efforts continue, and an Upgraded Engine design is underway (Fig. 14).

Baseline Vehicle Documentation: Performance measurements resulting from the installation of a 150 hp Baseline engine in a 1973 intermediate size sedan indicated an elapsed time for 0-60 mph on an 85°F day of about 12 seconds (Fig. 15). Peak fuel economy approaches 16 mpg (Fig. 16). Some noise measurements comparing the turbine to a standard S.I., reciprocating engine installation are as follows:

	Turbine	Reciprocating
Idle - Front (Fig. 17)	71 dB(A)	66 dB(A)
Idle - Rear	63 dB(A)	68 dB(A)
Interior - 30 mph (Fig. 18)	60 dB(A)	59 dB(A)
Interior - 60 mph	70 dB(A)	72 dB(A)

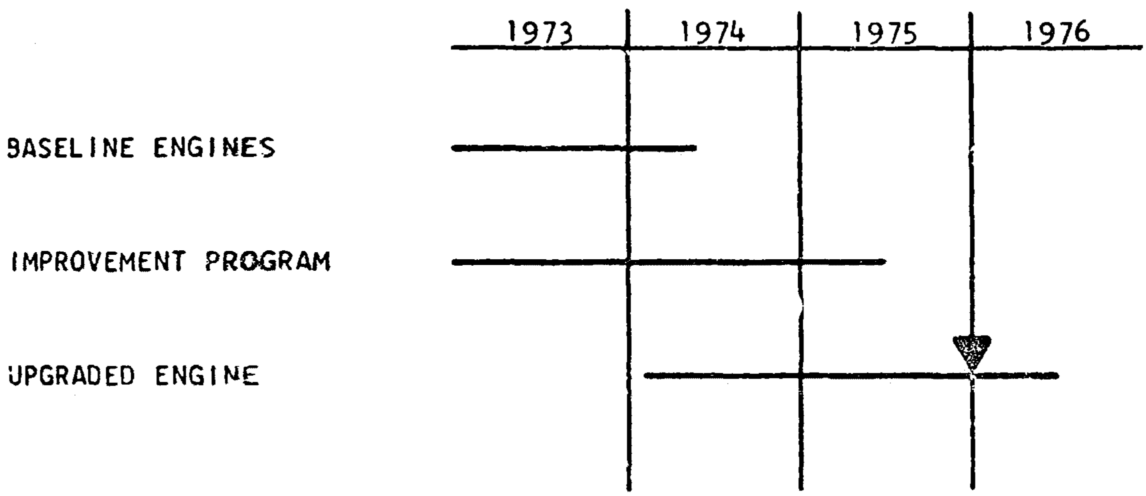


Fig. 14 Baseline Gas Turbine Development Program Timing

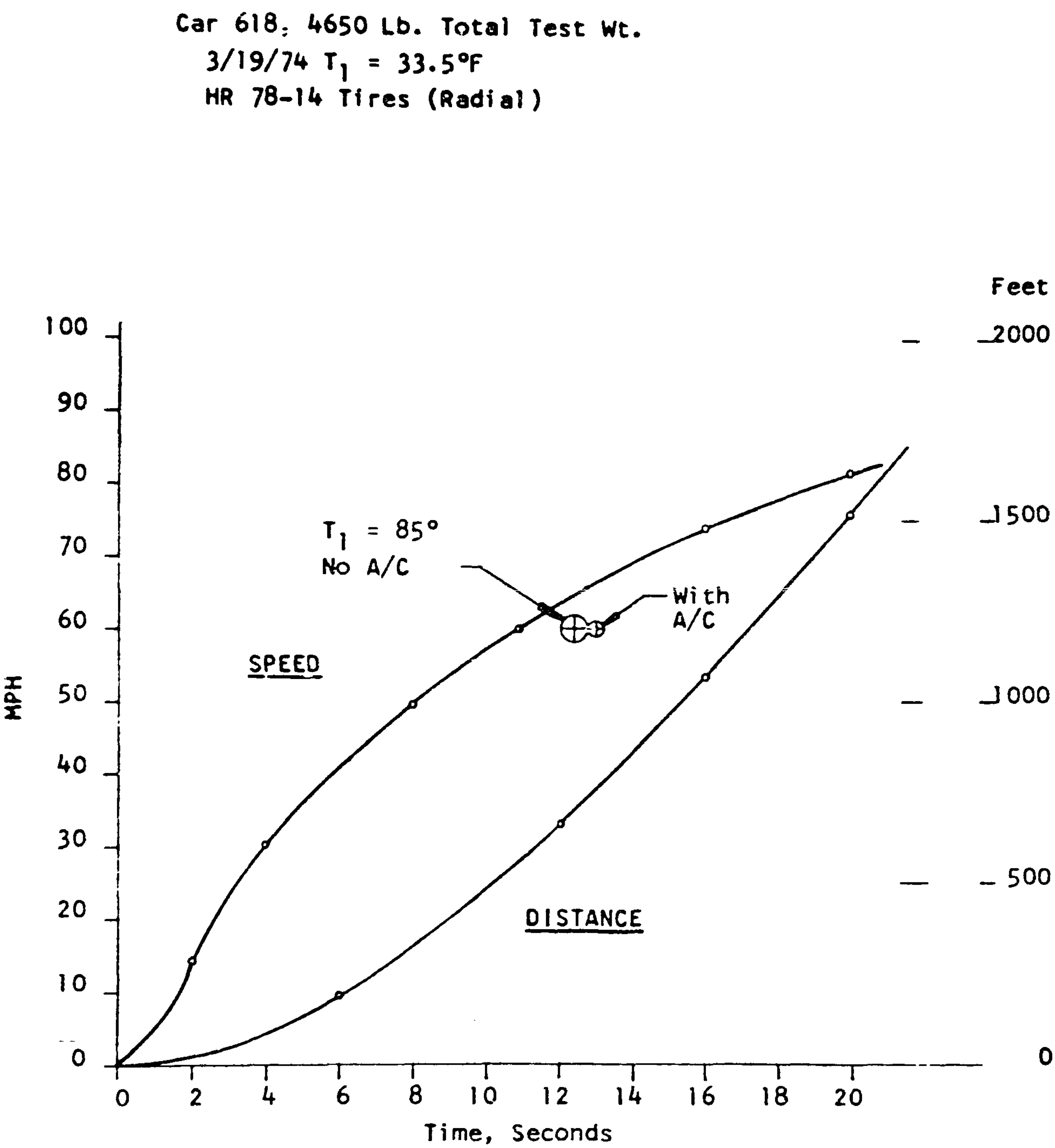


Fig. 15 Baseline Vehicle Performance Speed and Distance vs. Time

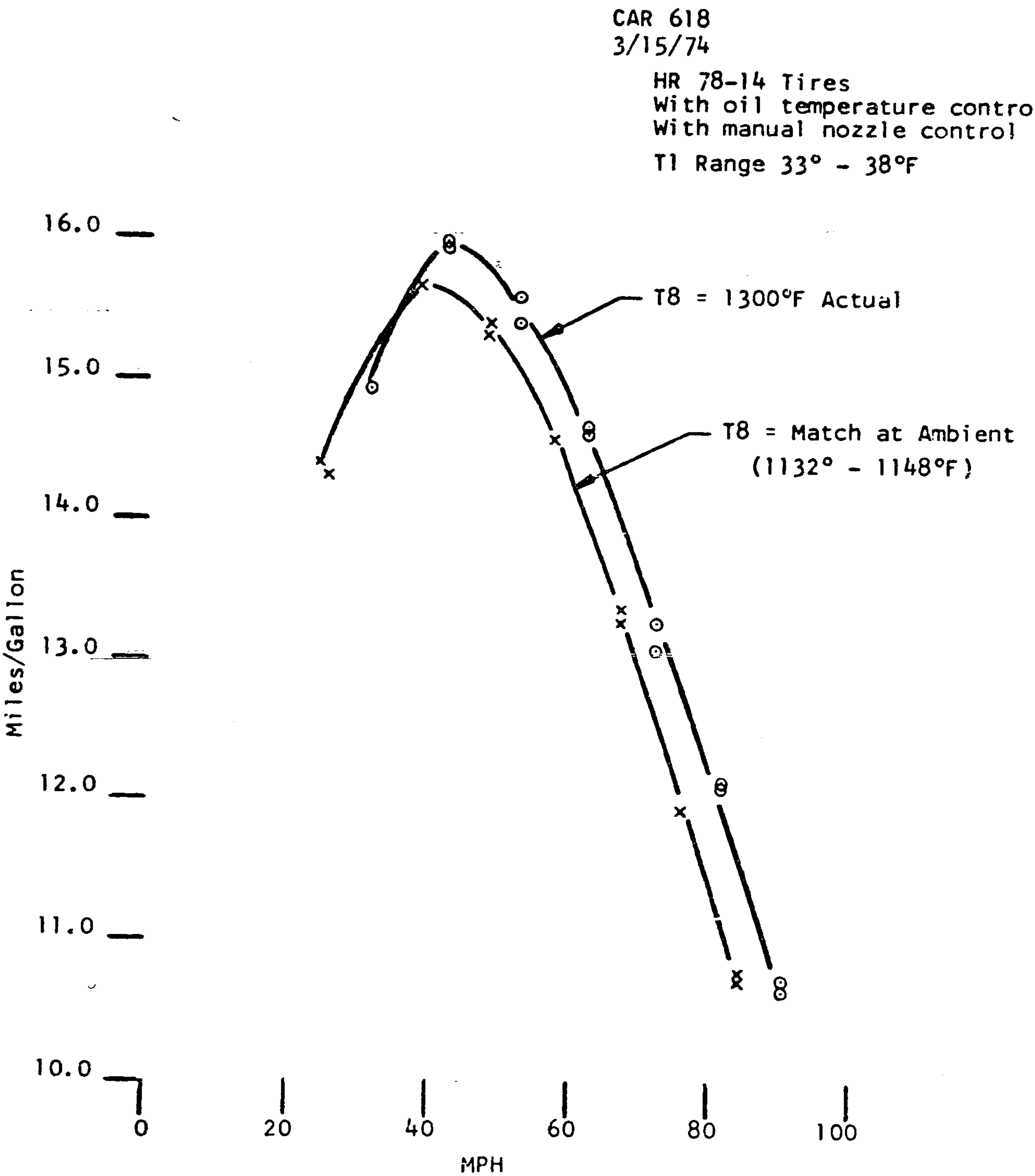


Fig. 16 Baseline Vehicle Fuel Economy — Effect of Match Temperature "At Ambient" on Fuel Economy (Economy vs. MPH)

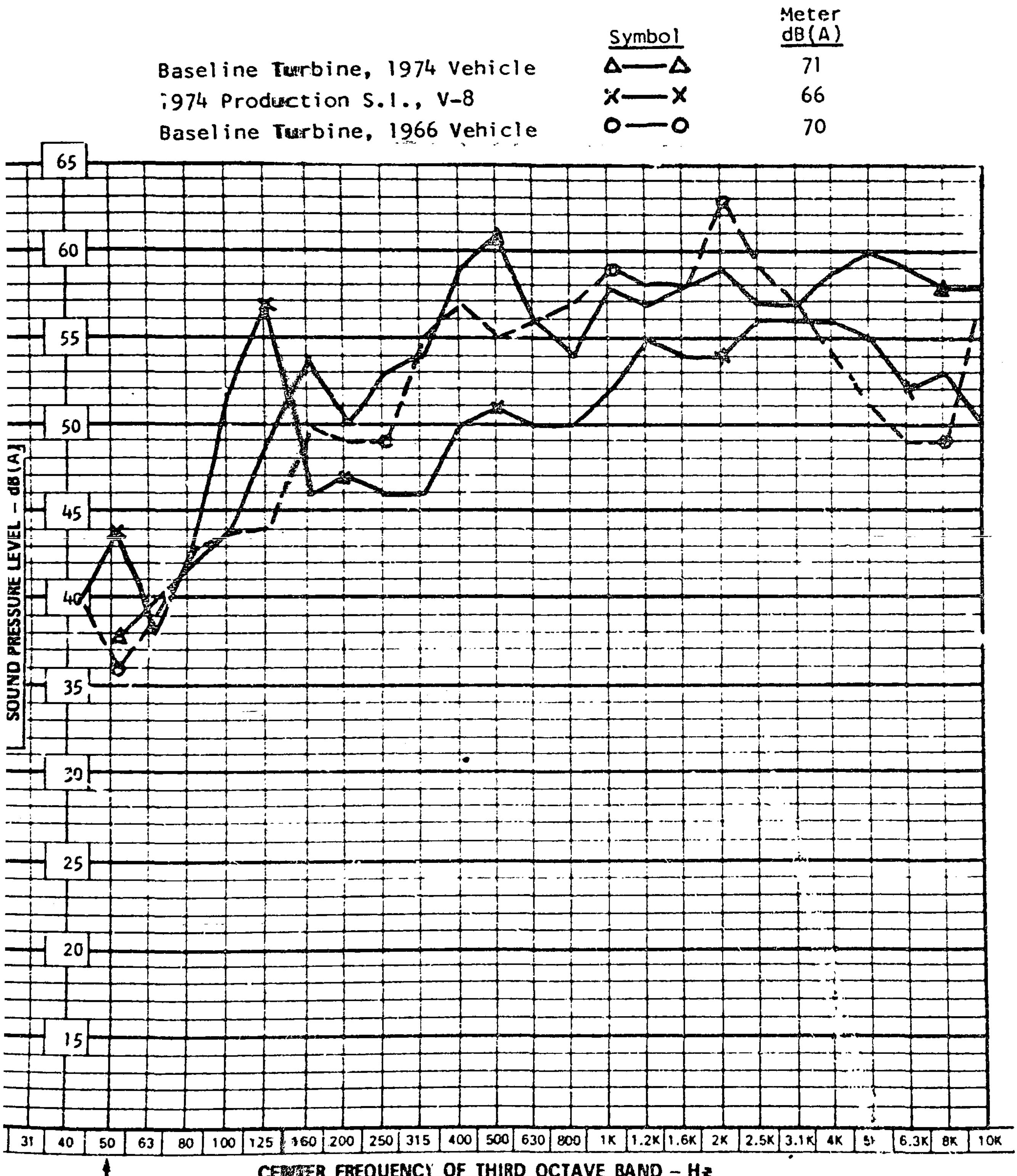


Fig. 17 Comparative Vehicle Noise Tests – Idle, Vehicle Front (3 Ft. Ahead, 5 Ft. Up)

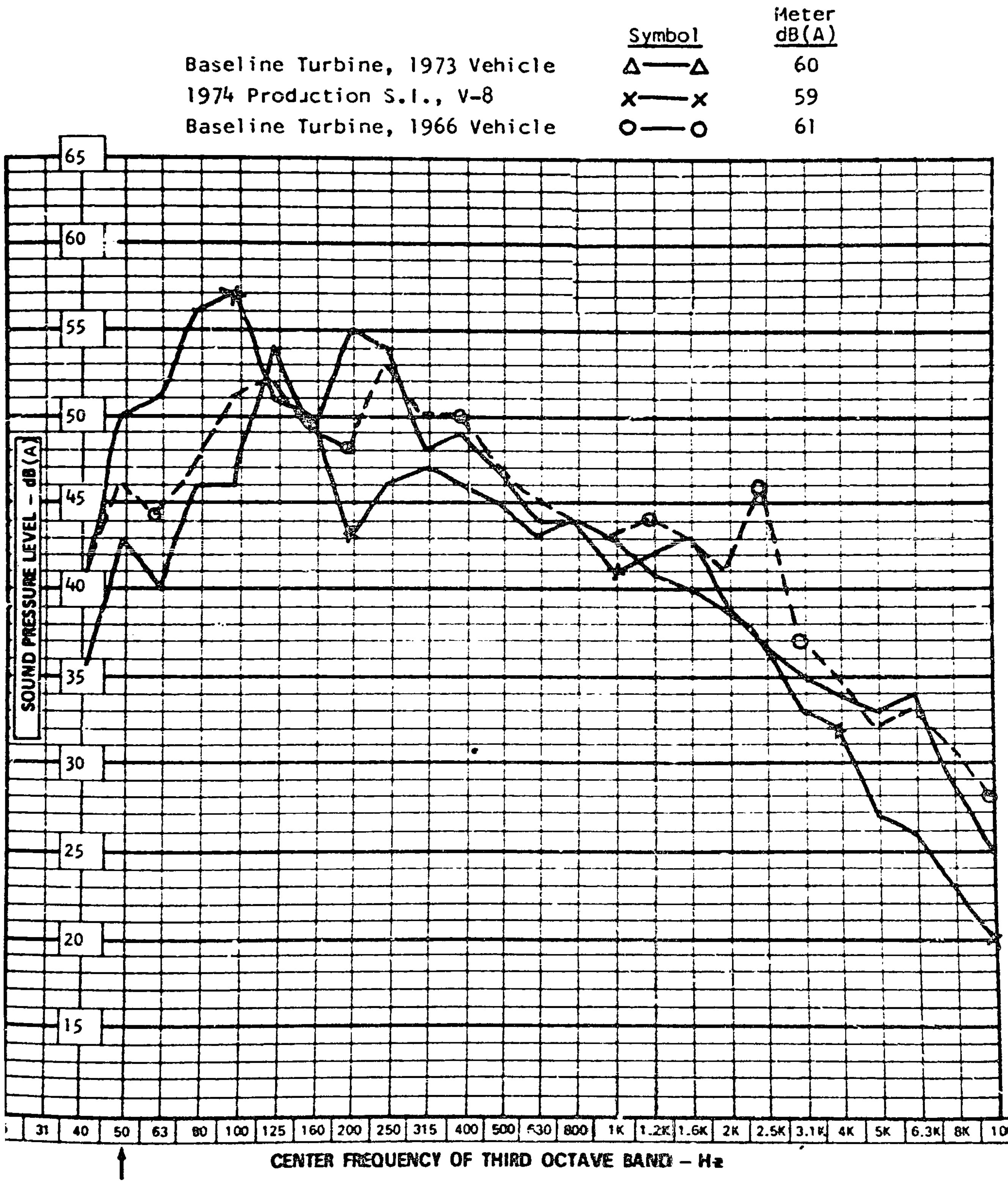


Fig. 18 Comparative Vehicle Noise Tests — 30 MPH, Driver's Right Ear

Engine Improvement - Burner/Emissions: Support of the Baseline Program has included providing necessary burner hardware for all engines and vehicles. General burner performance and durability are continually being upgraded, but current designs are generally satisfactory for the Program. Some Baseline Vehicle emissions are shown in Fig. 19.

Fixture and vehicle emission results for one Chrysler proprietary burner (FL15) are shown in Figs. 20, 21, and 22. This burner provides very good emissions when total engine systems are optimized as in Test 5 (Fig. 22). However, complete development of this burner is not being pursued as it does not show promise of meeting the long-range requirements of 0.4 gram/mile.

Results of a second proprietary burner are shown in Fig. 23 compared to Baseline and FL15 burners when operated over an engine dynamometer test cycle. Though by no means fully developed, this burner does show potential of meeting the 0.4 gram/mile NOx level if the transient spiking can be greatly reduced. Continued efforts on this burner and its control system will attempt to accomplish this.

An adaptor has been readied for evaluation of the Solar burner at Chrysler facilities (Fig. 24).

Engine Development - Ceramic Regenerator: This program consists of:

- Evaluating available state-of-the-art cores to determine performance life and cost potential in an automotive application.
- Developing a non-NiO rubbing seal.
- Arriving at a specification for the Upgraded Engine regenerator.

While an alternate seal material is being developed, NiO seals will be used. Extra processing precautions being taken by the supplier of NiO seals, however, have delayed delivery. Core evaluations to date have required use of graphite seals thereby limiting running to 1100-1200°F levels. The seal program is getting underway using four-head friction test units and a wear test unit (Fig. 25). Zirconium oxide is being evaluated initially as a possible alternative to nickel oxide.

Test No.	Test Type	Power Turbine Nozzle Cam	Corrected Grams/Mile		
			HC Hot FID	CO NDIR	NOx CI
7	Cold 1975	B	.742	8.70	1.52
8	Cold 1975	B	.540	9.51	1.80
9	Cold 1975	B	.546	9.05	2.09
16	Cold 1975	G	1.432	4.55	2.45
17	Cold 1975	G	1.500	3.91	2.61
18	Cold 1975	G	0.515	4.78	1.87
Original 1975 Standards, Goal			.41	3.4	3.1

Fig. 19 Selected Baseline Vehicle Emissions
Car 667 - Vehicle B

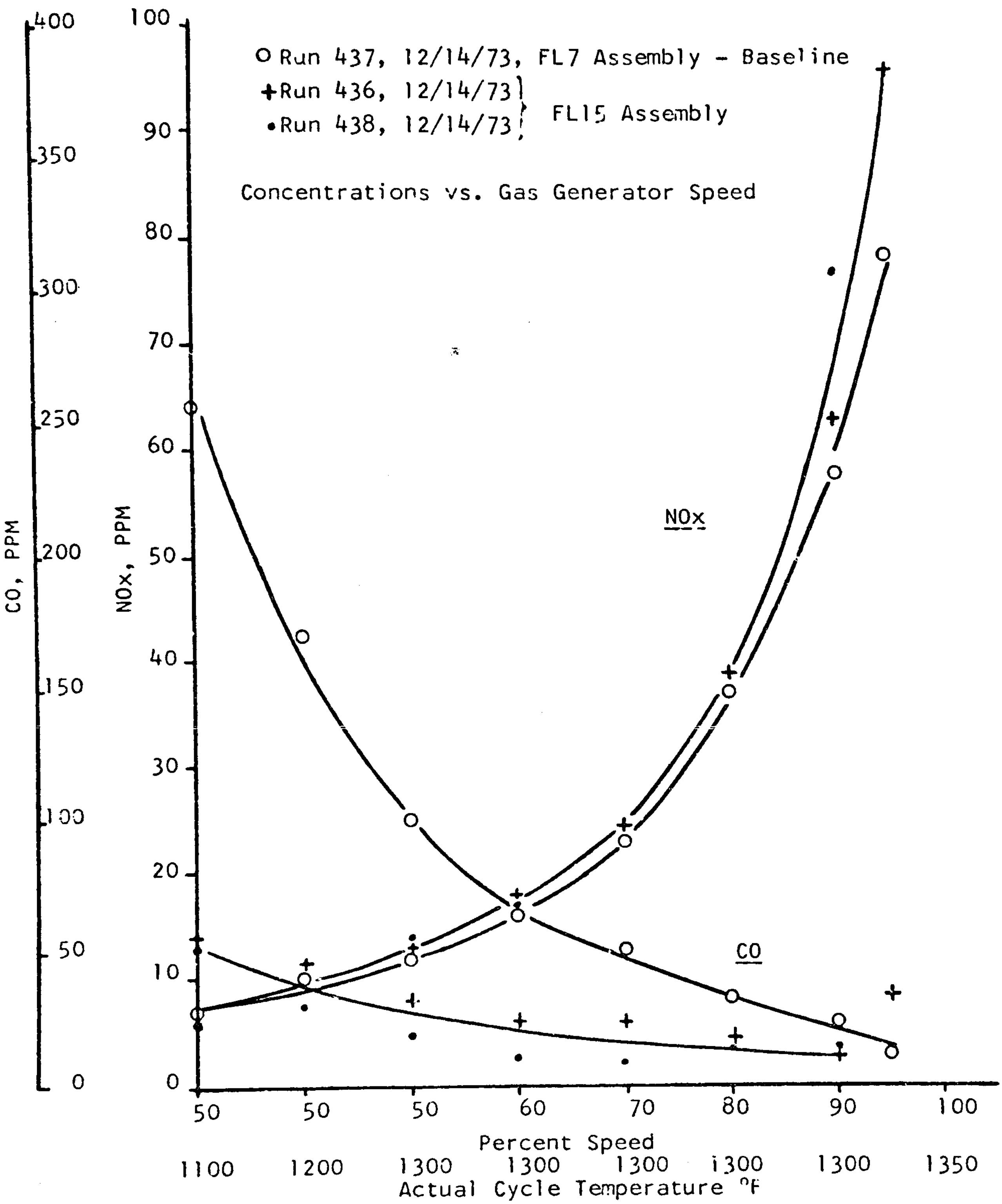


Fig. 20 Chrysler Burner Program - Steady State Emissions, A-Fixture

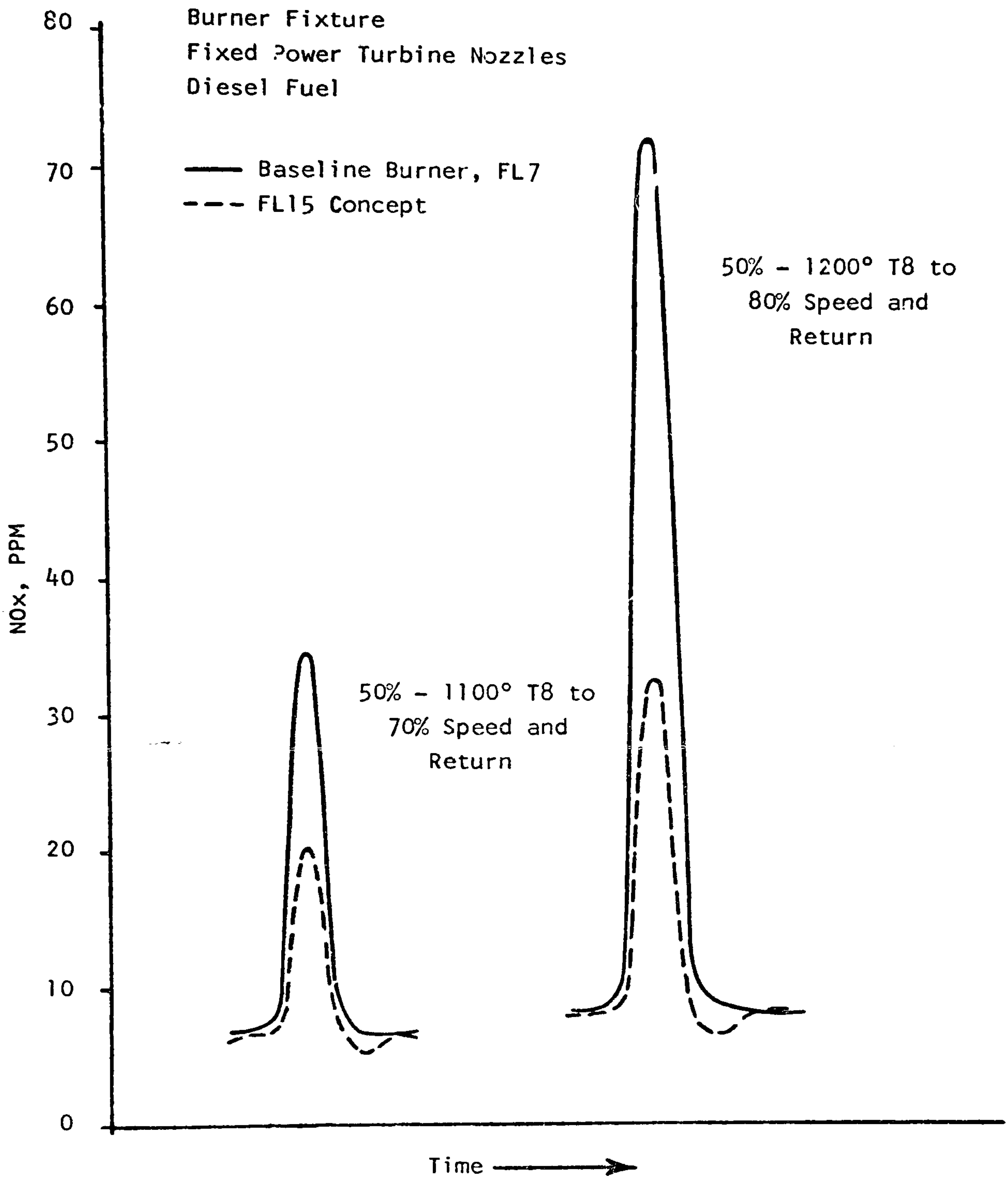


Fig. 21 Chrysler Burner Program Acceleration NO_x Formation

Test No.	Test Type	HC Control	Power Turbine Nozzle*	Blow-By Included	Corrected Grams/Mile HC Hot FID	CO NDIR	NOx CI
1A	Hot '72	Relight	M,B	No	1.52	1.55	2.69
1B	"	"	M,B	No	1.10	1.39	2.60
2	Cold '75	Continuous Flame	M,B	No	- .26	3.99	2.21
3A	Hot '72	"	M,B	No	- .16	3.68	2.03
3B	"	"	M,B	No	- .35	1.74	1.81
4A	"	"	F,B	No	- .39	4.94	1.63
4B	"	"	F,B	No	- .38	3.90	1.47
5A	"	"	F	No	- .40	3.08	1.46
5B	"	"	F	No	- .20	1.94	1.54

* M - Modulated for part load temperature scheduling.
F - Fixed at maximum power setting for all power levels.
B - With braking stroke.

Fig. 22 Chrysler Burner Concept FL15-Vehicle Tests
Diesel Fuel, 4500 Lb. Inertia
December 1973

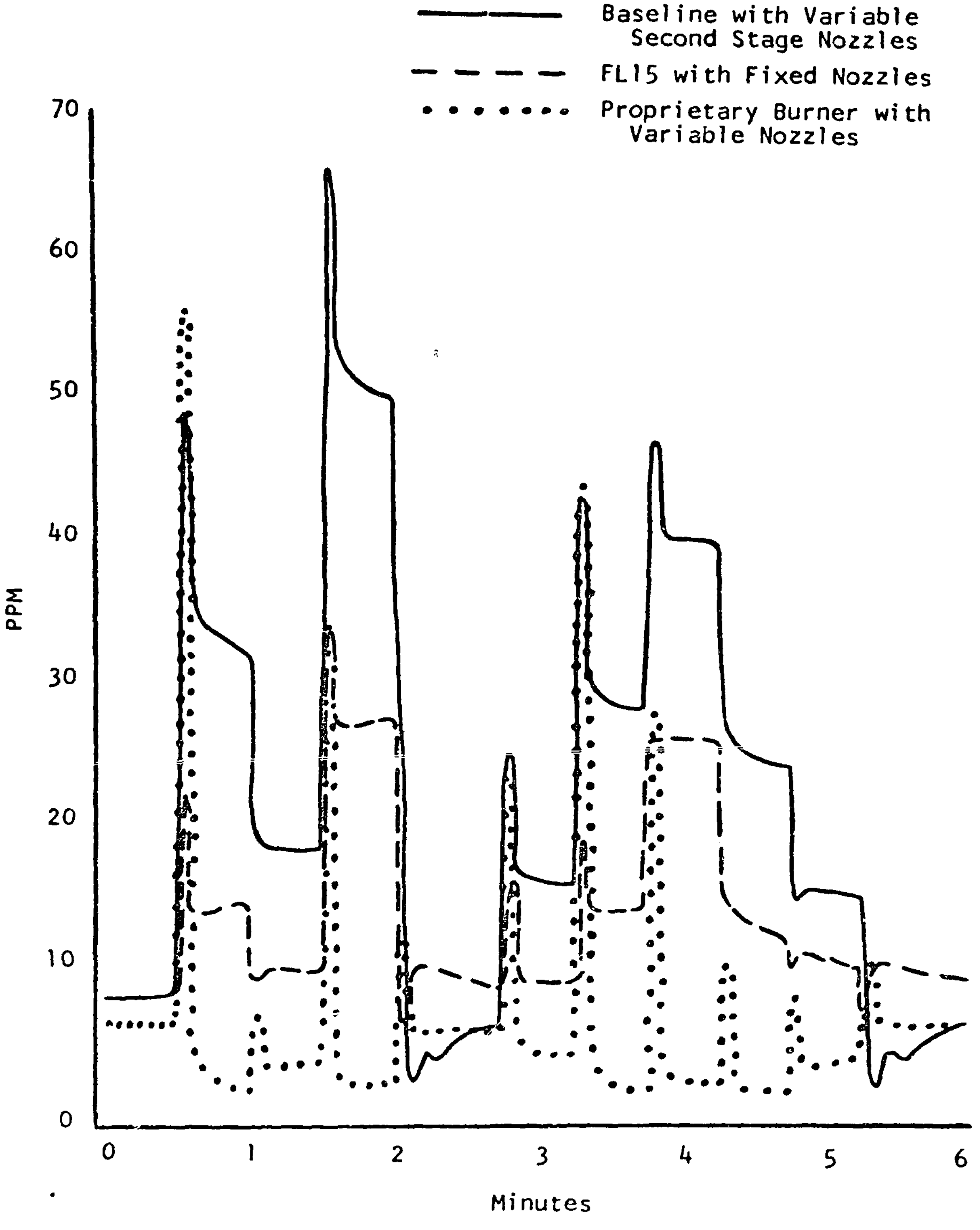


Fig. 23 Cycle NO_x, Room 4 Development Cycle

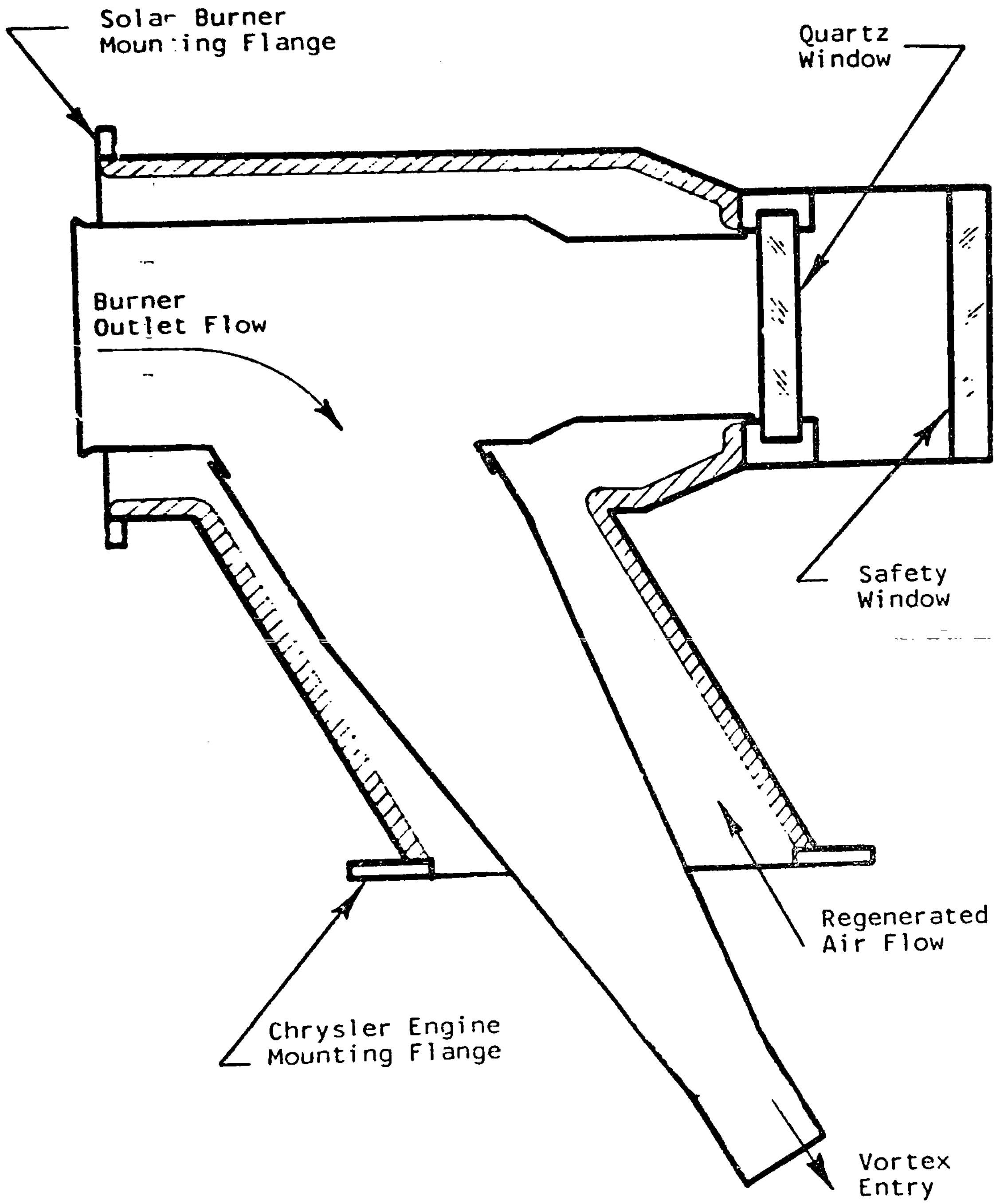


Fig. 24 Solar Burner Adaptor

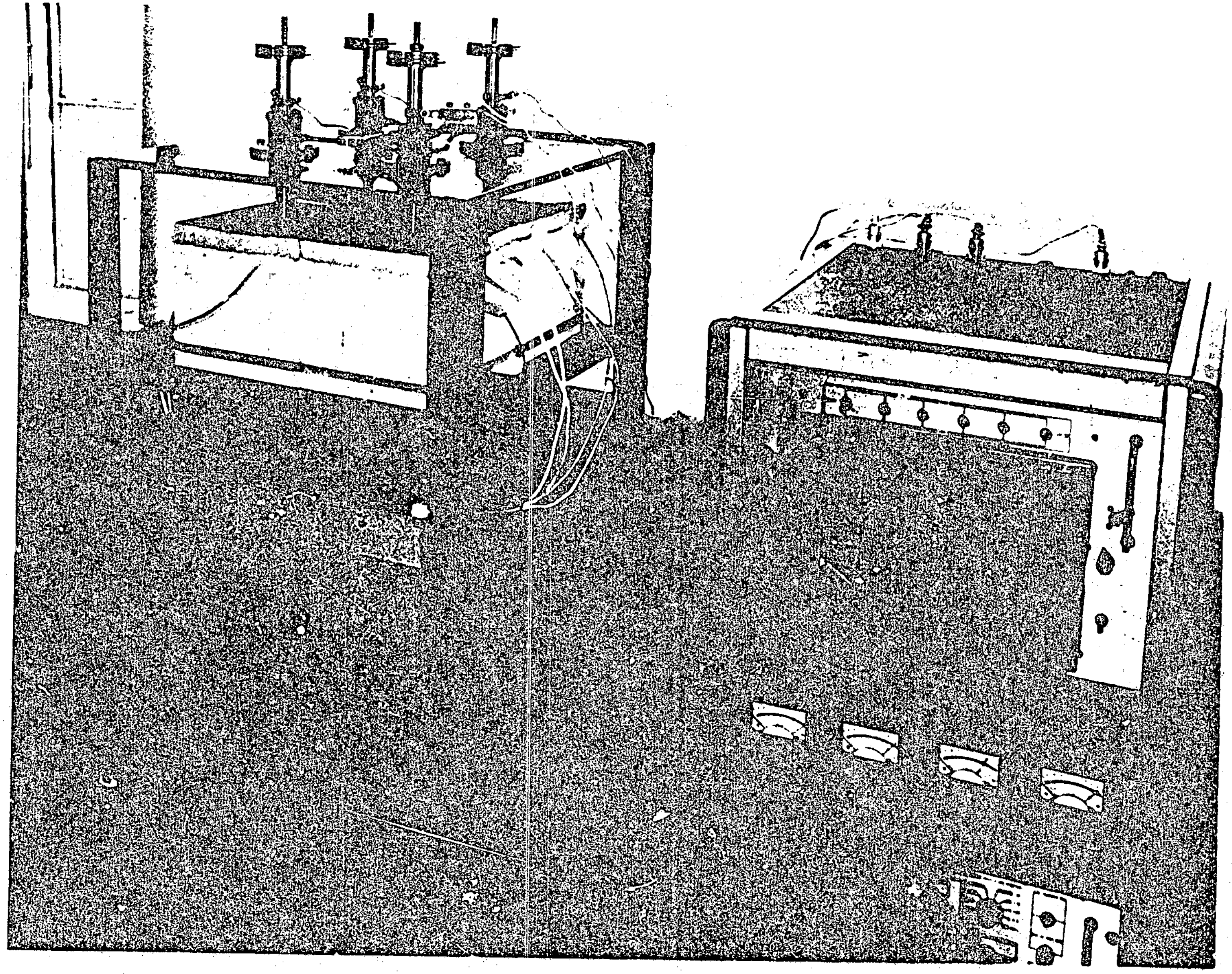


Fig. 25 Ceramic Regenerator Seal — Friction and Wear Test Fixture, Exterior

Engine Improvement - Integrated Control System: A low cost control system to meet Upgraded Engine requirements is being developed by Garrett Corporation under a subcontract. Their progress is summarized in Section III-D.

Tests have been run to determine engine characteristics while the gas generator is accelerating. Results, shown in Fig. 26, indicate that under a fast acceleration stable compressor operation well into the steady state surge range is possible.

Engine Improvement - Low Cost Turbine Wheel Manufacturing: Sample Baseline compressor turbine wheels are currently being cast from a proprietary Garrett Corporation reusable pattern process. Progress by Pratt-Whitney on their superplastic forging process is reported in Section III-E.

Engine Improvement - Torque Converter Lock-up: Preliminary evaluation (Figs. 27 and 28) indicates no fuel economy improvement on drive cycles. However, engine braking improvement is noticeable and the improved performance could be translated into a proportionately smaller base engine design.

Engine Improvement - Linerless Insulation: Both Foseco and Chrysler proprietary materials are being evaluated on the Program endurance engine (Fig. 29). To date, the materials have been tested for over 300 hours with no significant deterioration. In addition to life and performance, a prime objective of this task is an assessment of possible high volume cost advantages.

Engine Improvement - Variable Inlet Guide Vanes: The purpose of variable inlet guide vanes (VIGV) is to improve fuel economy by:

- power augmentation at 100% speed and
- lower operating-line flows at 50% speed.

At 100% speed (Fig. 30), the VIGV deflects the inlet flow opposite engine rotation to increase compressor pressure ratio and flow which increases engine power. This augmentation allows for the design of a basically smaller engine, which improves fuel economy in the driving range (50%-70% Ngg).

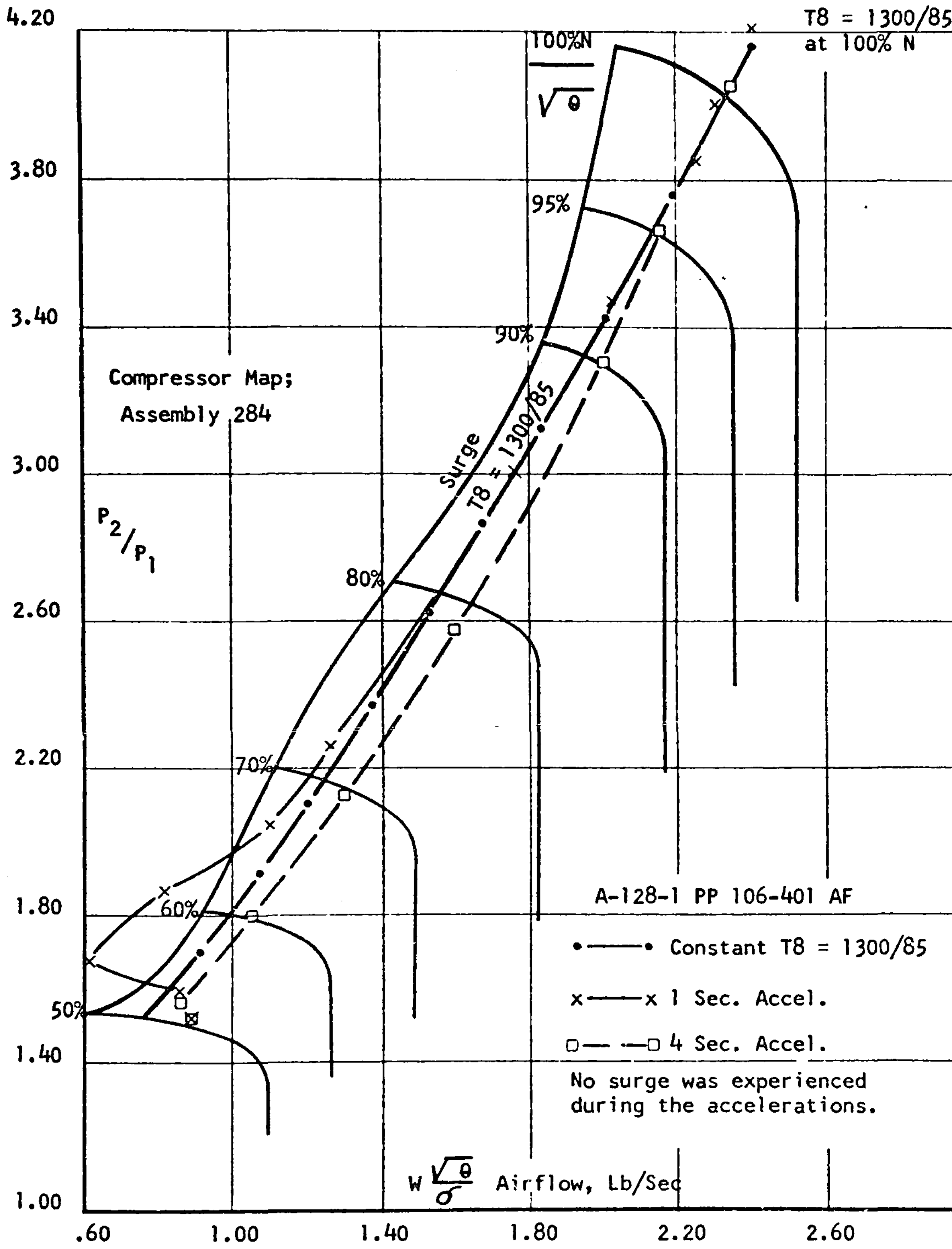
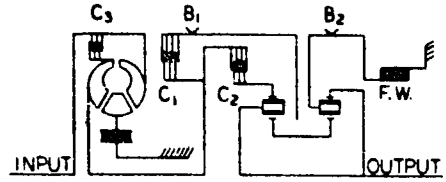


Fig. 26 Variation of Engine Operating Line with Acceleration Time



GEAR	RATIO	MEMBERS APPLIED
LOW	2.45	C_2 & B_2 OR F.W.
KICKDOWN	1.45	C_2 & B_1
DIRECT	1.00	C_1 & C_2
REVERSE	2.20	C_1 & B_2
PARK	—	C_1 C_2 & B_2
LOCK-UP		C_3 CAN BE APPLIED MANUALLY IN ALL DRIVE CONDITIONS

SHIFT SEQUENCE P-R-D-L

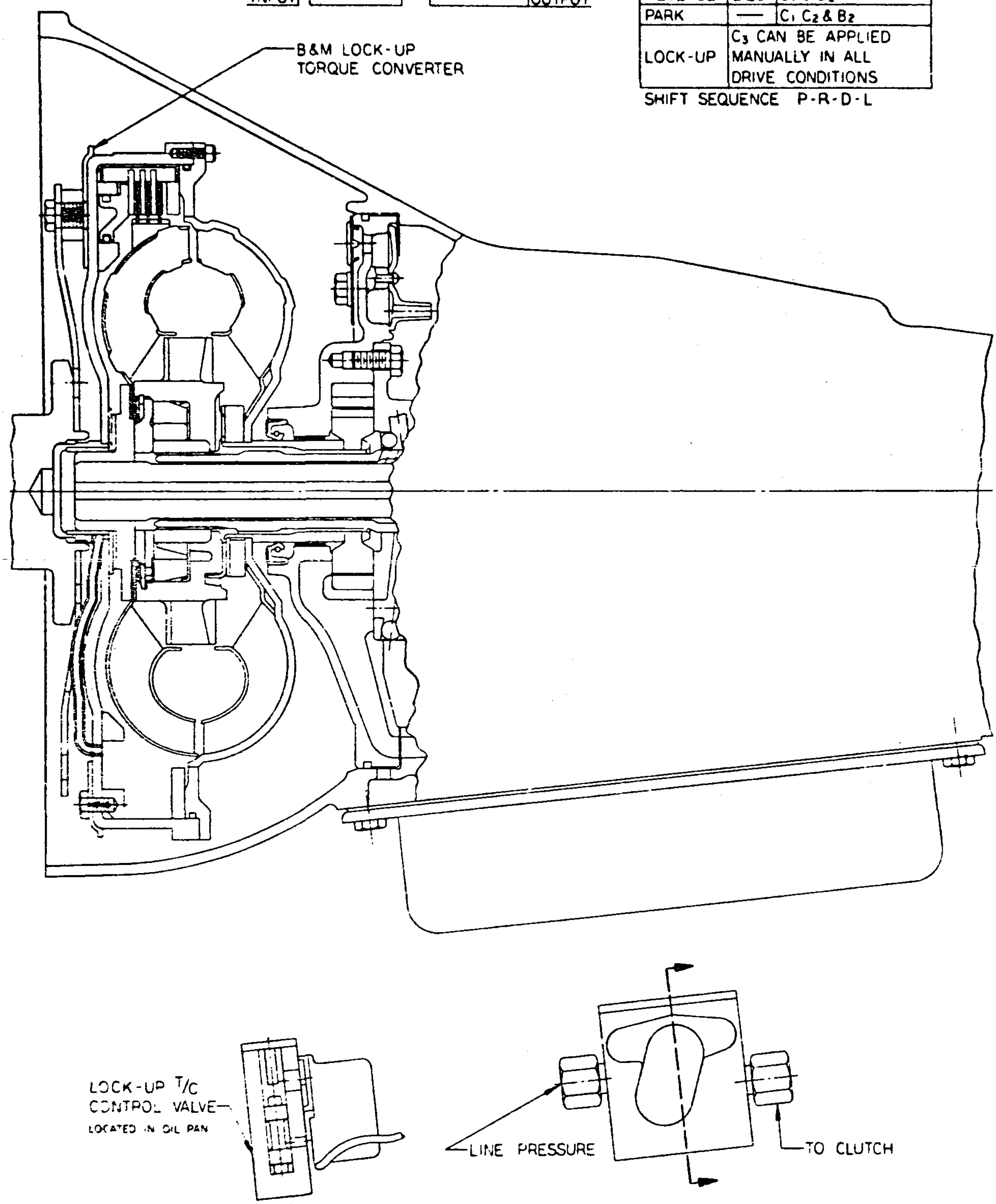


Fig. 27 Torque Converter Lock-Up System

	Lock-Up at 1-2 Shift	Standard (6% Slip)
Economy		
FDC	8.1 MPG	8.1 MPG
FEC	13.0 MPG	13.0 MPG
20-80 MPH Steady State, Avg.	13.0 MPG	12.5 MPG
Emissions		
NOx	10-15% Red.	Base
Performance		
0-30	4.3	4.3
0-60	11.7	12.1
50-70	7.1	7.6

Fig. 28 Torque Converter Lock-Up Evaluation (Preliminary Results)

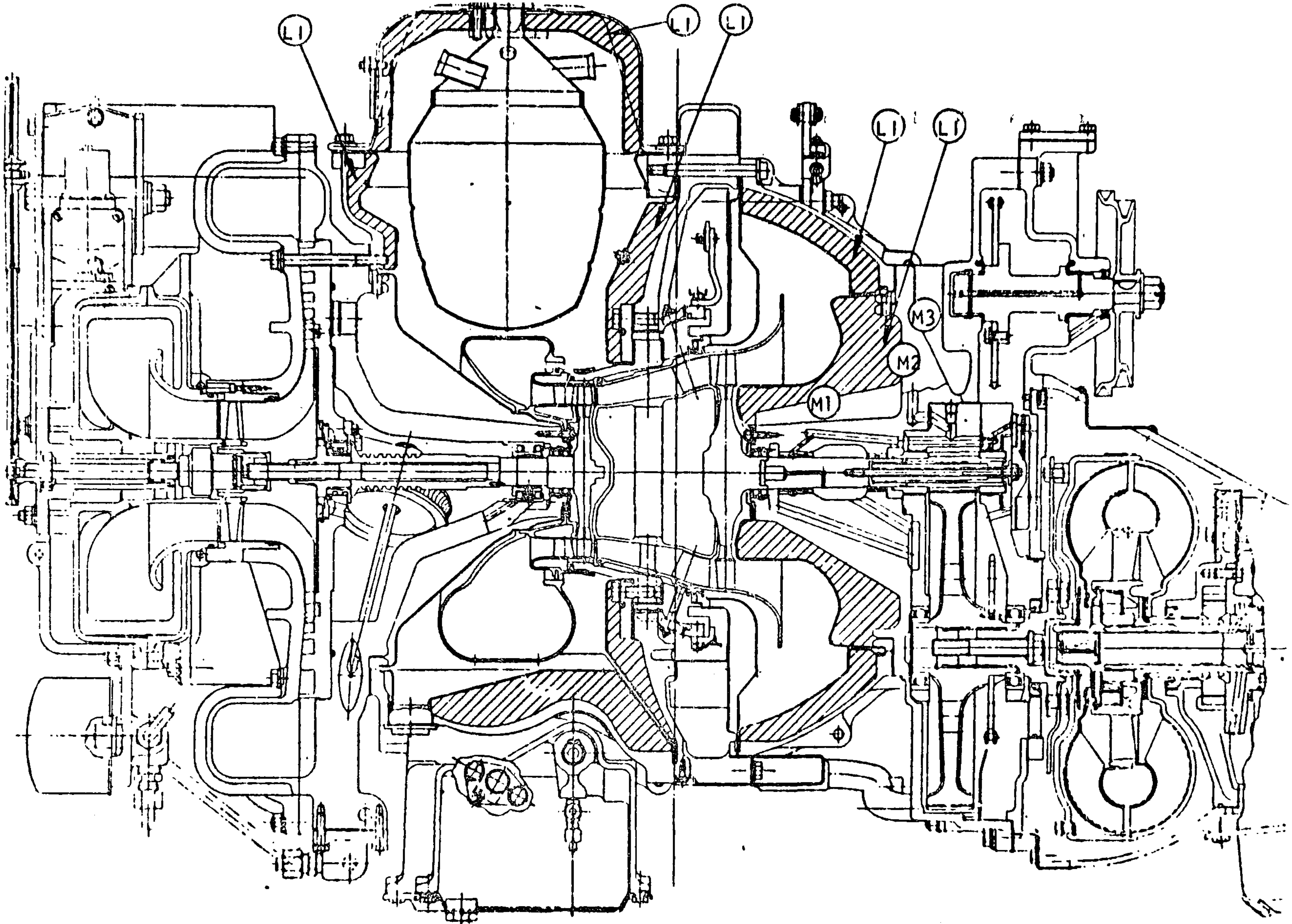


Fig. 29   Endurance Engine with Linerless Insulation

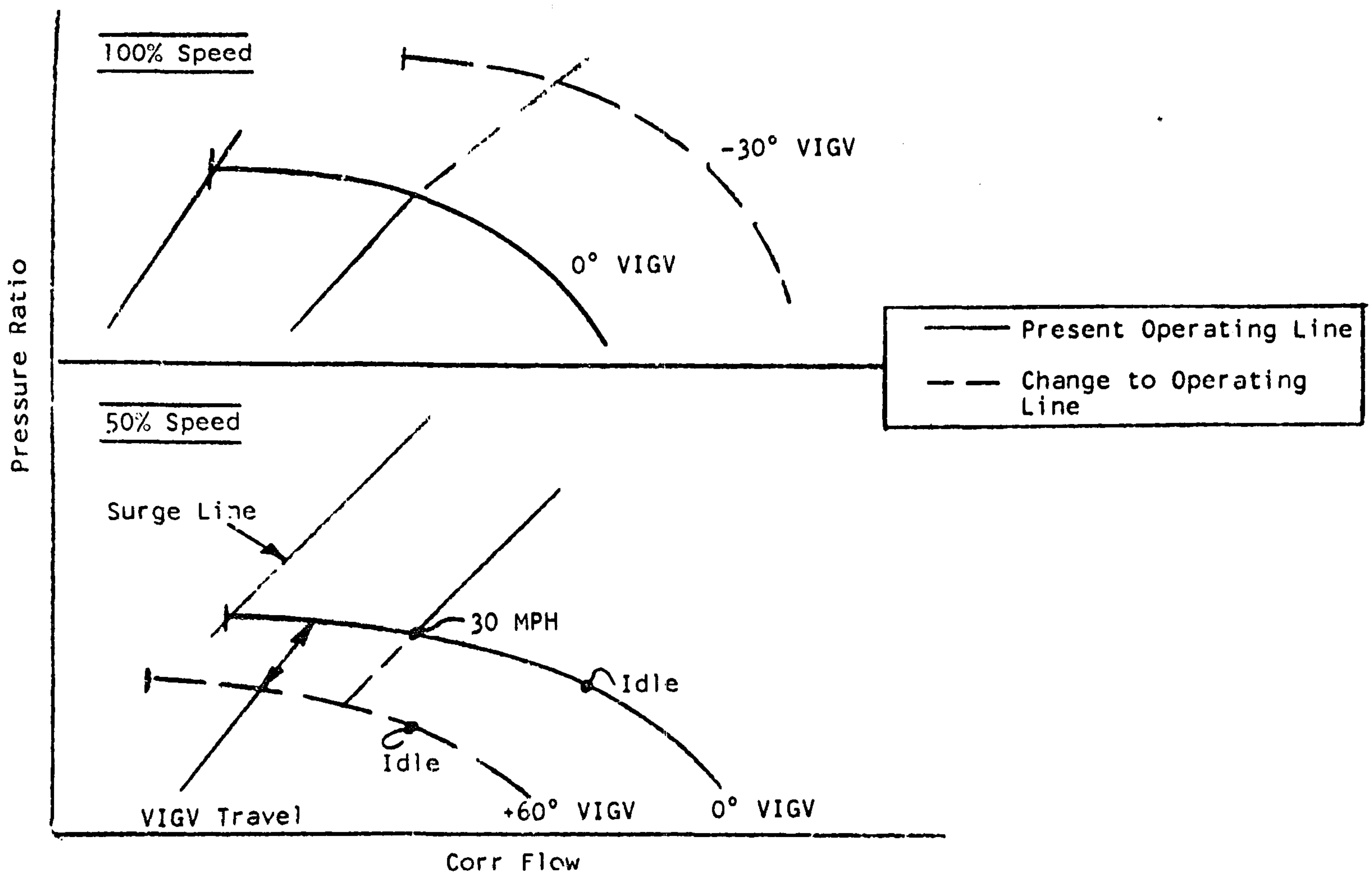


Fig. 30 Changes in Engine Operating Line on Compressor Map With VIGV Application

At 50% speed (Fig. 30), engine power levels in the driving range (between 30 mph and idle) are currently achieved by reduction in turbine inlet temperature. Improvement in fuel economy and better emissions control could be obtained if the turbine inlet temperature could be maintained at a high level, while compressor flow and pressure ratio are reduced. This can be accomplished by using the VIGV to deflect the flow in the direction of engine rotation. The amount of VIGV actuation would depend on the power level needed at any given point in the 30 mph to idle driving range.

Variable inlet guide vanes were adapted to the Baseline compressor (Fig. 31) and evaluated on a compressor test rig (Figs. 32, 33, and 34). The Baseline compressor rotor consists of the familiar integral inducer/impeller combination and an additional separate inducer. Tests were conducted with and without the separate inducer. The purpose of the separate inducer is to provide a wide range of stall-free flow between 50% and 100% speed for a fixed geometry compressor. It seemed possible that the use of VIGV might preclude the need for a separate inducer.

Test results showed that, at 50% speed, the low inlet blade angle of the integral inducer provides 3 points higher efficiency at 60° of VIGV deflection angle than the high inlet blade angle of the separate inducer (Figs. 35-38). At 100% speed and -30° of VIGV deflection angle, the separate inducer provides 6% change of flow and pressure ratio, while the integral inducer provides only 2%.

Thus, the test results show that the VIGV can perform as intended with a properly matched inducer. The goal now is to obtain a single angle which will provide the best compromise of optimum fuel economy between high-speed and low-speed operation.

<u>Upgraded Engine Design</u>: The goals of the Upgraded Engine Program are to provide much better fuel economy while meeting the original 1976 emission standards in an otherwise satisfactory automotive powerplant. This can be accomplished with a 100 hp basic Upgraded design using augmentation to 122 hp for vehicle acceleration. Installation of this engine (Fig. 39) in a compact vehicle

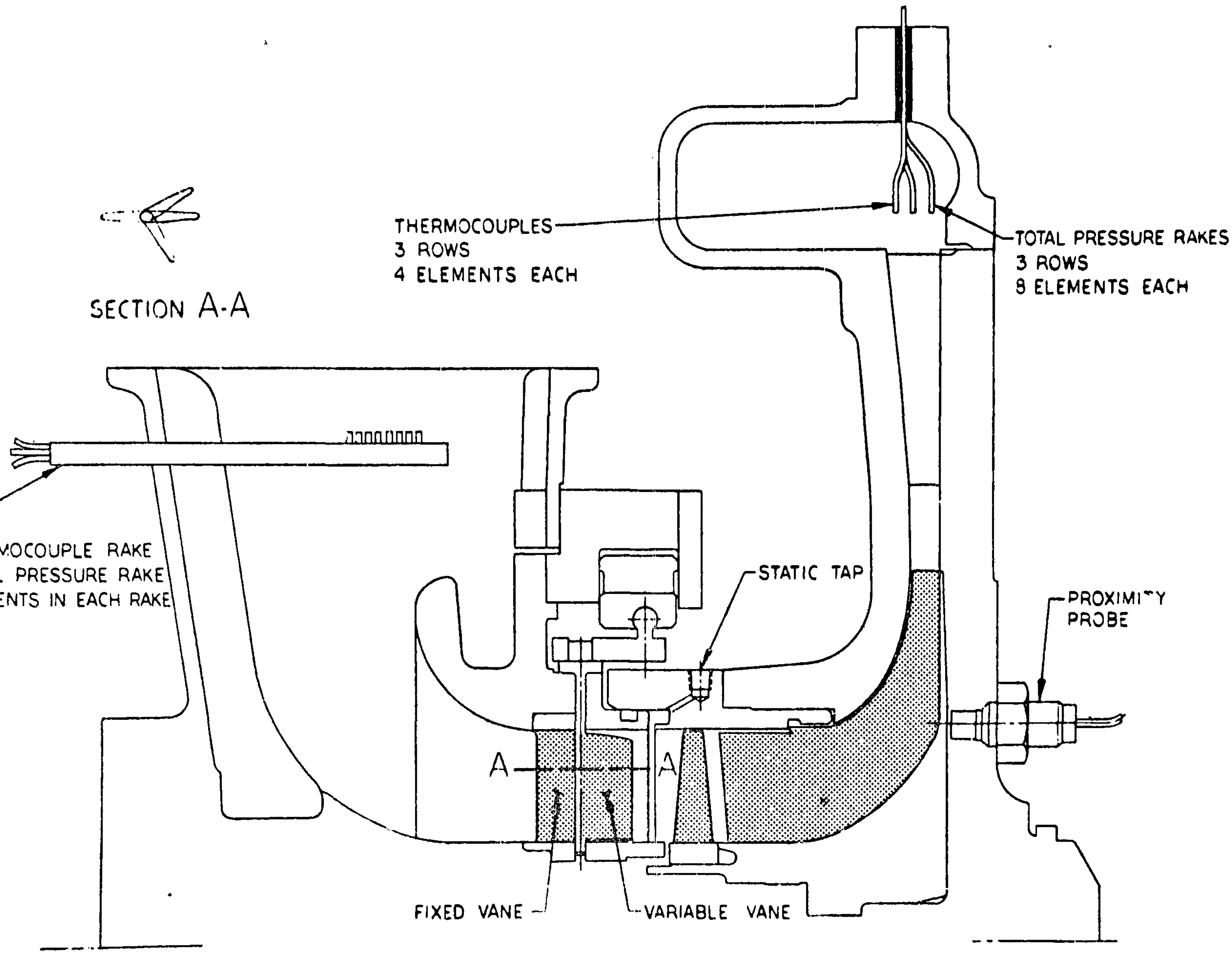


Fig. 31 Instrumentation of Baseline Engine Compressor Test Rig with Variable Inlet Guide Vanes

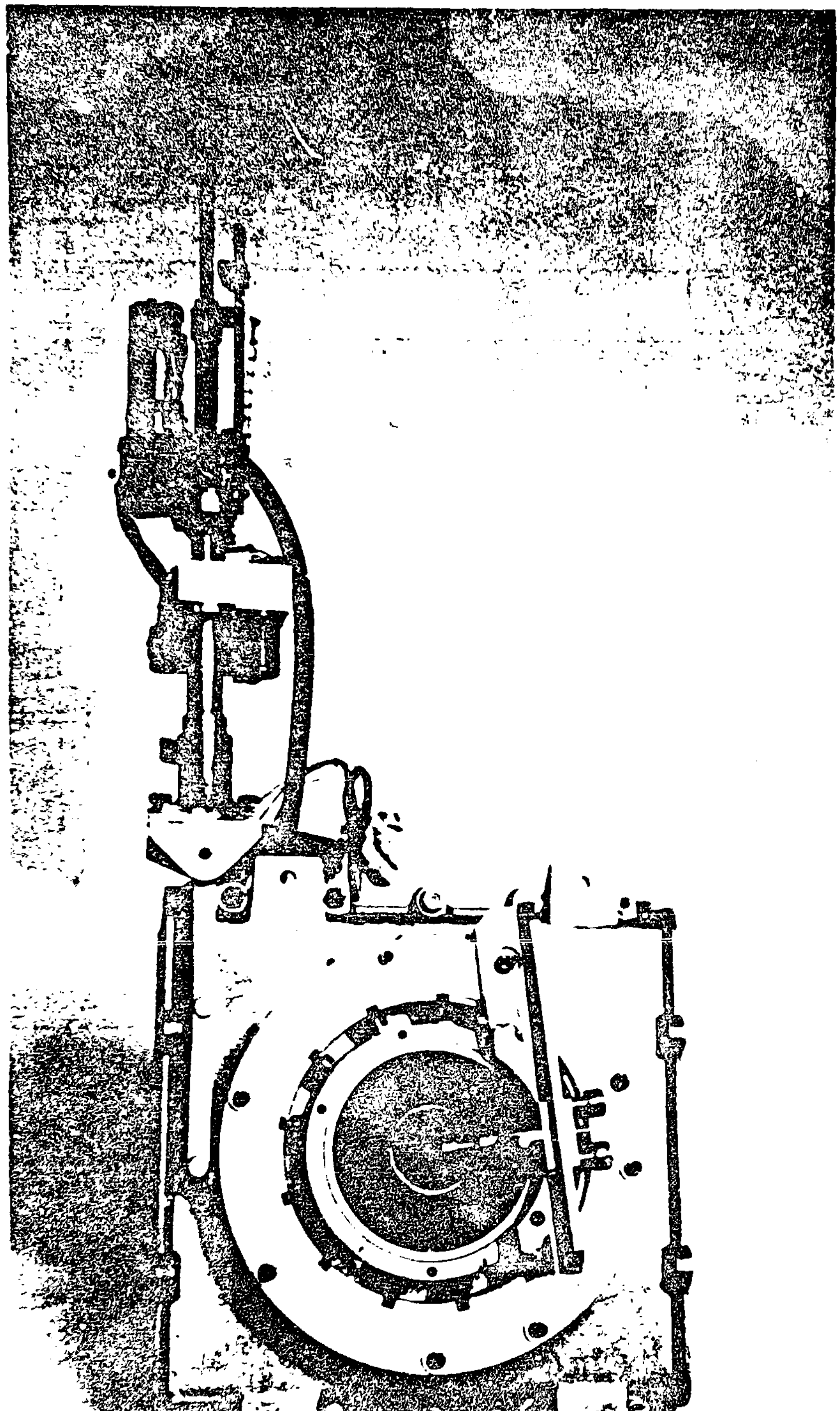


Fig. 32 Baseline Engine Variable Inlet Guide Vane Assembly With Actuator and Guide Vane Angle Calibration Fixture

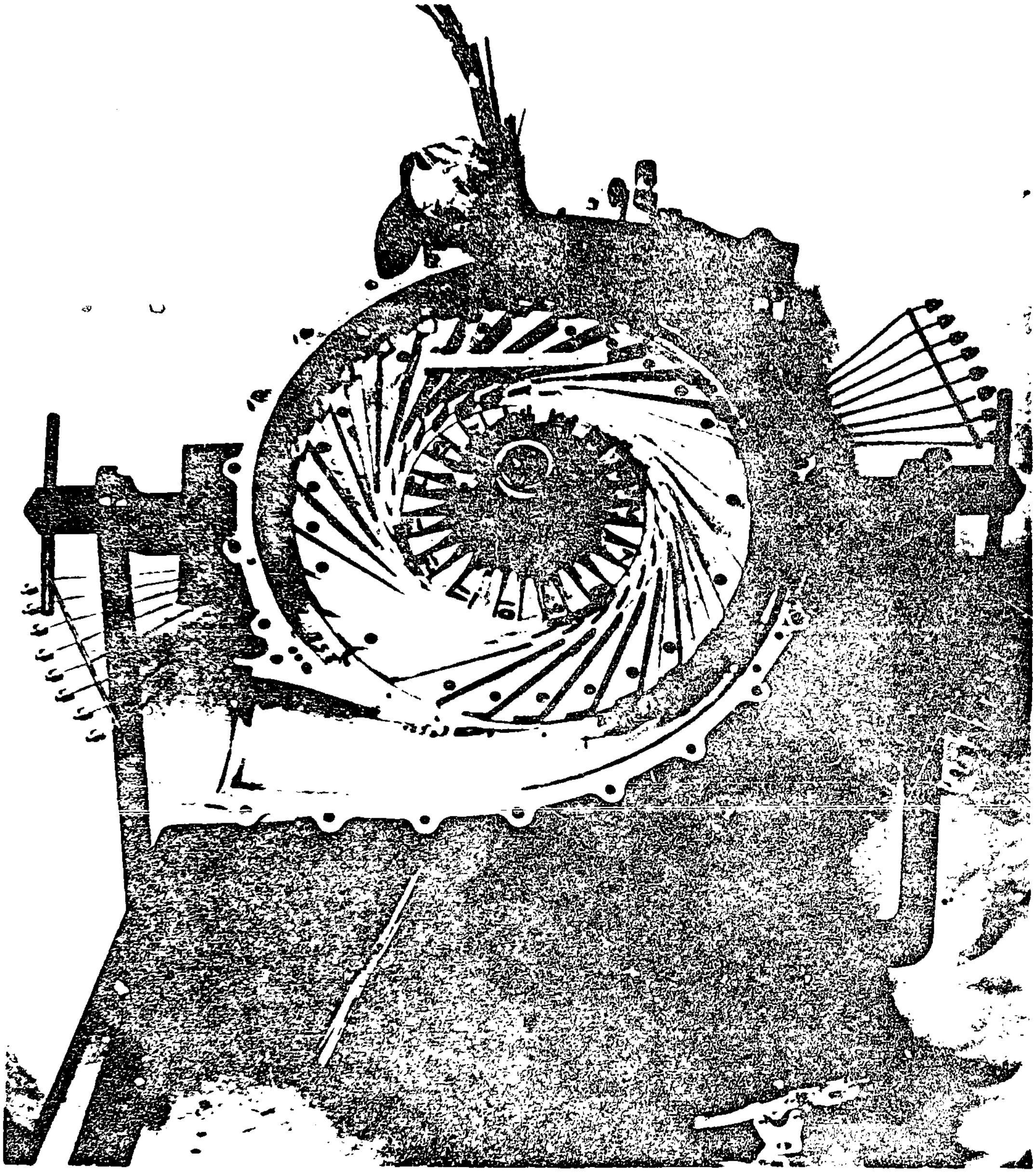


Fig. 33 Baseline Engine Compressor Test Rig Compressor & Diffuser Assembly with Impeller Discharge Total Pressure Probes

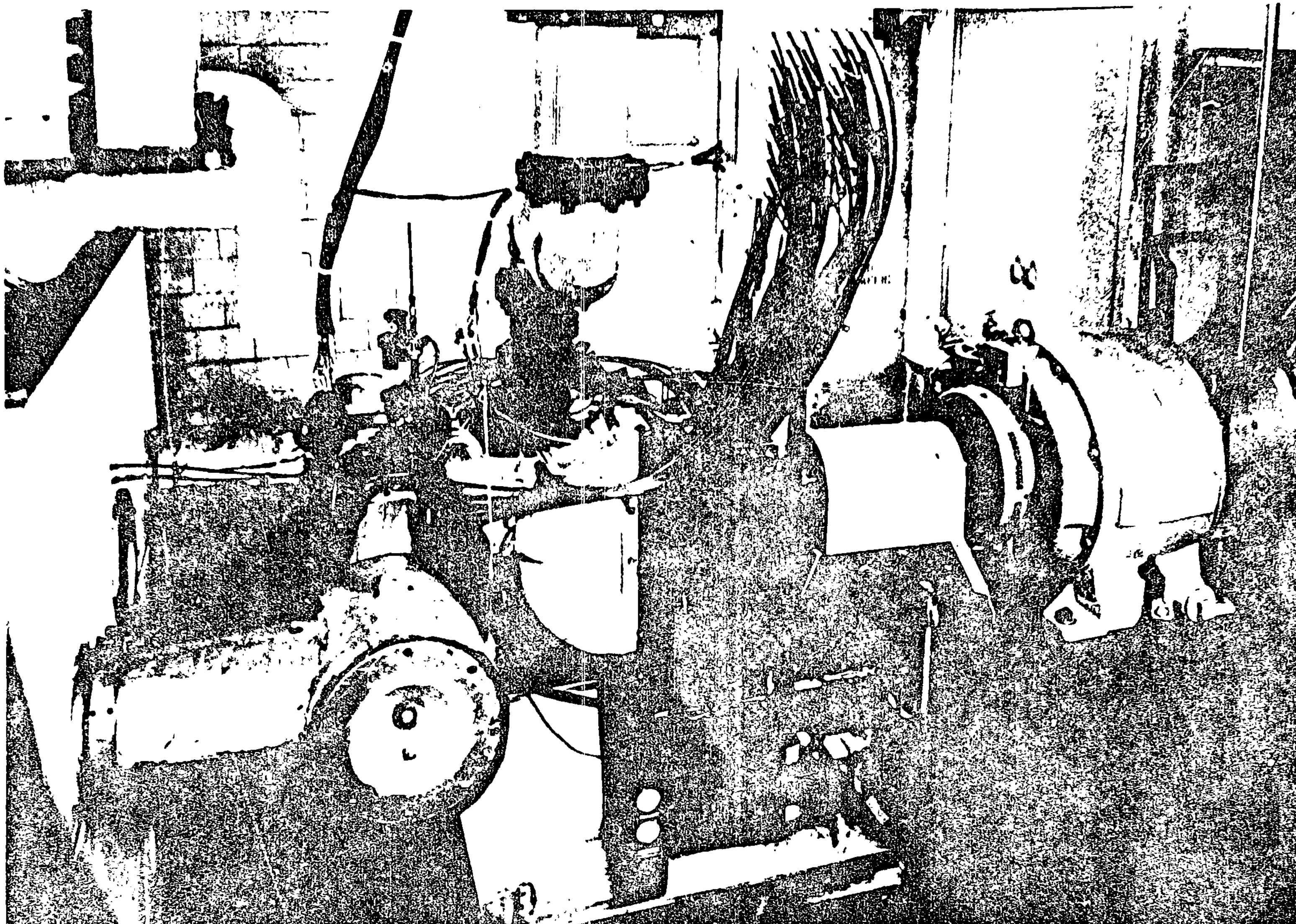


Fig. 34 Baseline Engine Compressor Test Rig with Simulated Car Inlet System and With Actuator For VIGV'S

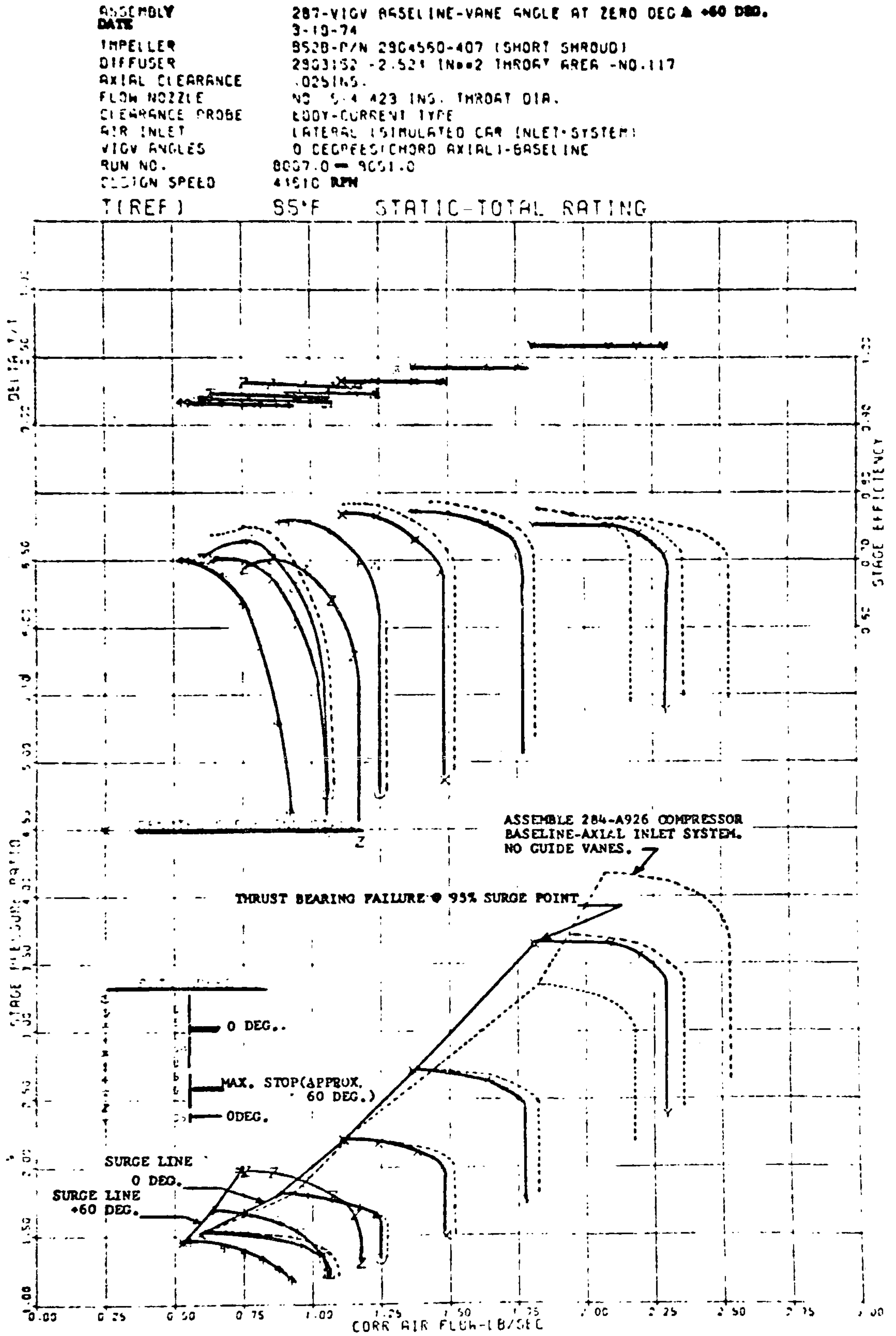


Fig. 35 Compressor Stage Performance

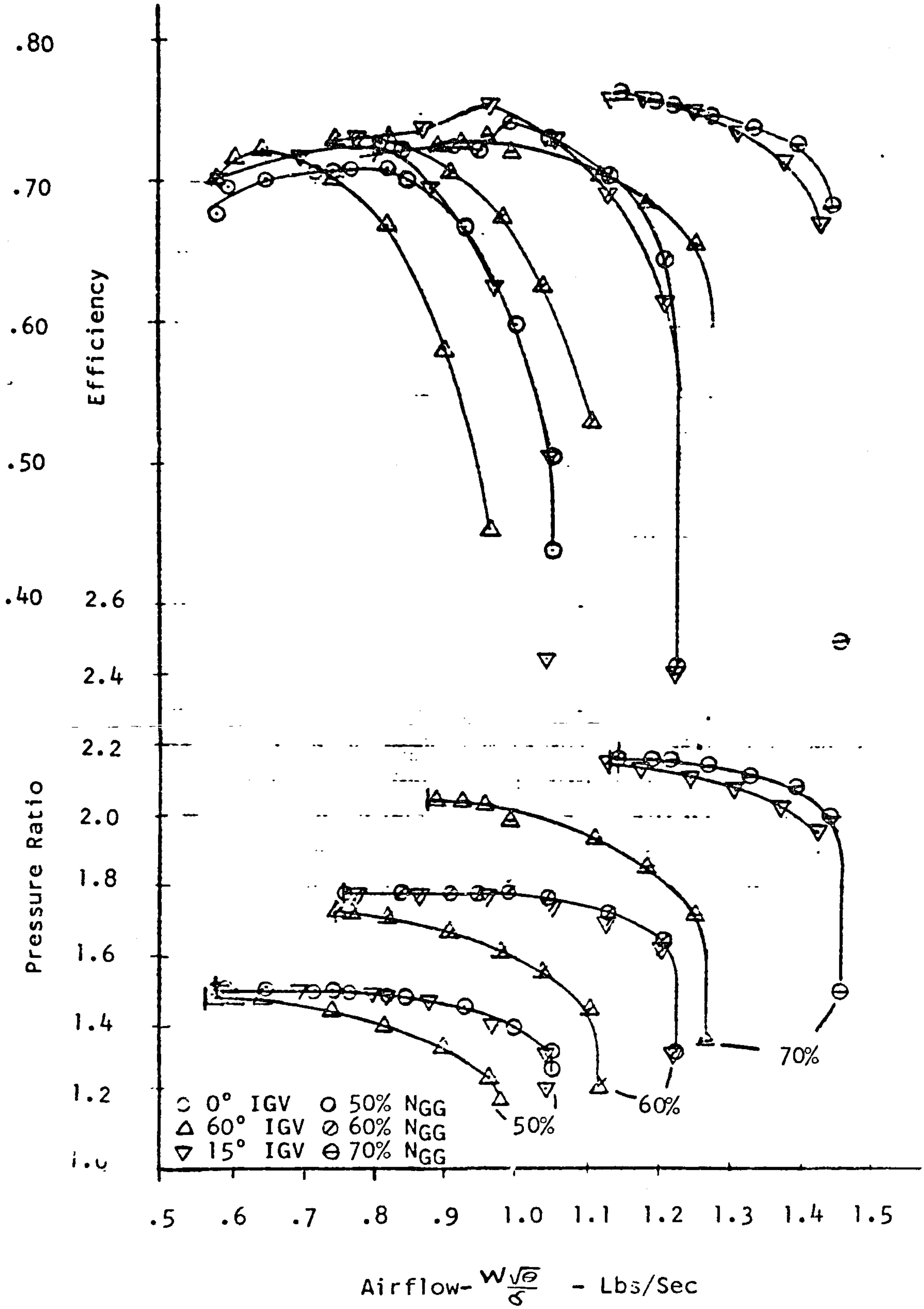


Fig. 36 B-36 Compressor with VIGV

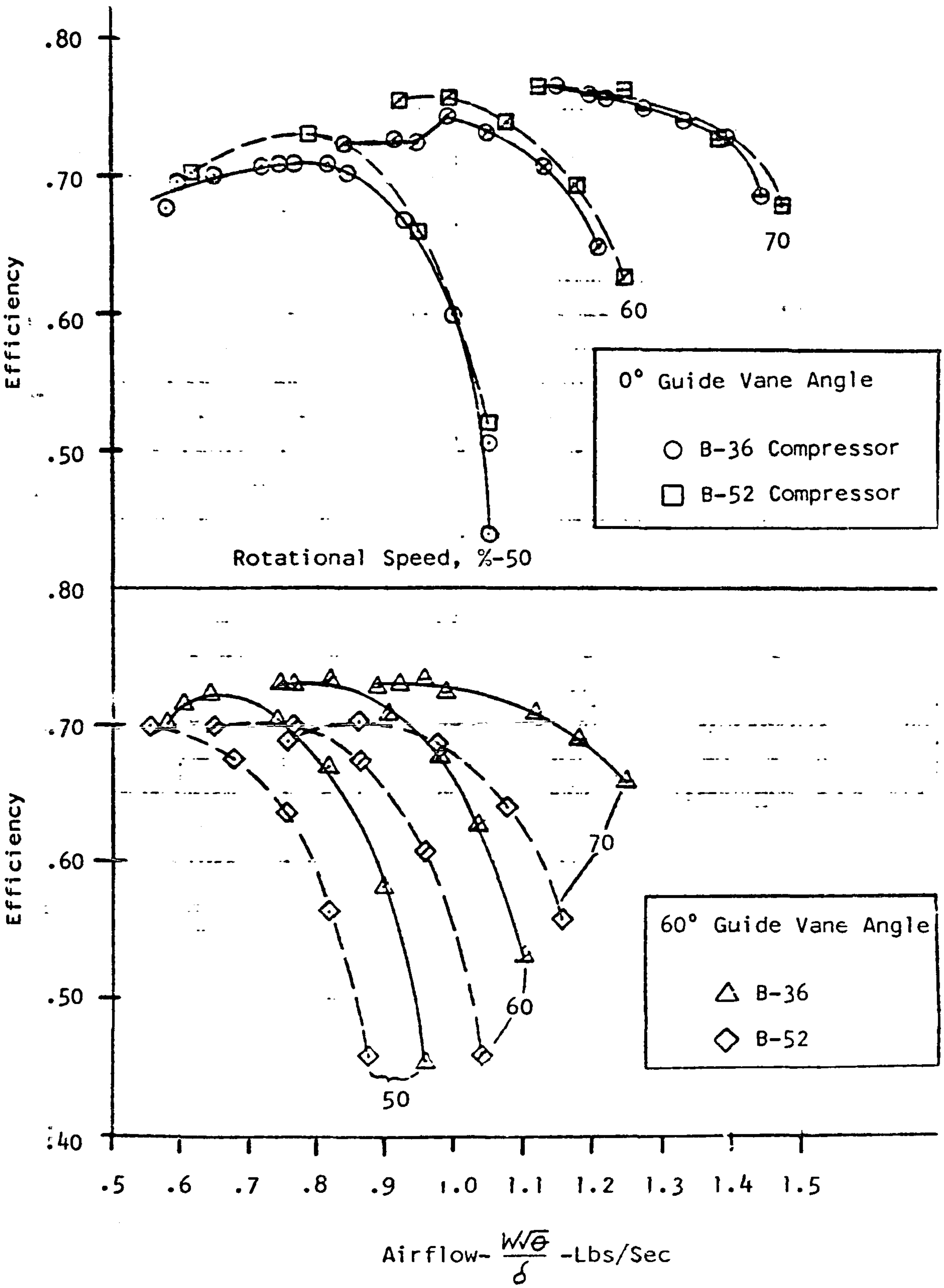


Fig. 37 Performance Comparison of B-52 and B-36 Compressors With Variable Inlet Guide Vanes

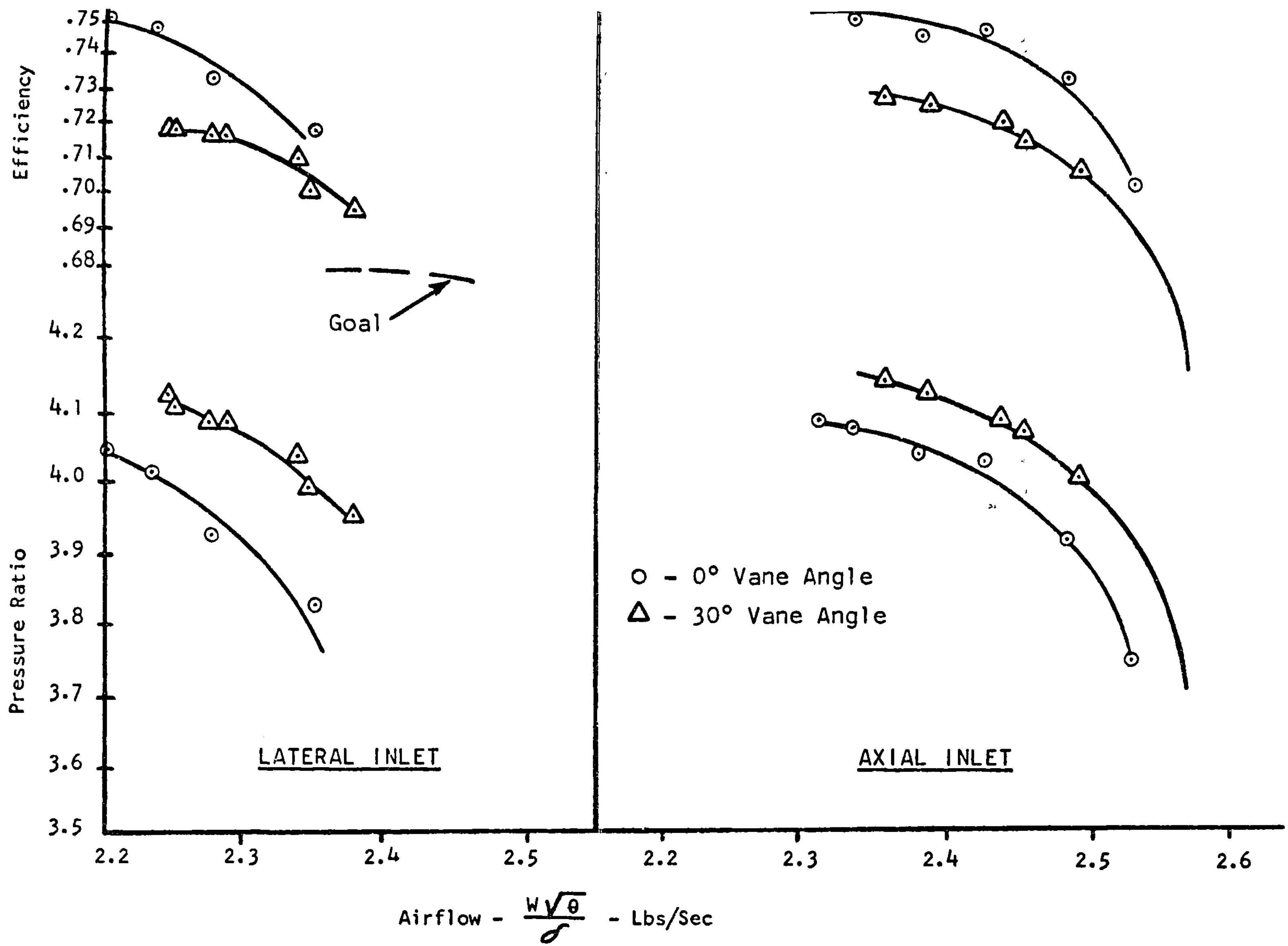


Fig. 38 B-36 Compressor Performance with VIGV at 100% Speed with Laterial and Axial Inlets

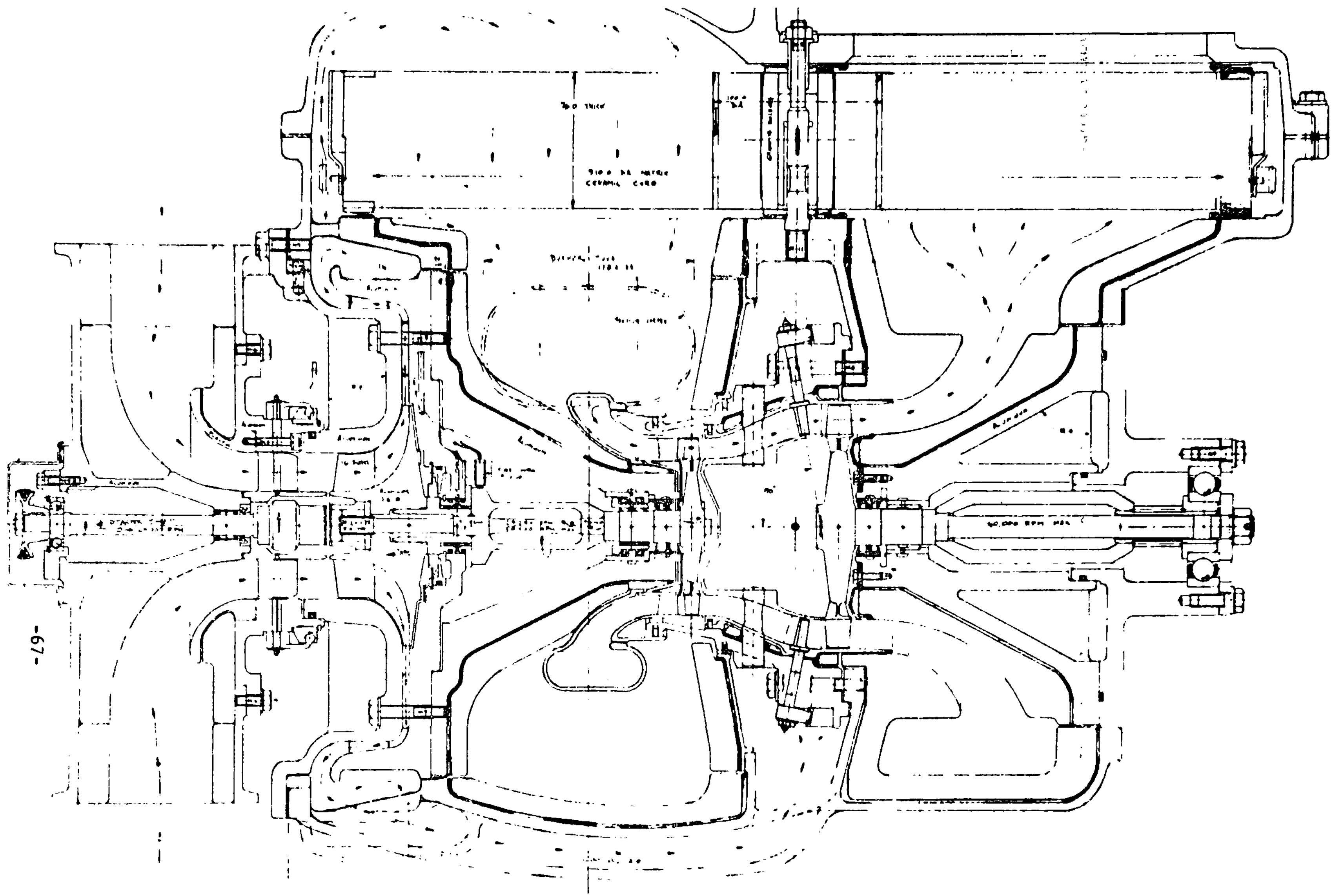


Fig. 39 92 K.W. (123 HP) Upgraded Engine for Compact Vehicle
Horizontal Cross Section

engine compartment (Fig. 40) requires no major vehicle modifications. The accessory drive system (Fig. 41) is of the free rotor concept whereby both engine and vehicle accessories are driven from the power turbine.

Predicted low speed fuel consumption for the Upgraded Engine in a compact vehicle is about 50% less than that for the Baseline Engine in an intermediate size vehicle (Figs. 42 and 43). This improvement is due to three major factors. Improvement in component efficiencies (Fig. 44) account for 15% of the total. Reduction of internal leakages account for 8%, and reducing the engine and vehicle size accounts for the remaining 18%.

Questions and Comments

Question: Two materials (Foseco and a Chrysler proprietary material) are being evaluated for the linerless insulation. Does this not constitute a vendor comparison?

Answer: The prime concern is to assess the true potential engine cost with the linerless insulation, particularly since the high cost and complication of the metal liner is recognized. Production is still too far off to begin to limit potential vendors; all likely avenues are being considered.

Question: What is the life of the current graphite ceramic regenerator seals?

Answer: It depends on the running temperature. Present rig tests are limited to about 1200°F which gives 20-30 hours (50 hours maximum) of life for a set of seals - almost unsuitable except for very limited testing at light load, low torque operation. The hot cross arm seals are critical.

Question: What seals are used in the Baseline Engine?

Answer: The Baseline Engine uses a metallic regenerator and a Chrysler proprietary seal. The cross arm seal is a sprayed metal seal of proprietary composition. This gives excellent, full engine life and has many thousands of hours of operation. However, the trend is to higher cycle temperatures for the Upgraded Engine; hence it is believed that ceramic regenerators will be necessary. The seals for metallic regenerators are inappropriate, and so different seals must be developed.

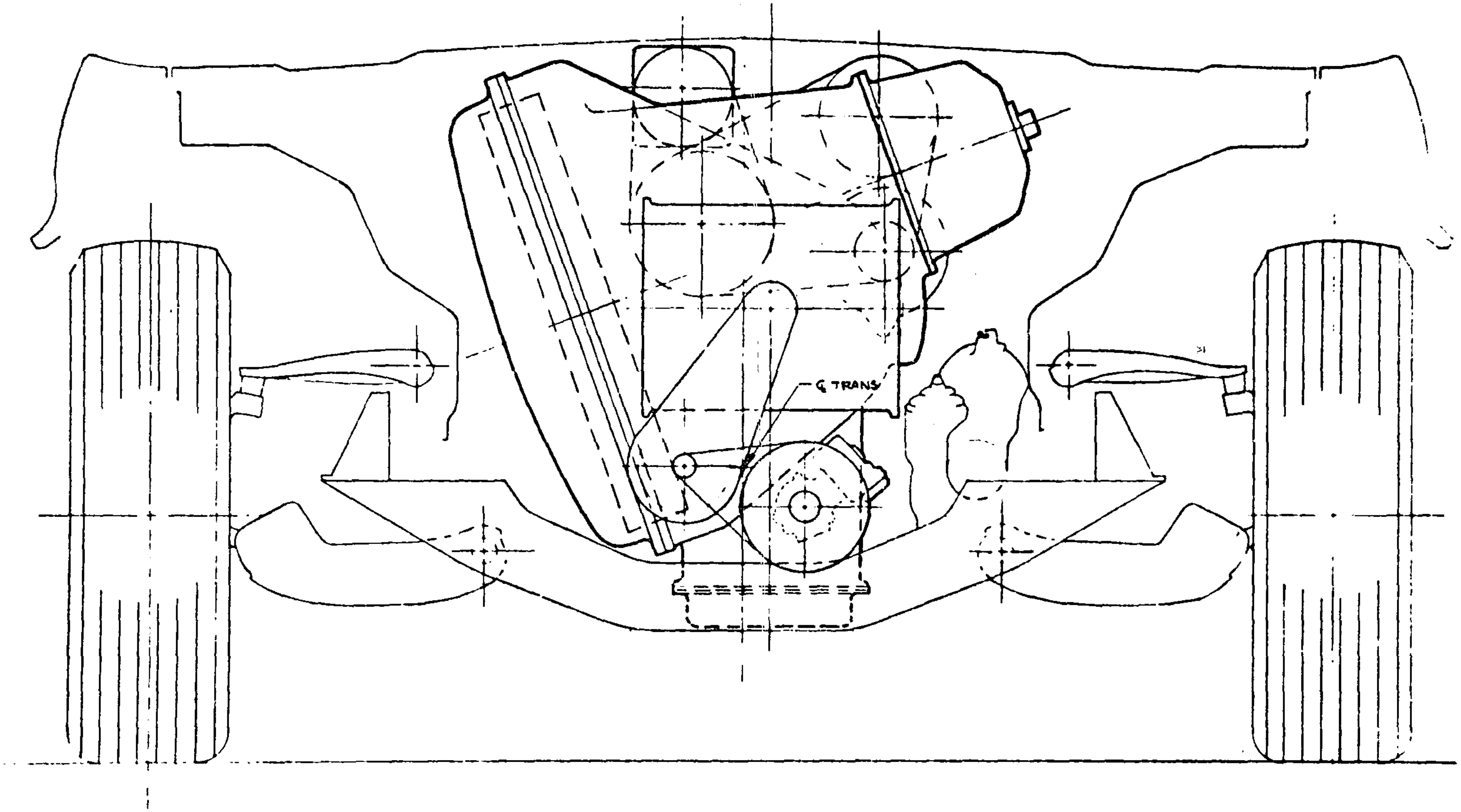


Fig. 40 91 K.W. (123 HP) Upgraded Engine with Single Ceramic Regenerator Tilted 20° Compact Vehicle Installation

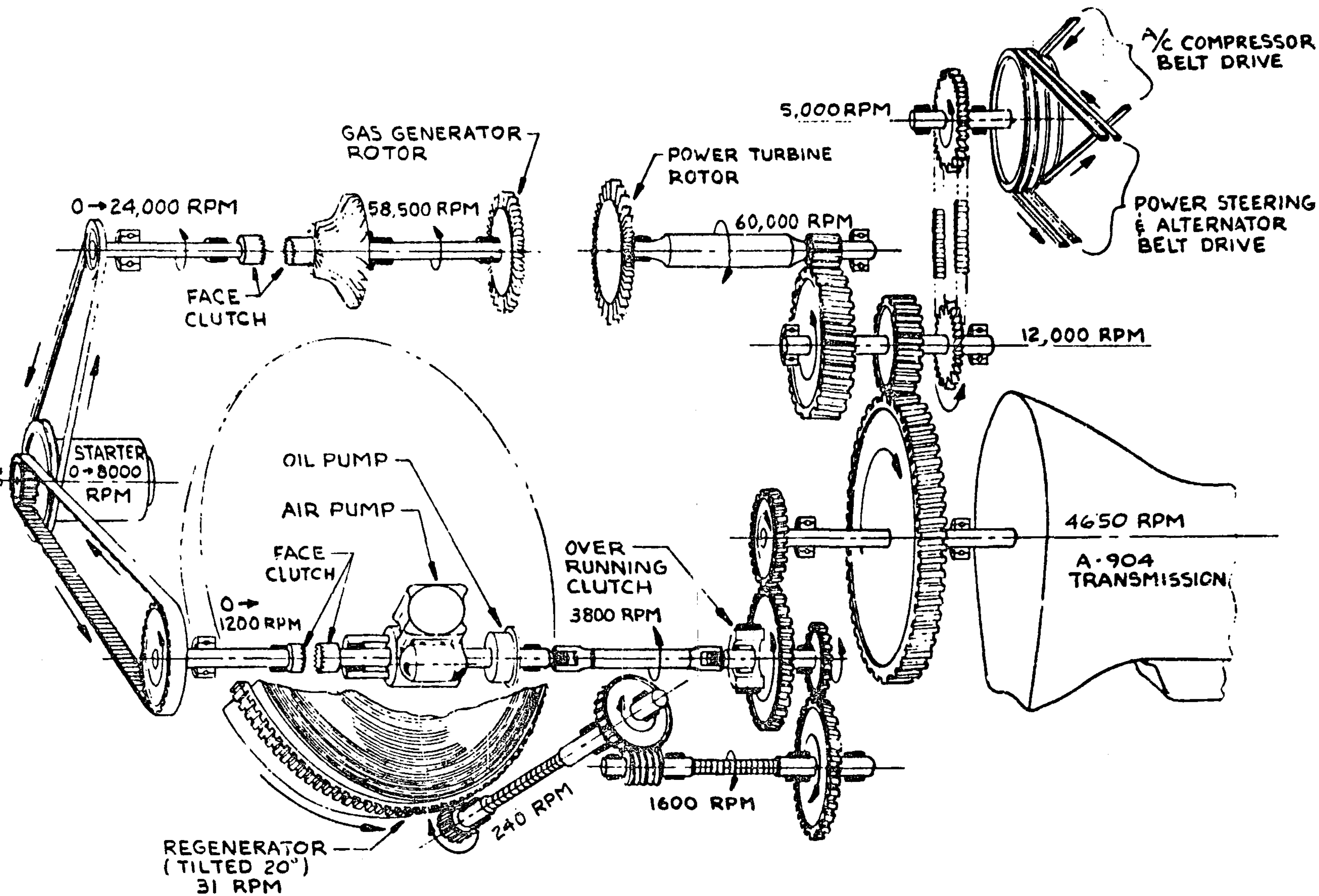


Fig. 41 Gear Schematic for Upgraded Gas Turbine
(Preliminary)

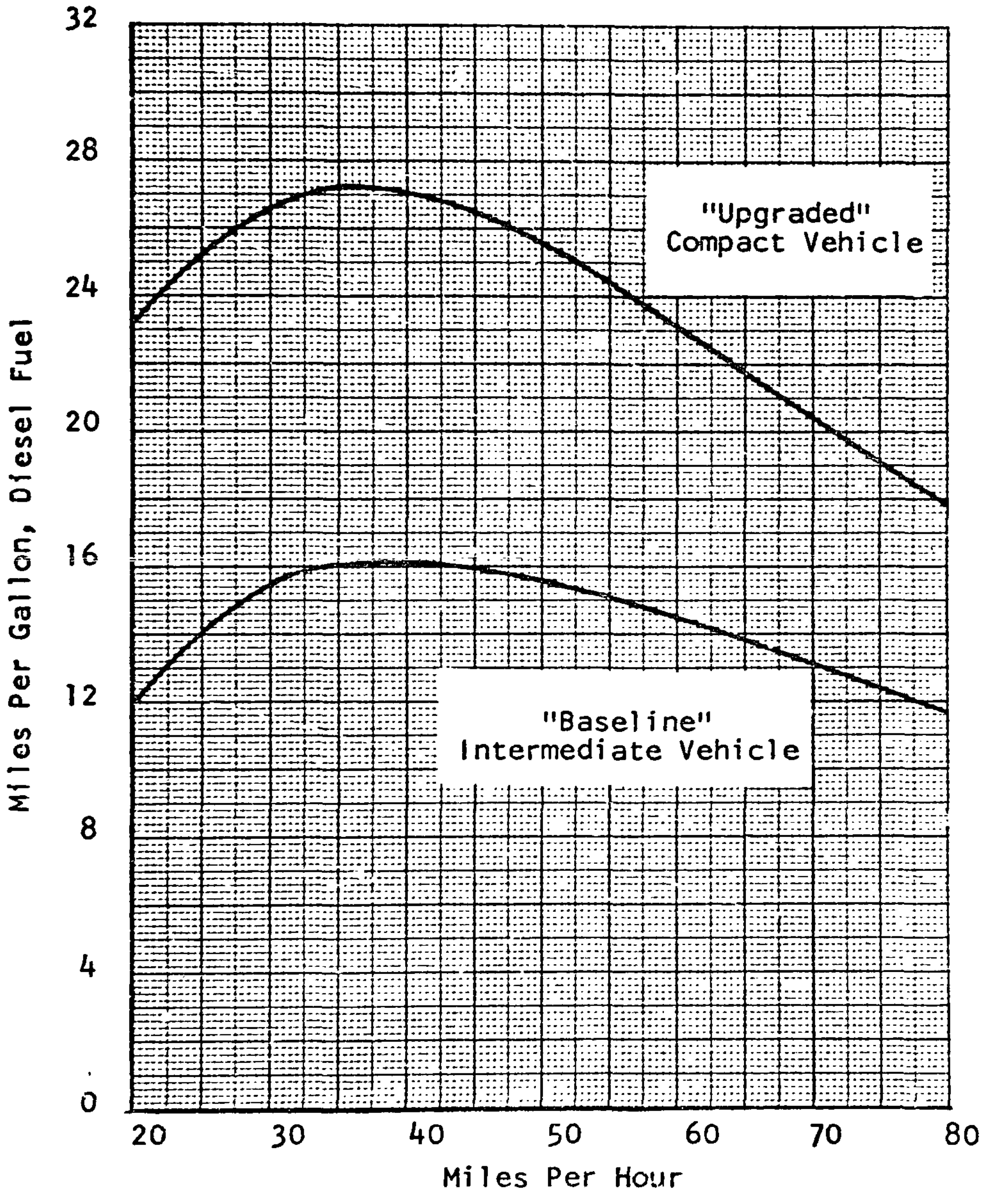


Fig. 42 Road Load Fuel Economy

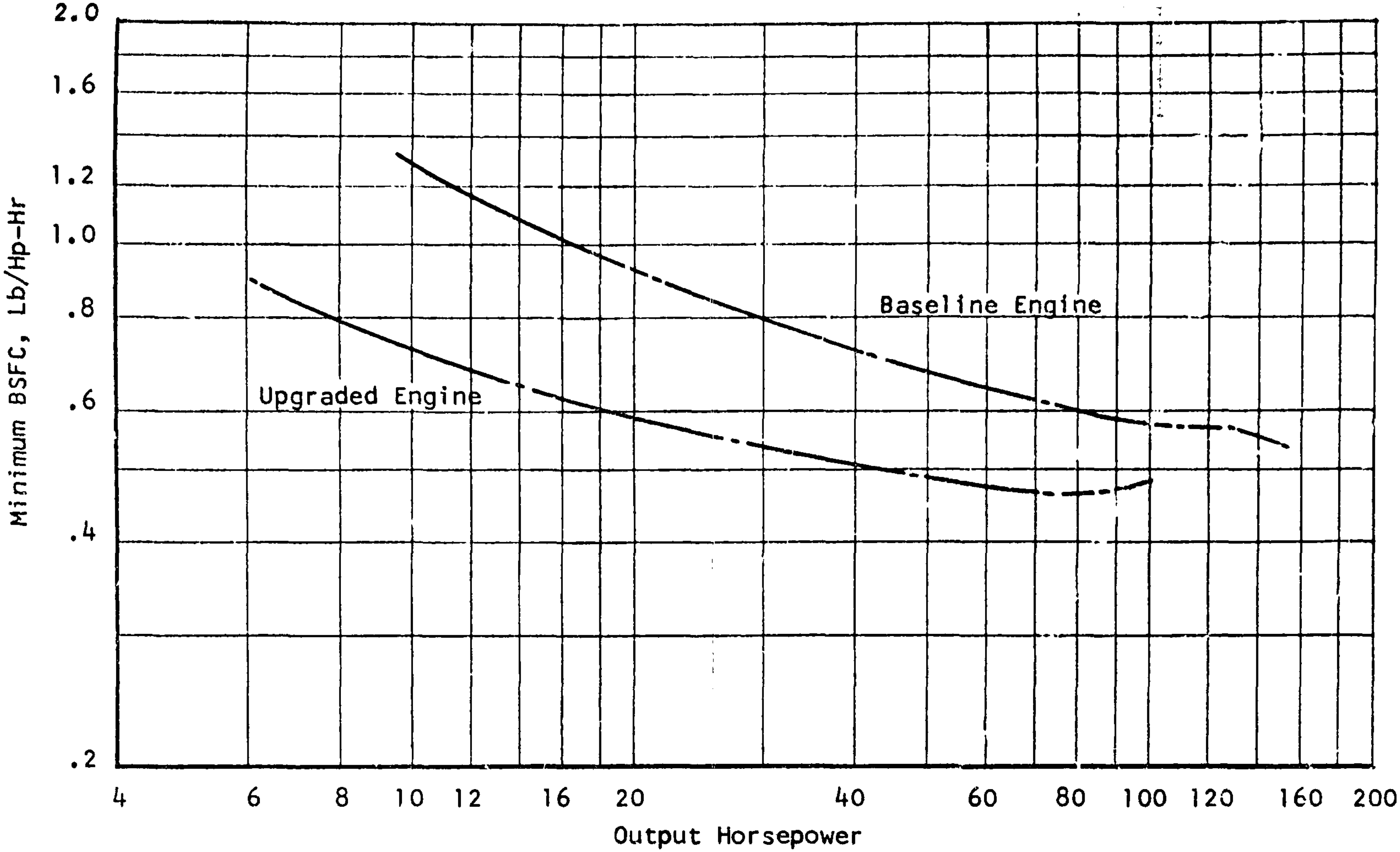


Fig. 43 Engine Characterization

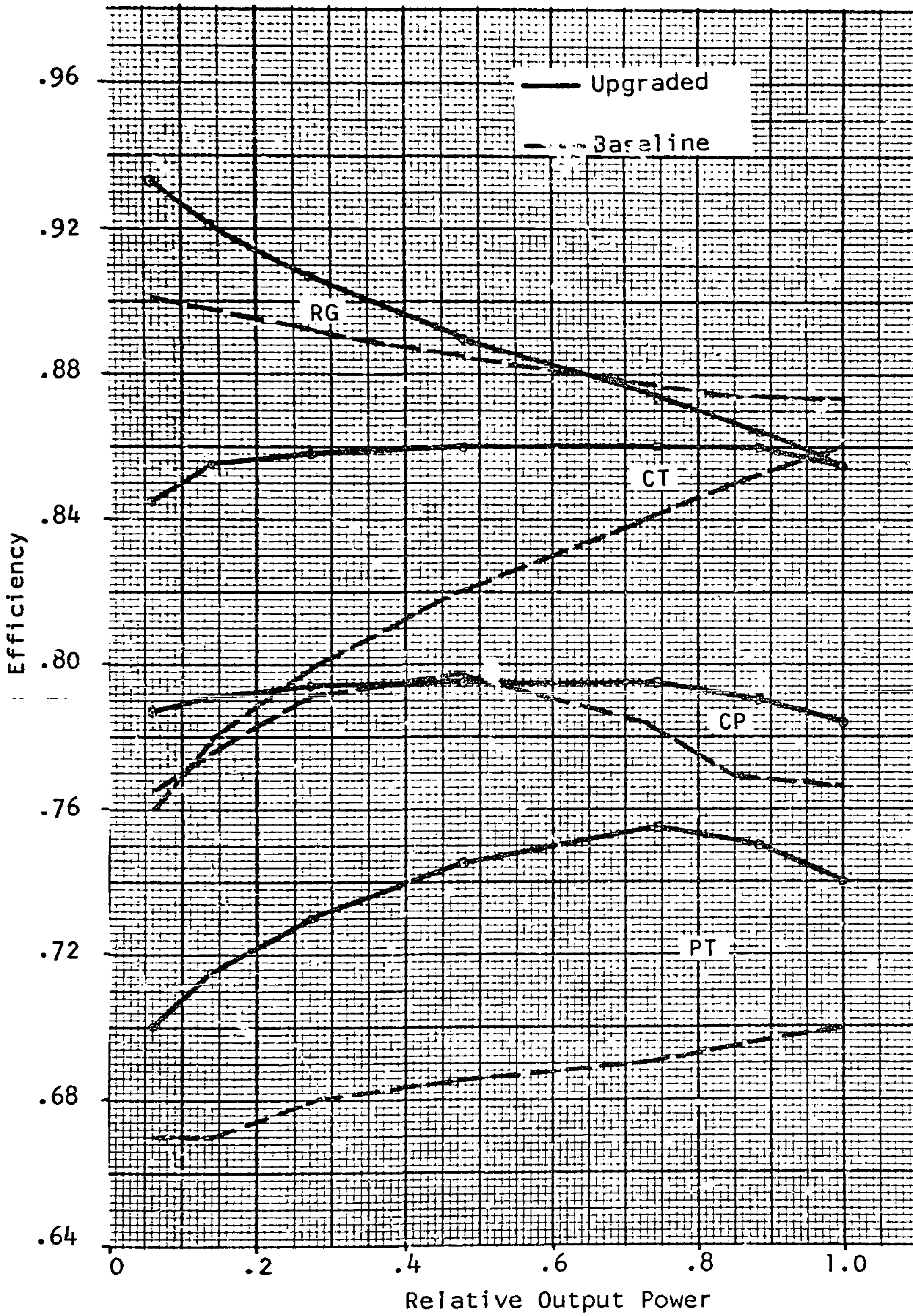


Fig. 44 Component Efficiency Comparison

Question: What is the goal in cycle temperatures?

Answer: There is no real limit; once the regenerator limitation is overcome the turbine wheel temperature will be limiting. Nominally, the higher the cycle temperature the higher the specific output of the engine, the better the engine package and the higher the fuel economy. Present regenerator temperature is limited to 1350°F; the Upgraded Engine is designed for 1400°F. If the rest of the engine would allow it, temperatures would be pushed even higher.

Comment: Although NOx is the most difficult pollutant to eliminate in the gas turbine, it is emphasized that all of the pollutants (unburned hydrocarbon, carbon monoxide and oxides of nitrogen) must be reduced. There are still important variations in test results due to test systems as indicated in tests 3A and 3B and 5A and 5B in Fig. 22. For the most promising burner (proprietary burner of Chrysler's) the 50% speed CO levels are down to about 100 ppm.

Question: Has the burner development emission test cycle used by Chrysler for burner development test results been correlated with test results from a vehicle running the actual Federal Driving Cycle?

Answer: There has been only very limited testing of burners on both test cycles; it is believed to be premature to try to establish a detailed correlation at this time. However, the general results and trends of one cycle seem to be reflected in the results of the other cycle.

Question: It was stated that reduction of emission "spikes" during the transients will require close coordination of both burner design and the control system. Does this imply that Chrysler's proprietary burner has variable geometry?

Answer: It is not appropriate to discuss that point at this time.

Comment: The Chrysler proprietary burner gives somewhat better emission results on gasoline (mainly NOx) than on diesel fuel, but efforts continue to get low NOx on diesel fuel.

Question (Dr. Bucheim, Volkswagen): Does the endurance test cycle include both high and low load operation?

Answer: The endurance cycle is more severe than actual road operation. It includes, in addition to both high and low load operation, numerous transients of rapid acceleration and deceleration, and shut down for maximum soak back.

Question (Dr. Bucheim, Volkswagen): What background emission levels have been experienced in testing?

Answer: Background emissions have been running 1-2 ppm of Hexane with 6-12 ppm Carbon - moderately high ambient levels. Corrections are made for these to approach the Standards. In some instances emissions lower than ambient levels are measured indicating very low or close to zero emissions from the engine. These low levels correlate with probe measurements made in various parts of the burner.

Question (Arthur Underwood, Consultant): Just as emphasis seems to have shifted from emissions to fuel economy, it appears that the need for NOx levels as low as 0.4 grams/mile may not really be necessary. What is EPA doing to raise the value for the NOx Standard quickly, so that less time and money will be wasted meeting unnecessarily low NOx Standards?

Answer: The AAPS Division works toward satisfying the Standards set by other groups. The program is formed to satisfy these requirements. When the requirements change, the program will be modified accordingly.

Question (Dr. J. E. Davoud, D-Cycle Power Systems): In this presentation the approach to reducing NOx seems to have been mutually exclusive of effort to increase cycle temperature and fuel economy. Also, the problem is being approached from predominantly an engineering basis. Has any attention been given to the basic chemical and more scientific approach such as determining activation energy of NOx, etc?

Answer: The general approach to NOx reduction is with lean combustion, particularly in the primary zone because the turbine operates on an overall lean fuel-air ratio. Increasing the cycle temperature helps because it extends the lean limit; combustion temperature can be reduced with increased cycle temperature. Significant NOx formation starts above 3000°F; however, depending on the burner configuration, residence time, etc., significant NOx can begin to form above 2600 to 2700°F. Some of the earlier AAPS programs on combustion supplied fundamental guidance for the current engineering developments. Practical hardware development certainly requires a combined scientific-engineering approach.

Question: Is there a design using inlet guide vanes which will satisfy the extremes of operating conditions and, if the IGV's replace the variable power turbine nozzles, what happens to the dynamic braking capability? What is the resulting net gain or loss in efficiency?

Answer: Based on the compressor tests to date, it does appear that a practical design over the operating range of the engine is achievable using IGV's. The net gain in fuel economy over the driving cycle has not yet been determined. At the outset of the IGV investigation it was recognized that an alternate means of dynamic braking would be required. Several potential alternates were identified, but have not yet been investigated.

Question (Homer Wood, H. G. Wood and Associates): The compressor efficiency levels seem to be low relative to the state-of-the-art of a few years ago. Is this because of the low specific speed? If so, the optimization process with IGV's will have to be repeated when the specific speed is raised to get higher efficiencies.

Answer: The specific speeds are not that low, but performance is based on outlet static/inlet total measurements and the discharge is diffused down to about 0.05 Mach Number in the regenerator (compared to aircraft practice of about 0.2 Mach Number into the burner). The higher diffusion and perhaps a less efficient wheel cause lower efficiency. There are a number of detailed aerodynamic improvements which can be made in the compressor design.

Question (Prof. W. Hryniszak, Clarke Chapman): What is a reasonable compressor efficiency to expect for the future production compressors in this size range? It seems the value varies from a "mystic" 85% to a "realistic" 75%.

Answer: A concise answer is not possible since there must be a compromise between full power, where very little operation is required, and part power, where most of the operation takes place (50 to 75% gas generator speed). Compromises involve specific speed, running clearances on front face (0.010 inch at rated speed; larger at lower speed rather than 0.003 inch), low speed pressure ratio with ability to accelerate to high pressure ratio. It was also pointed out that the current program (scheduled to conclude in 1975) is a stepping stone, and an advanced program aimed perhaps at 1979 (with much more ambitious fuel economy targets), might be expected to have an entirely different engine concept and configuration.

Question (Peter Walzer, Volkswagen): Is it not better to design for a larger surge margin and sacrifice efficiency, so that higher temperatures can be used for part load operation?

Answer: Consideration is presently being given to backward swept compressor blades, so that maximum efficiency can be achieved without sacrificing surge margin.

Question: What fuel is used for the fuel economy projections? What is vehicle weight? What is projected acceleration time of the engine from idle to maximum?

Answer: Diesel fuel is used; the test weight of the vehicle is 3500 pounds. The engine acceleration is competitive. In the compact vehicle with augmentation (122 hp) 0-60 mph is 13 seconds. It is also expected to test the Upgraded Engine in the intermediate sized vehicle.

Question: Is there any rough idea of the production cost of the Upgraded Engine compared to the Baseline Engine and the conventional piston engine?

Answer: No numbers are presently available, but ultimately it must be competitive. At present, because of increased complexity, it will cost more. Prime objectives of the current program are low emissions and high fuel economy. Obviously a lot remains to be done to reduce production cost and optimize performance.

Question: What are the metal temperatures on the gas generator and power turbine wheels?

Answer: Under steady state conditions the nozzle temperature is very close to the gas temperature. The wheel temperature is about 200°F lower than gas temperature. The Chrysler quarterly report will contain these values.

Question: Is the accessibility of the regenerator satisfactory from a maintenance viewpoint?

Answer: The Upgraded Engine configuration (Figs. 39 and 40) is very satisfactory. Ultimately, it is hoped that the regenerator core and the seals will not have to be repaired or replaced.

Question: How would engine packaging change for different vehicle restrictions? What about rear engine mounting?

Answer: The present engine configuration seems well suited for both intermediate and compact vehicles. It circumvents many problems encountered in previous vehicle installations getting the large exhaust ducts out and interference with the steering column and gear. No consideration has been given to rear mounted engines or vehicles of different configuration. The single regenerator results in a narrower engine.

Question: How is an 18% improvement in fuel economy obtained by reducing engine size? It is generally believed that the efficiency of an engine decreases with reduction in size.

Answer: In the vehicle application the 18% improvement in fuel economy, due to reduced engine size, is attributed to: (1) engine operates at higher specific power (fuel rate at 70% rated power is lower than at 50% power), (2) power augmentation due to water injection (increases mass flow through turbine without exceeding temperature limits), and (3) the weight of the vehicle is lower (switch from standard to compact car).

Question (Dr. J. E. Davoud, D-Cycle Power): Carter Enterprises, Inc. has been demonstrating and riding people in their steam car here at the conference. Will information on this privately funded development be presented at the meeting?

Answer: The information and data on this car have not yet been fully processed for presentation.

B. Baseline Engine Project Support, by D. Packe, NASA, Lewis Research Center

This is a brief overview of the status of NASA efforts to support EPA's successful demonstration of a gas turbine-powered vehicle.

NASA's major areas of effort are in providing aerodynamic designs for the three rotating components of the Upgraded Engine (including their gas flow paths), component testing, and work on selected advanced technology.

In the October, 1973 meeting Mr. Hal Rohlik presented preliminary NASA design data on the two turbines and compressor for the 120 hp Upgraded Engine. Since that meeting, EPA has redirected the program to the intermediate vehicle size and correspondingly reduced the engine size to 100 hp. New aerodynamic designs for the smaller engine are now being coordinated with Chrysler to verify their physical compatibility with the Upgraded Engine mechanical design constraints.

Instrumentation and installation of the ambient air aerodynamic test rigs at Lewis are proceeding on schedule. These will be employed to obtain detail performance maps of each of the engine aerodynamic components.

The gas turbine engine test facility and data acquisition system are now fully operational. A complete performance map of the Baseline Engine has been obtained and the data are in general agreement with earlier Chrysler data. Currently attention is focused on an experimental investigation to determine the sources of major engine heat losses. Some of these should be recoverable.

In the areas of new technology NASA combustion specialists have initiated an R&D effort on low-emission catalytic combustors. Promising catalytic substrates will be procured from industry and integrated with in-house combustor designs using fuel/air premix and prevaporization features. Both fixed and variable geometry configurations will be investigated.

In another area, using a NASA-developed Strainrange Partitioning analysis, the low-cycle fatigue behavior of several automotive turbine alloys will be experimentally determined. The results of these tests will provide a rational basis for alloy selection. When the test results are used in conjunction with the stress/strain/thermal analysis, the expected thermal fatigue life of the integral turbine disc and blades may be calculated. It is planned to test AF2-1DA and P.A. 101 alloys over a range of cycle-to-failure, time-to-failure, temperature, strainrange, and cycle wave shape. Two publications on these techniques are from ASTM Special Technology Publication No. 520, 1973:

- "Temperature Effects on the Strainrange Partitioning Approach for Creep Fatigue Analysis"
- "The Challenge to Unified Treatment of High Temperature Fatigue - A Partisan Proposal Based on Strainrange Partitioning"

The remainder of the NASA portion of this report summarizes the work to date on the part load performance of the 120 hp Upgraded Engine (before recent EPA redirections to the 100 hp engine for the compact and intermediate vehicle size). This is of prime importance because the vehicle will be operating under part-load conditions during most of its useful life.

An existing NASA jet engine performance computer program was modified to reflect a two-shaft automotive engine configuration as shown schematically in Fig. 45. The modified program can provide:

- Component matching; i.e., with given component maps the performance of the system can be defined; or with given system design or performance, the individual component maps can be defined.
- Off-design performance can be computed.
- Simulation can be incorporated for variations in: aerodynamics, combustors, heat exchangers, bleed flows, thermal losses, and pressure drops.

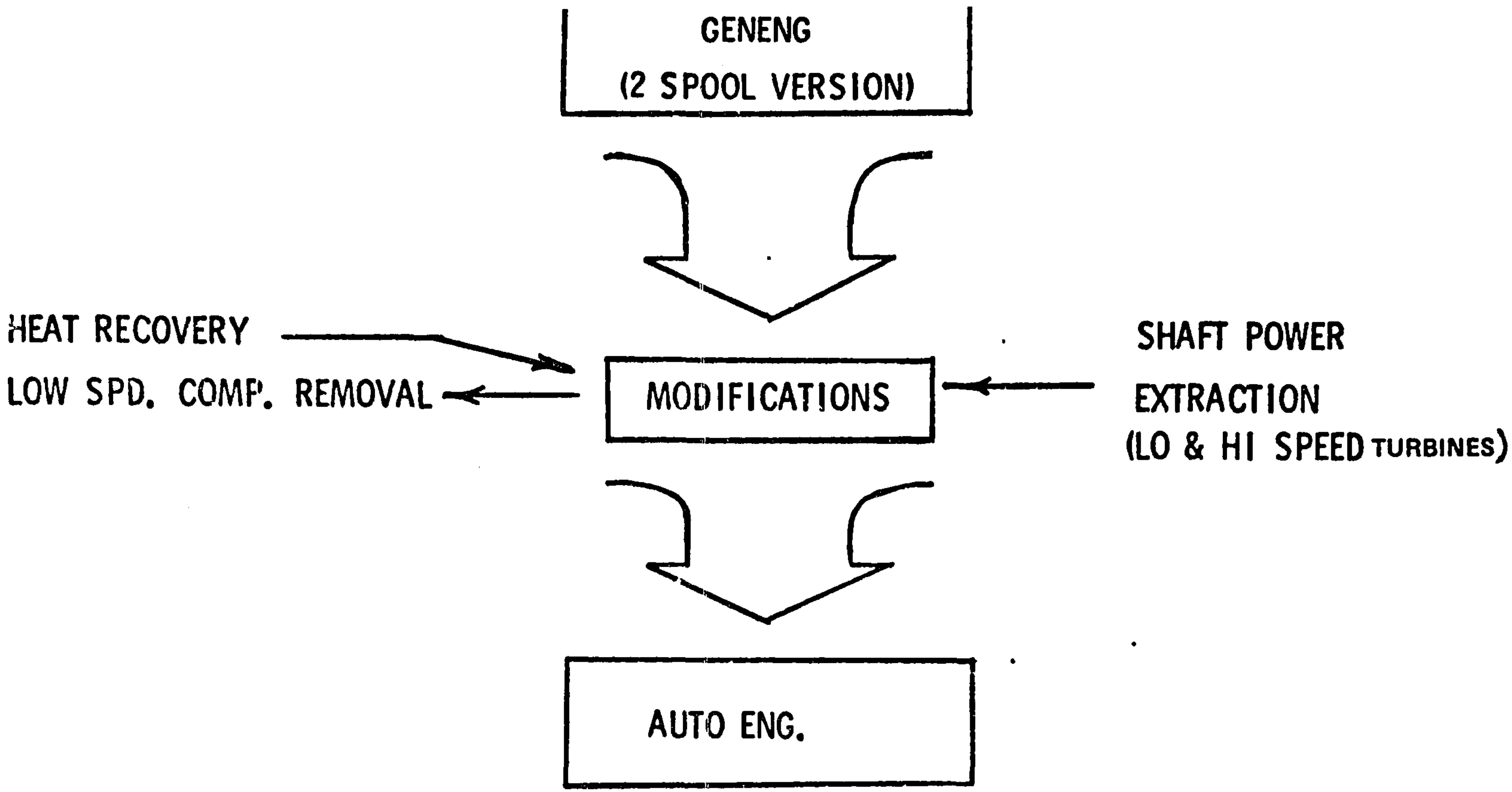

GENENG
(2 SPOOL VERSION)
HEAT RECOVERY
LOW SPD. COMP. REMOVAL
MODIFICATIONS
SHAFT POWER
EXTRACTION
(LO & HI SPEED TURBINES)
AUTO ENG.

Figure 45

Figure 46 is a schematic of the engine showing how the program is set up to account for these various factors. This very closely models the Baseline and Upgraded Engines.

Compressor and turbine maps are shown in Figs. 47 and 48. The corresponding SFC curve over the load range is shown in Fig. 49 and is also compared with Baseline Engine test results.

The series of three curves (Figs. 50, 51, and 52) show the effect of various match point criteria and that a gear change (Fig. 52) can produce a better match over the load range without an undue sacrifice in SFC and without exceeding the creep stress limit.

This type of investigation is now being repeated for the 100 hp Upgraded Engine in accordance with EPA's redirection of the program to the compact vehicle.

As reflected by the above material, major emphasis has been on the short term support of the AAPS Program particularly on aerodynamics and heat loss areas for the Upgraded Engine. However, it should be mentioned that discussions are in progress between NASA and EPA on a longer range, technology oriented gas turbine program.

Questions and Comments

Question (C. Amann, General Motors Technical Center): On the compressor map, maximum efficiency islands are well removed from the surge limit. This is not typical of radial bladed compressors. Does it mean that backward swept blades are being used? If so, what effect does polar moment of inertia have on angular acceleration? Also, on the turbine map (Fig. 48) it appears that the operating line is removed off of maximum efficiency by about 1½ points. Why is this?

Answer: Backward swept blades are not being used. Although efficiency levels are about as expected at design, these are calculated off-design results. It is expected that the tests of the actual engine will show the maximum efficiency lines will be closer to the surge limit.

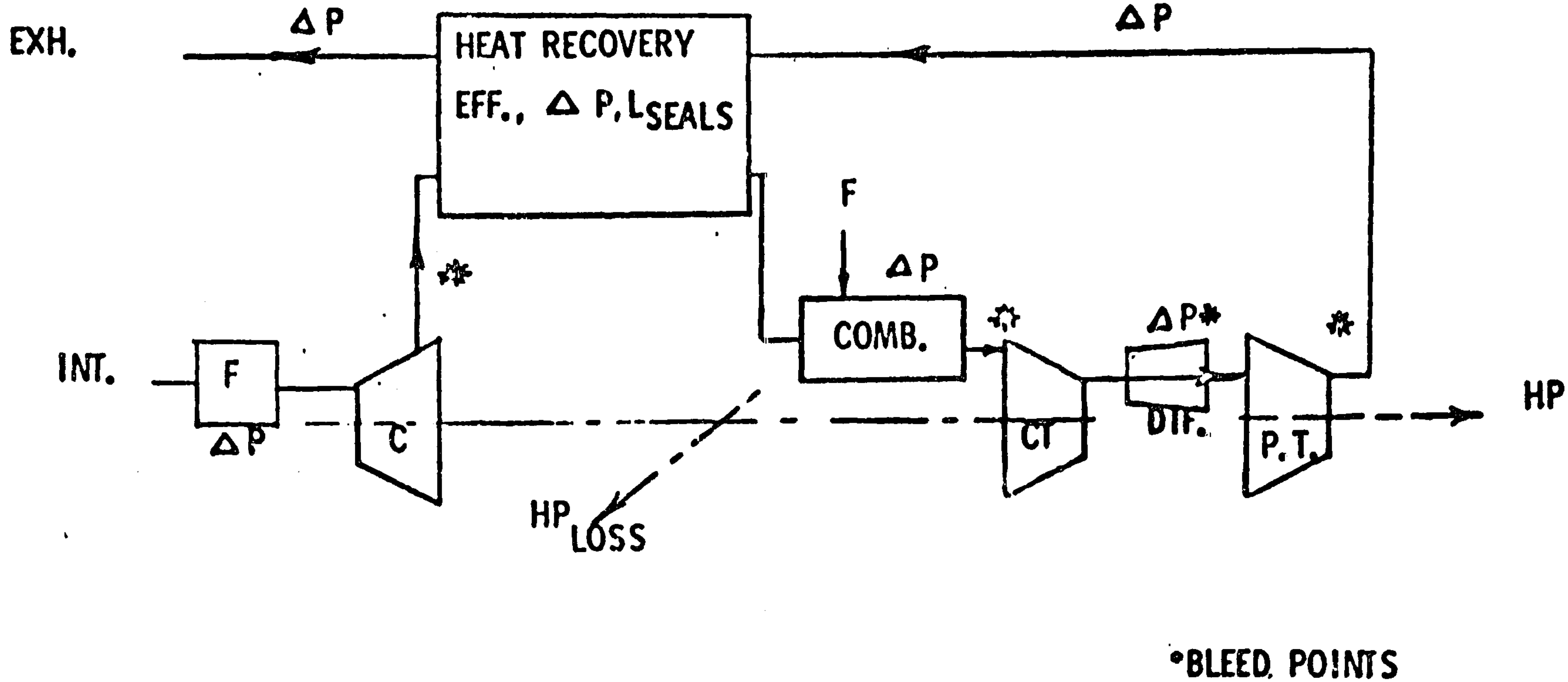


Fig. 46 Gas Turbine Engine Model Schematic

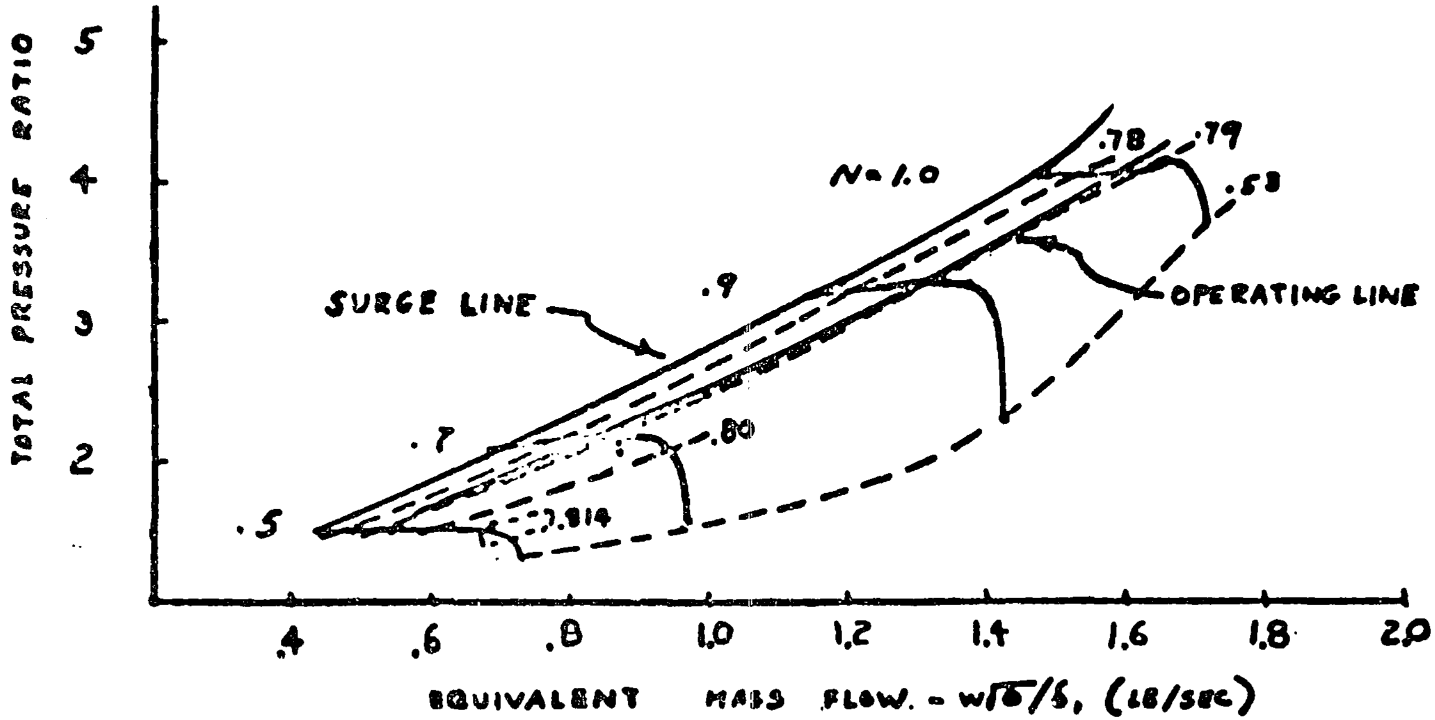


Fig. 47 Radial Compressor 120 HP Upgraded Engine

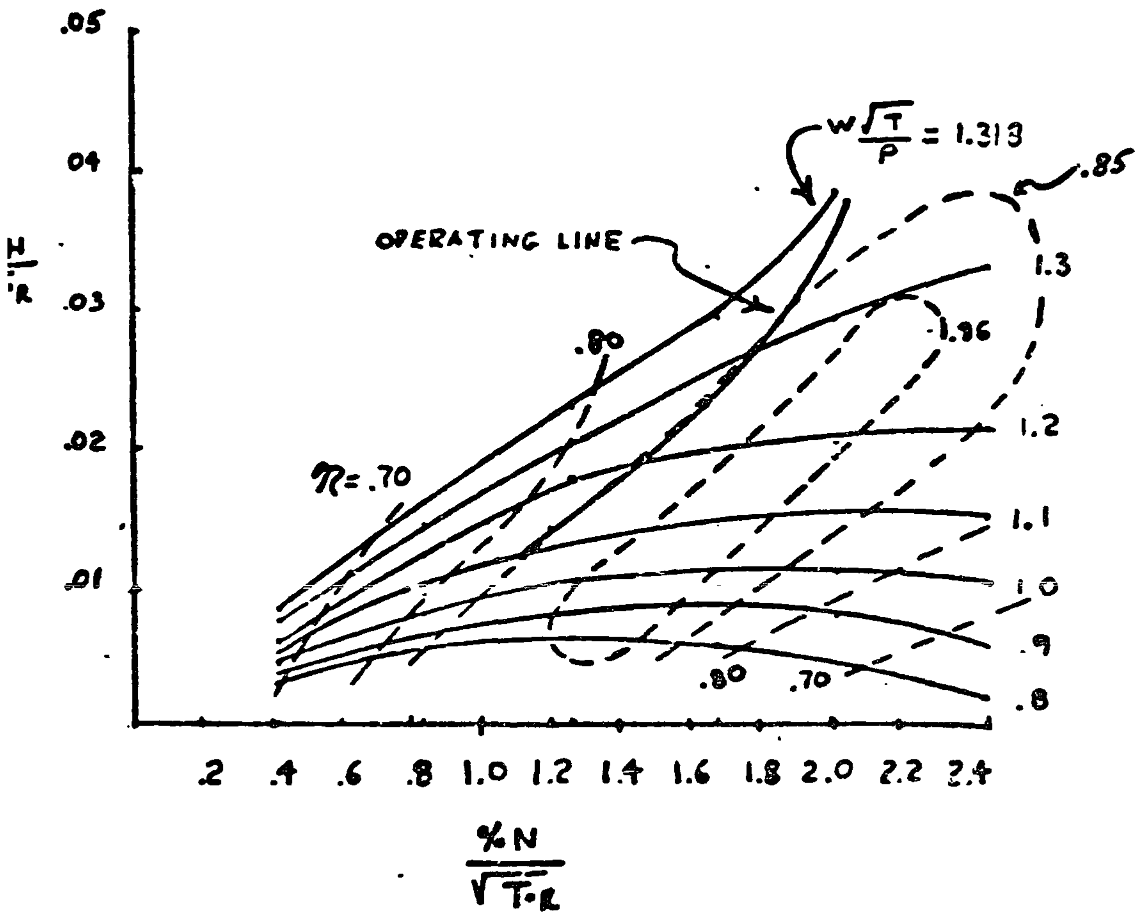


Fig. 48 Radial Compressor Drive Turbine 120 HP Upgraded Engine

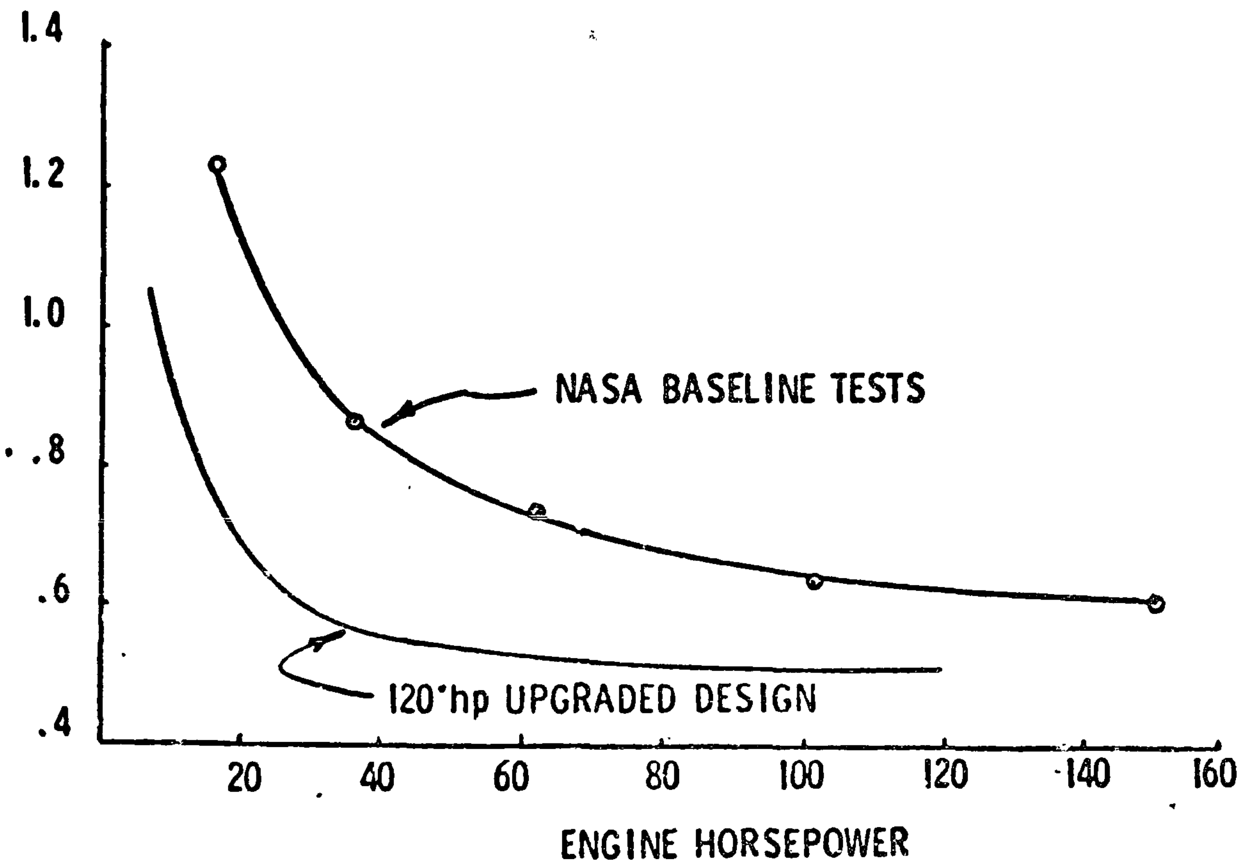


Fig. 49 SFC Versus Power 2-Spool Automotive G.T.

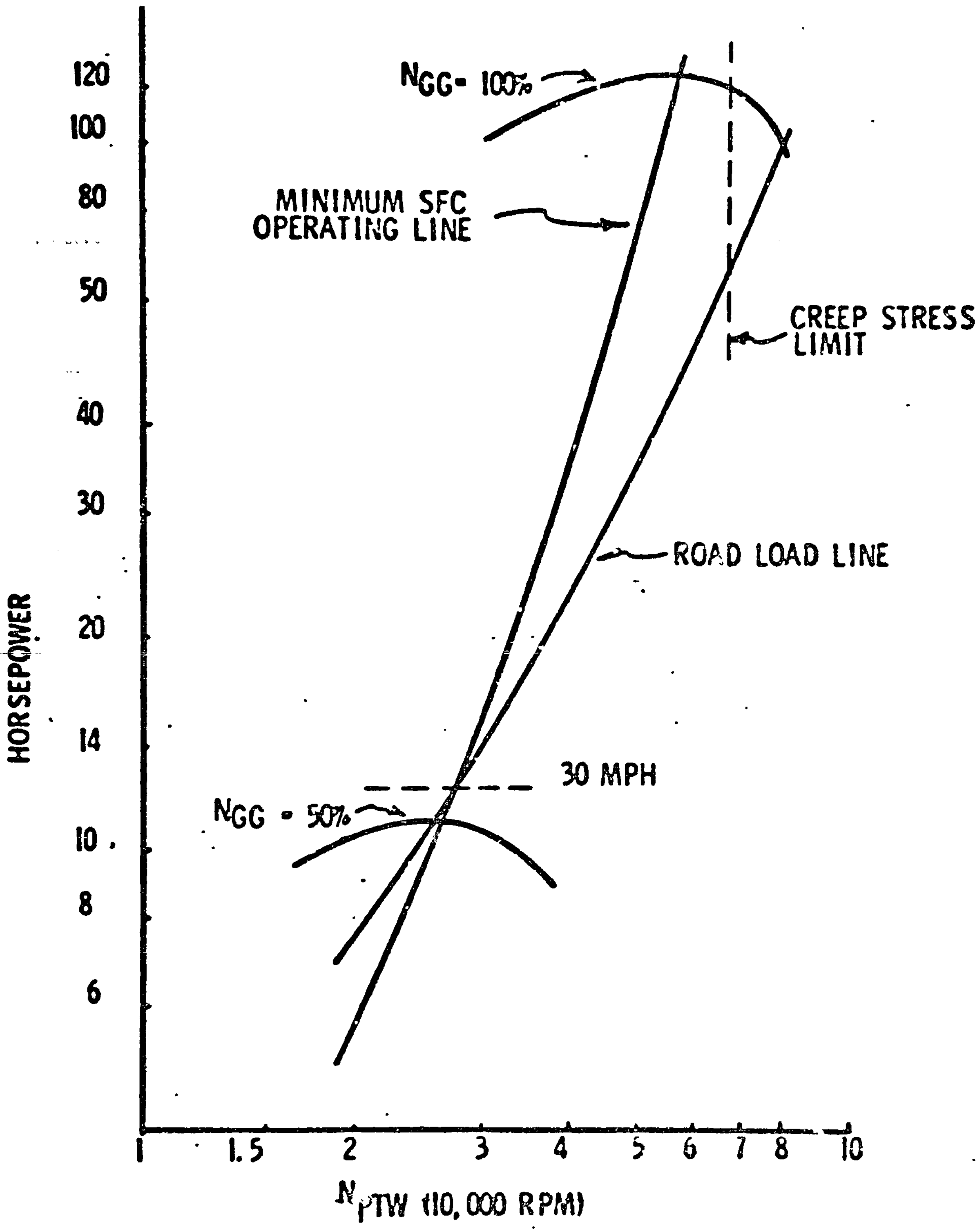


Fig. 50 120 HP Upgraded Engine Low Speed Match

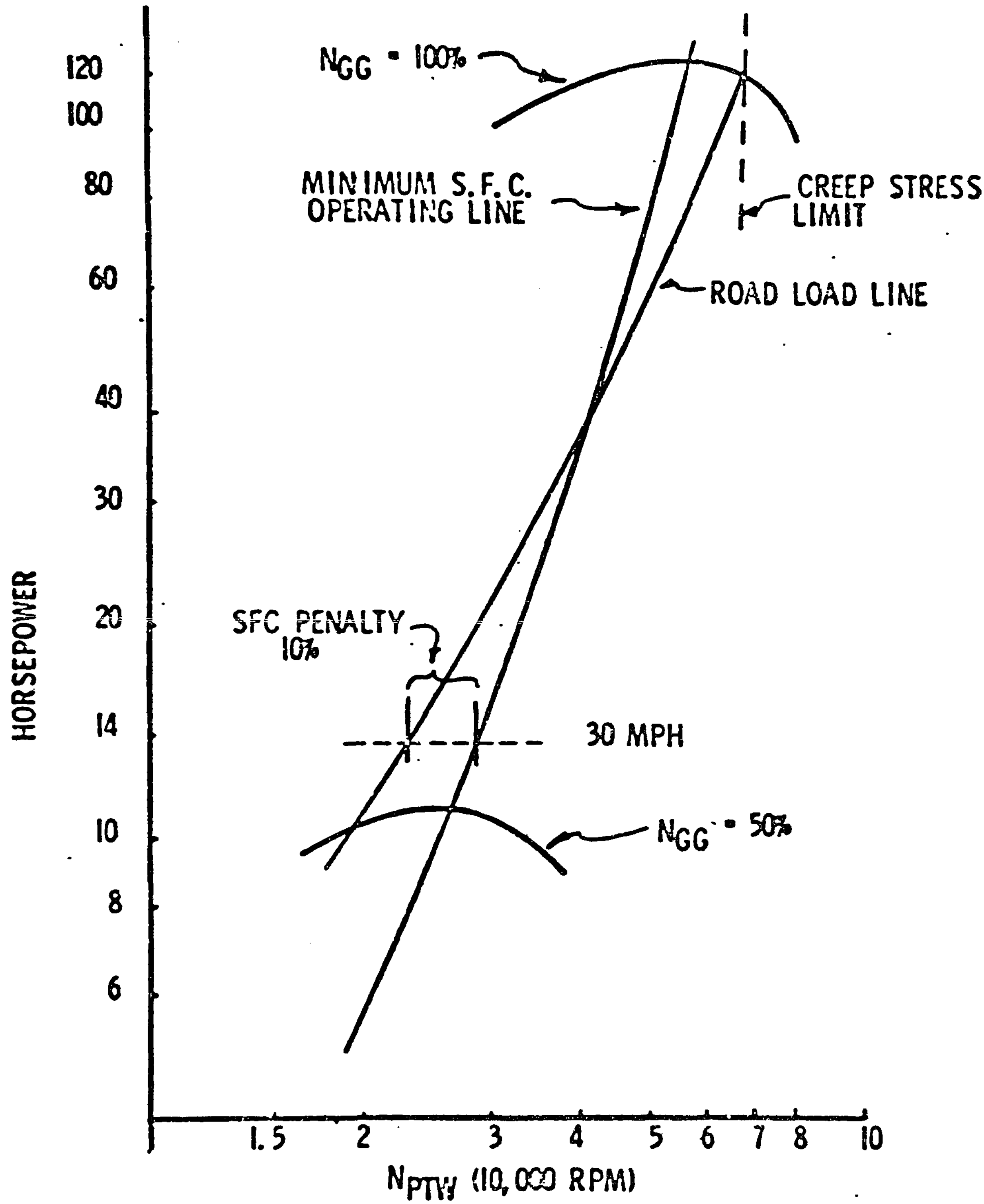


Fig. 51 120 HP Upgraded Engine Creep Stress Limit Match

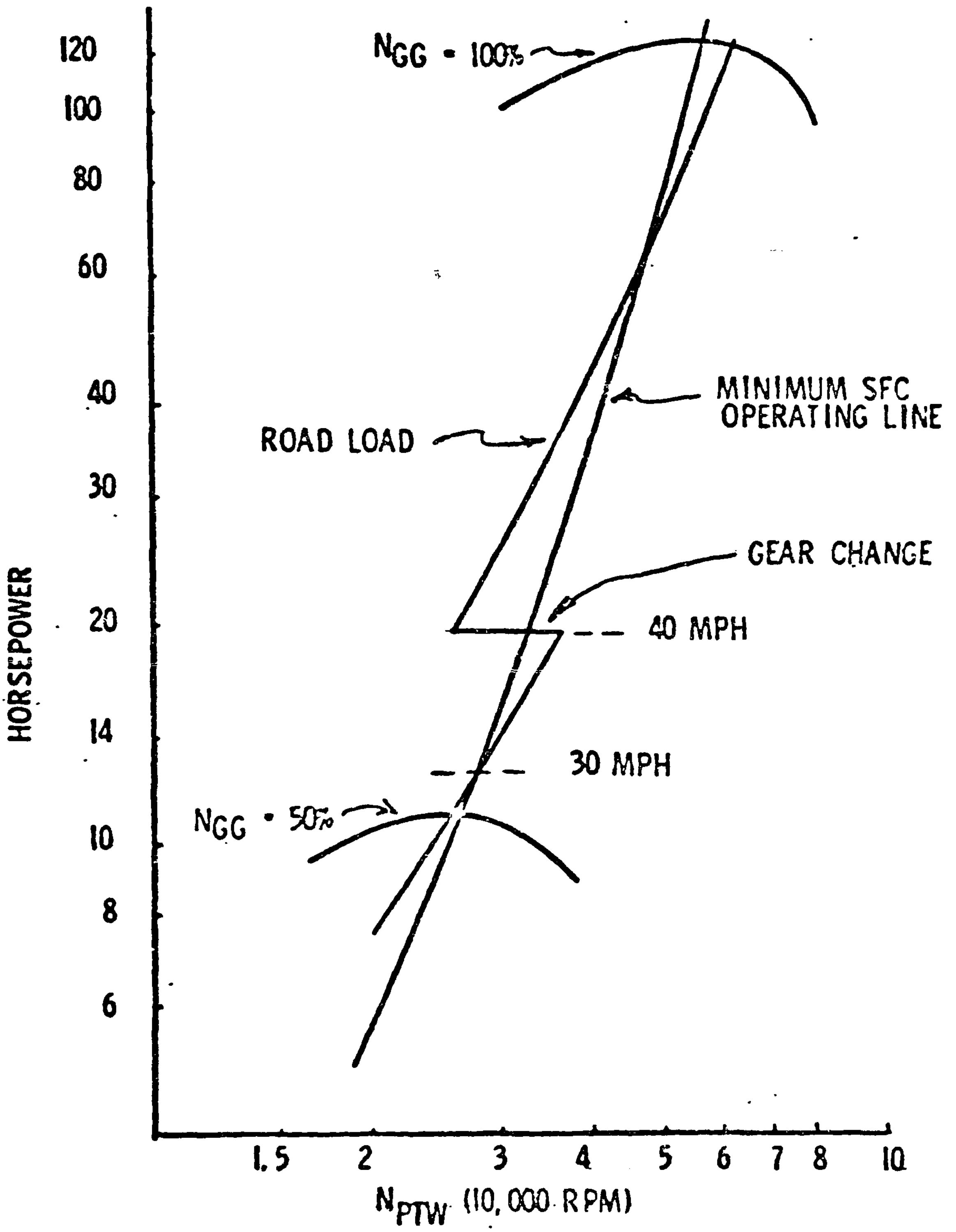


Fig. 52 120 HP Upgraded Engine with Gear Change

Concerning the turbine performance, in upgrading the turbine there were some residual constraints, believed to be stress in the case from the earlier design, which had to be satisfied. Hence, the operating line is not on the maximum efficiency line.

C. Baseline Vehicle Tests to Date - EPA, by Anthony Barth, Emission Control Technology Division

Because the gas turbine exhaust flow far exceeds the capacity of the standard emission measuring equipment used for piston engines and because the concentration of pollutants is much smaller, new procedures for testing turbine vehicles must be developed.

The approach is to use the dynamometer room as the constant volume as in the standard CVS method of testing emissions. The flow into the room is sampled to get the background or ambient emission level; the room outflow is sampled to determine engine emission level. The outflow is restricted to 5500 cfm.

The vehicle is run over the Federal Driving Cycle sampling continuously in the standard way. To calibrate the air flow, a known mass of propane is injected into the room and the mixture sampled before and after the tests. Because of the large size of the room and the inherent cleanliness of this type of engine, the concentration of pollutants is very low; so care and some improvements in techniques are required.

Only a limited number of tests have been run to date. CO levels of 3.5 grams per mile, NOx levels of 2.7 grams per mile, and a fuel economy of 7.3 miles per gallon have been measured over the Federal Driving Cycle. These should be corrected to account for a higher temperature in the room after the test than before the test. This will result in less than a 5% change (decrease in emission levels and increase in fuel economy).

Questions and Comments: None

D. Low Cost Integrated Control for Baseline Gas Turbine Program, by Leon Lewis, AiResearch

AiResearch has been working since last November with Chrysler Corporation to develop a low cost integrated control system for the Upgraded Gas Turbine Engine. The latest Program Plan, reflecting recent modifications to include two additional sets of equipment, is shown in Fig. 53. Emphasis to date has been on analysis of the Baseline Engine characteristics and simulation studies for the Upgraded Engine along with the design and fabrication of the first Preprototype system. The program status is as follows:

- Analytical tools have been established.
- Preliminary engine tests of fuel metering system completed.
- First Preprototype control system in final stages of integration testing at AiResearch; delivery to Chrysler scheduled before end of May.
- Second and third Preprototype control systems in advanced stage of construction.
- Design concepts established for development of Prototype control.

Engine simulation, a joint effort by Chrysler and AiResearch, is based on the notation shown in Fig. 54 and the following simulation input data:

- Compressor maps (including variable I.G.V.)
- Heat exchanger maps
- Combustor functions
- Turbine maps (including variable nozzle)
- Flow leaks (one of the more difficult elements to allocate)
- Heat leaks (one of the more difficult elements to allocate)
- Drive train characteristics
- Vehicle road load and accessories
- Water injection

The simulation model can then be used to produce steady state and transient solutions on the behavior of the engine and be used for:

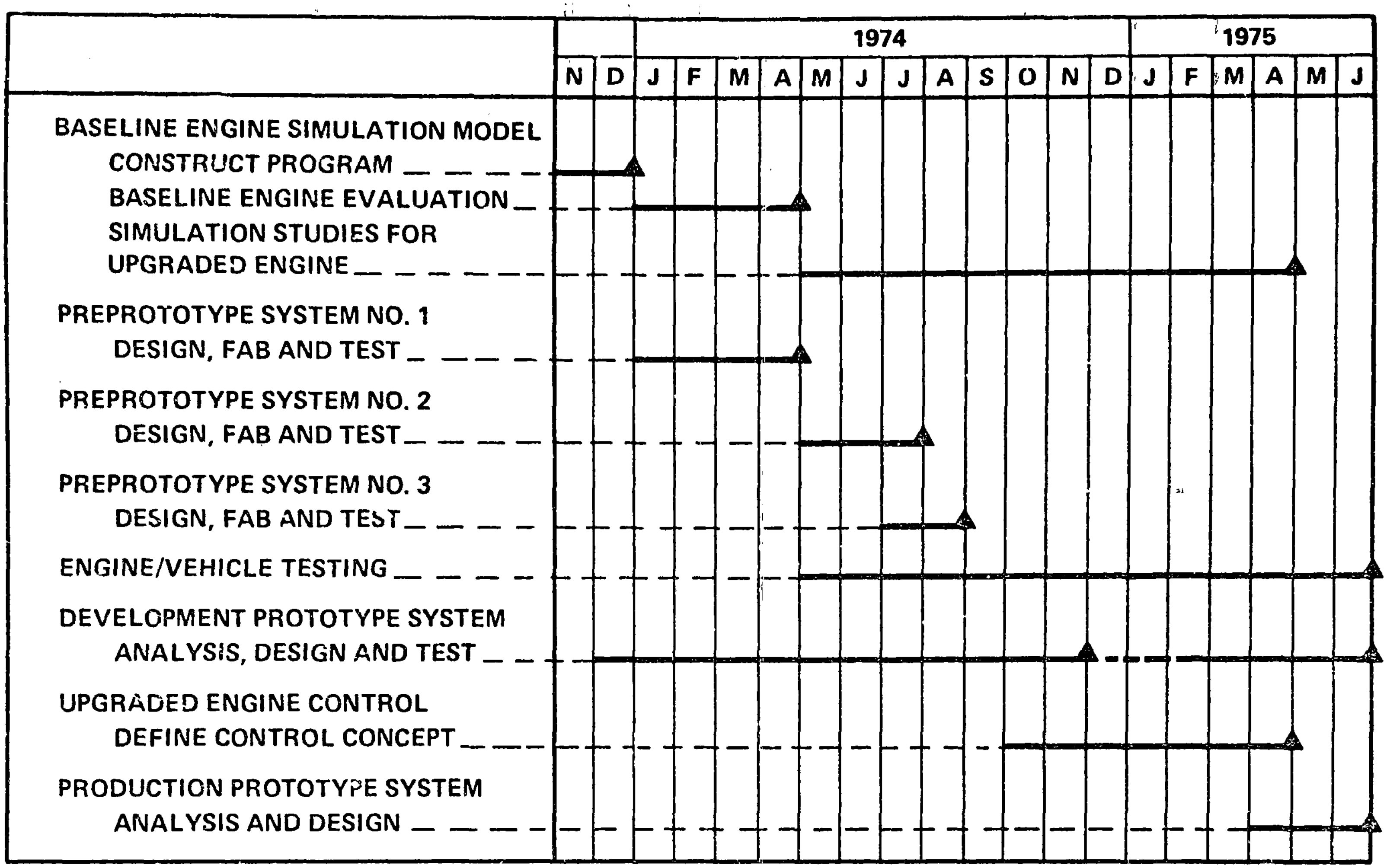
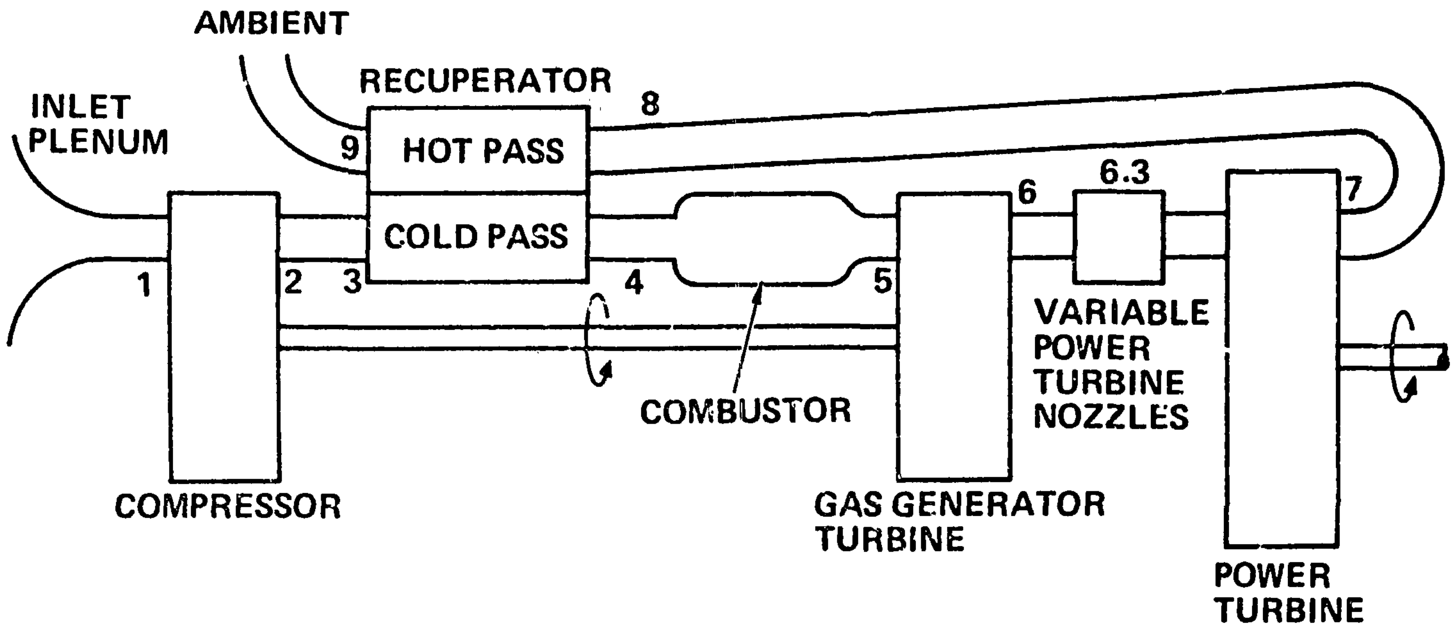


Fig. 53 Integrated Engine Control System Program Plan



STATION NO.	DESCRIPTION		
1 ———	COMPRESSOR INLET	6 ———	COMPRESSOR TURBINE OUTLET
2 ———	COMPRESSOR OUTLET	6.3 ———	POWER TURBINE NOZZLE INLET
3 ———	REGENERATOR COLD SIDE INLET	7 ———	POWER TURBINE OUTLET
4 ———	REGENERATOR COLD SIDE OUTLET	8 ———	REGENERATOR HOT SIDE INLET
5 ———	COMPRESSOR TURBINE INLET	9 ———	REGENERATOR HOT SIDE OUTLET

Fig. 54 Chrysler Engine Station Notation

- Steady-state control requirement definition
- Transient control requirement definition
- Control concept tradeoff studies
- Control system sensor selection
- Control system failure mode analysis

A comparison of model results and engine test data in Fig. 55 show the accuracy of the simulation. Some further improvements are still being incorporated.

Thus, the achievements to date are:

- Model is operational in both steady-state and transient modes.
- Preprototype control system defined and evaluated on model.
- Model transient accuracy verified by preliminary engine tests at Chrysler.

A functional diagram of the Preprototype integrated control system is shown in Fig. 56. A table of corresponding symbols is in Fig. 57. All possible options which might be required are included for evaluation. From this point on, the intent is to reduce and simplify the number and complexity of the system elements.

Figure 58 shows one of the electronic modules which is typical of the mini-computers used for each of the functions shown. Features of the fuel system computer are:

- Gas Generator Range Governor
  - Idle power augmentation
  - Maximum power computation
- Acceleration Fuel Schedule
  - Hot restart limiting
  - T_5 limiting
  - Minimum acceleration fuel
- Deceleration Fuel Schedule
- Alternate Fuel System Deceleration Shut-Off
- Max. Gas Generator Speed Control with Start/Park Limiting
- Power Turbine Overspeed Governor

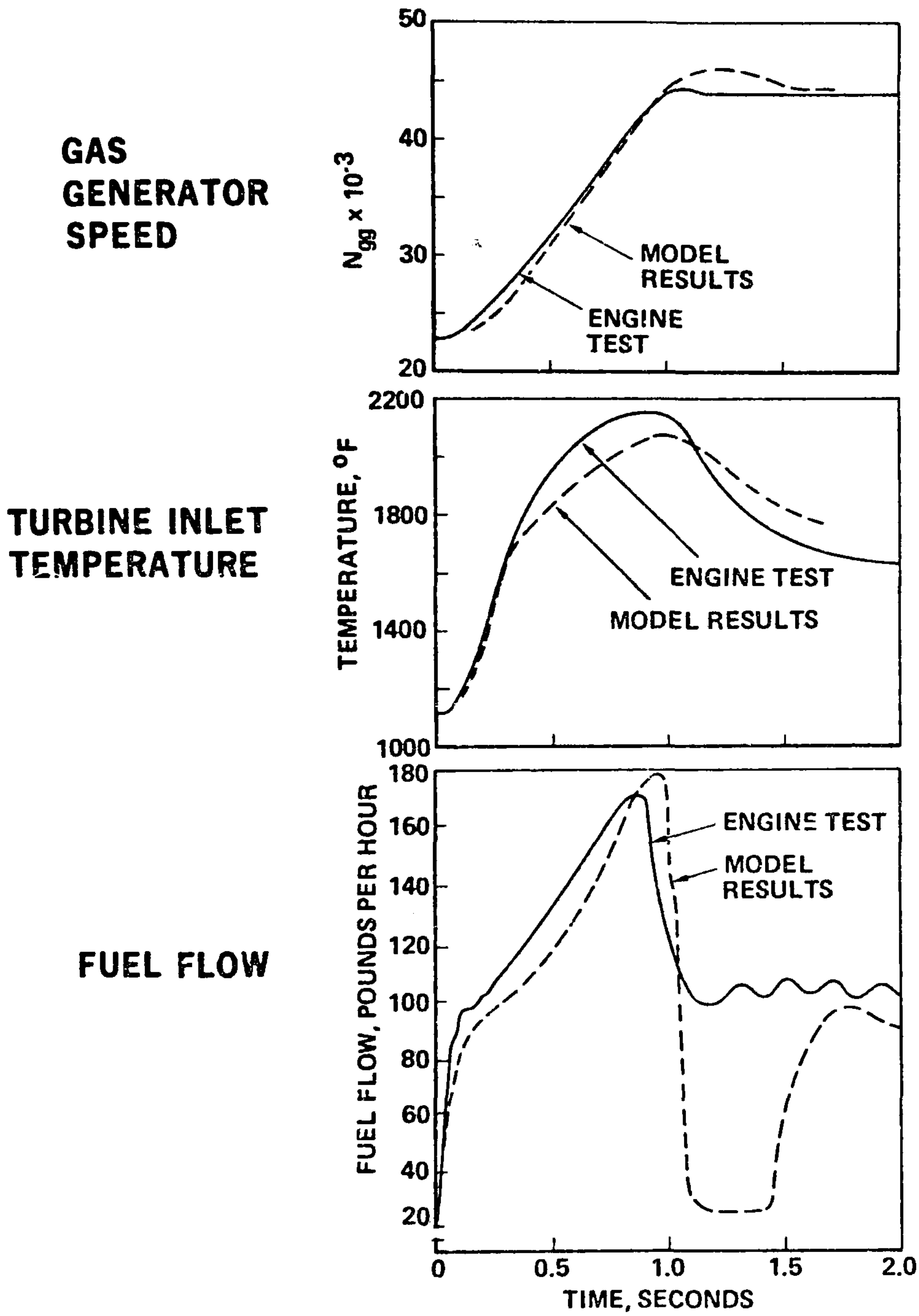


Fig. 55 Comparison of Model Results with Engine Test Data (Acceleration From 50% Ngg to 100% Ngg)

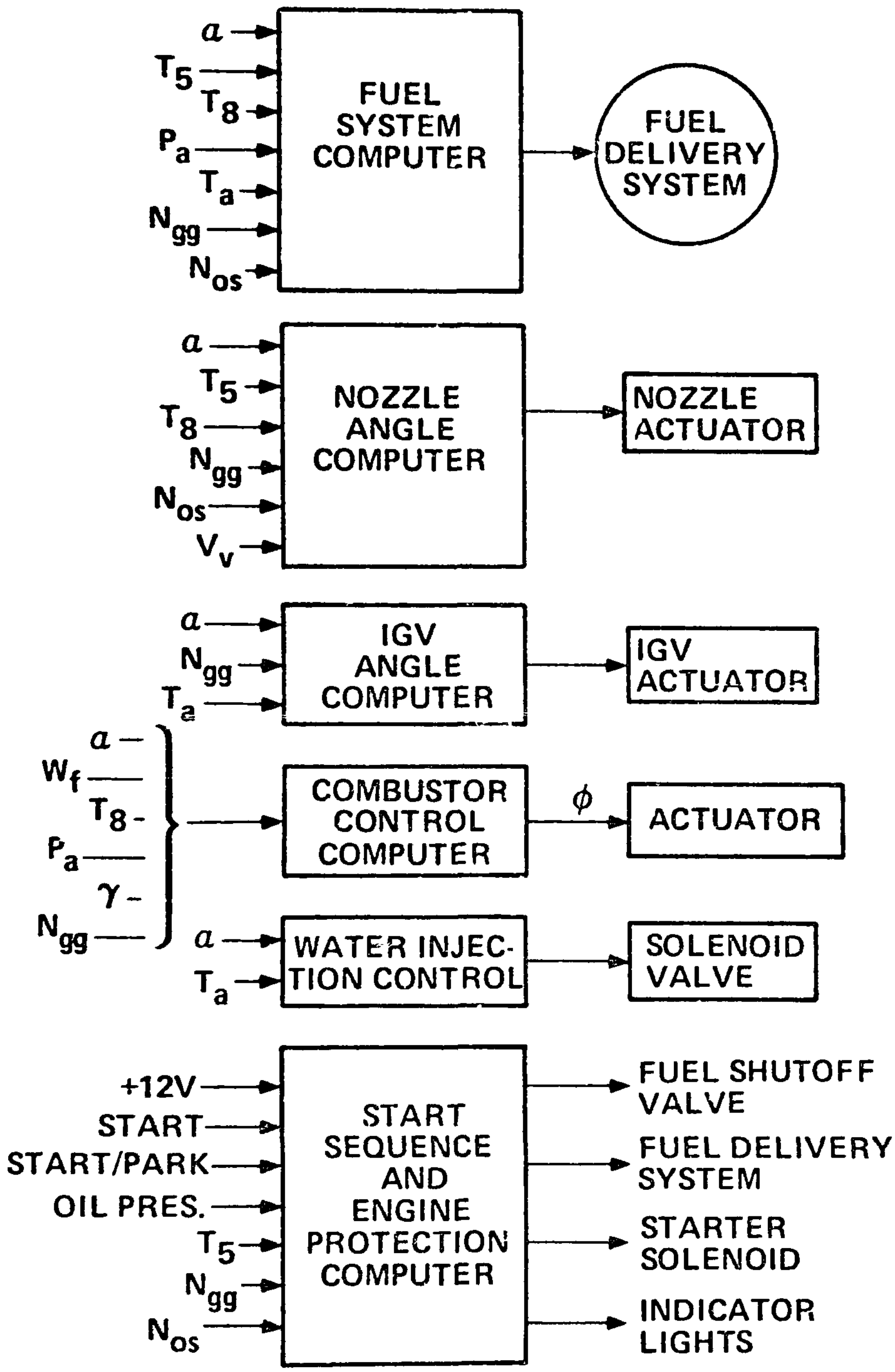


Fig. 56 Simplified Functional Diagram Preprototype Integrated Control System

T_5	GAS GENERATOR TURBINE INLET TEMPERATURE
T_8	LOW PRESSURE REGENERATOR INLET TEMPERATURE
T_a	AMBIENT TEMPERATURE
P_a	AMBIENT PRESSURE
N_{gg}	GAS GENERATOR SHAFT SPEED
$\frac{N_{gg}}{\sqrt{\theta}}$	CORRECTED GAS GENERATOR SPEED
δ	AMBIENT PRESSURE CORRECTION, $= \frac{P_1 \text{ PSIA}}{14.7 \text{ PSIA}}$
θ	AMBIENT TEMPERATURE CORRECTION, $= \frac{T_1 {}^{\circ}R}{545^{\circ}R}$
N_{os}	OUTPUT SHAFT SPEED
α	THROTTLE PEDAL POSITION
β	POWER TURBINE NOZZLE ANGLE POSITION
λ	INLET GUIDE VANE ANGLE POSITION
ϕ	VARIABLE GEOMETRY BURNER POSITION
W_f	FUEL FLOW IN POUNDS PER HOUR

Fig. 57 Table of Symbols

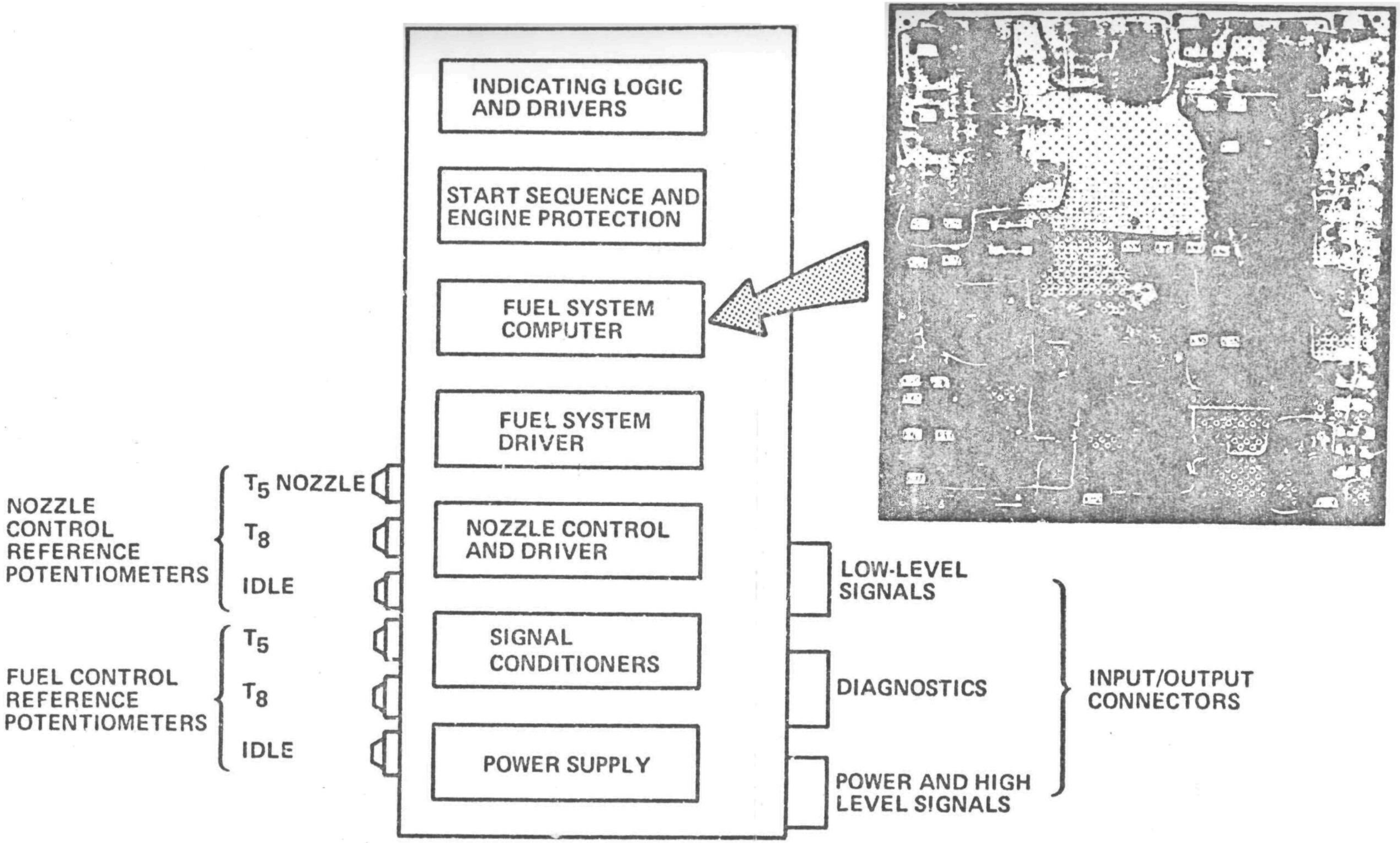


Fig. 58 Electronic Controller, First Preprototype Control

The nozzle control computer incorporates the following:

- Nozzle braking logic
- T_8 temperature control in power mode and braking mode
- Idle and low speed power turbine governing
- Power turbine overspeed control
- T_5 temperature control

The nozzle trim actuator is shown installed on the engine in Fig. 59. The nozzle trim actuator:

- Provides trim function by operating in series with Chrysler nozzle actuator
- Powered by 50 to 100 psi fluid pressure from the turbine lubrication system
- Responds to signals from integrated gas turbine system controller
- Designed for full stroke against operating load in 0.10 seconds
- Frequency response flat to three cps
- Thirty thousand cycles of endurance testing complete prior to delivery of first unit
- First unit shipped March 26, 1974

The Prototype nozzle actuator is in development (Fig. 60). It provides power modulation, braking function, and braking modulation as well as power modulation velocity and braking velocity additive for maximum response. Component development tests have started; design is scheduled for completion June 30, 1974; endurance tests are to start September 30, 1974; and two units with spares are to be shipped November 30, 1974.

Parallel development of the inlet guide vane actuator is in progress. Its functions and status are as follows:

- Positions guide vanes at inlet to compressor
- Powered by 50 to 100 psi fluid pressure from the turbine lubrication system
- Responds to signals from integrated gas turbine system controller

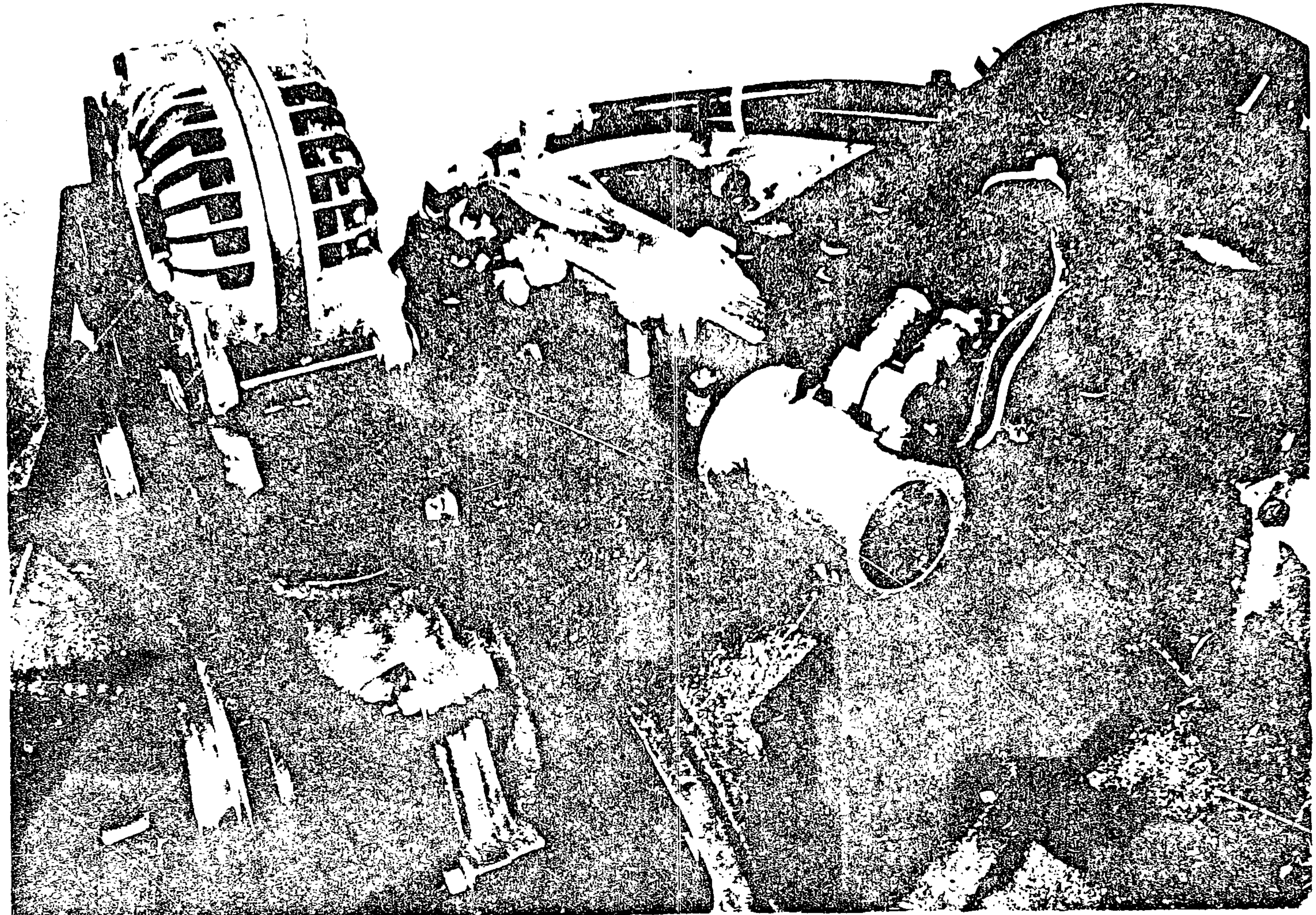


Fig. 59 Chrysler Fuel Control Nozzle Trim Actuator Installation

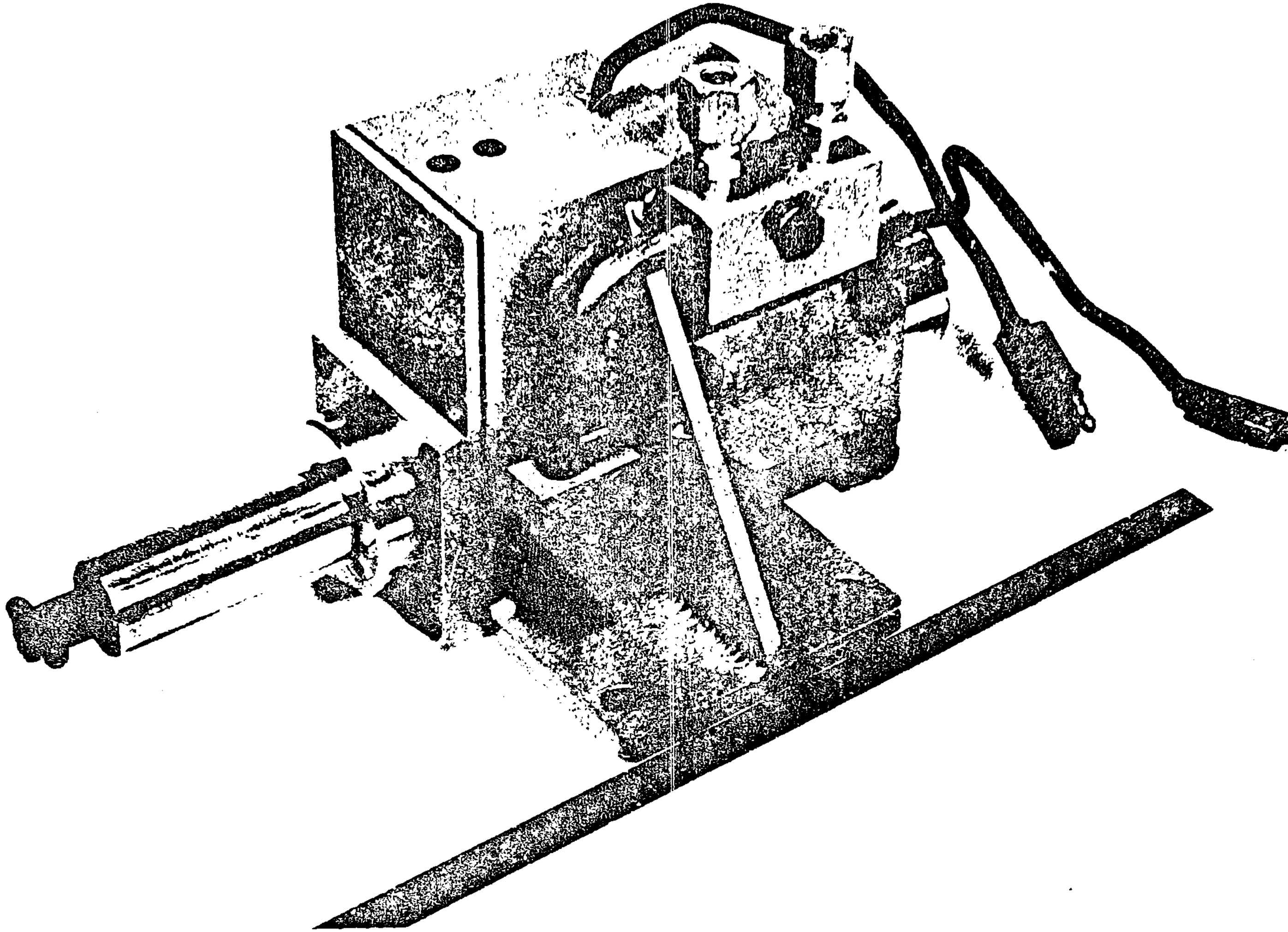


Fig. 60 Chrysler Fuel Control Development Nozzle Actuator

- Designed for full stroke against operating load in 0.20 seconds
- Servo loop closed by side mounted potentiometer
- First unit scheduled for assembly week of May 13, 1974 and shipment July 31, 1974
- Frequency response expected equivalent to trim actuator

A schematic of the motor driven fuel pump and its performance is shown in Fig. 61.

Questions and Comments

Question: Concerning the motor driven fuel pump, does the system postulate a constant volumetric efficiency for the pump, or is there a feedback of actual fuel flow rate?

Answer: The present philosophy is that performance degradation due to loss of volumetric efficiency effects only the transient response and has no effect on steady state accuracy of the system. If the system goes to production, it means the scale factor for pump speed to fuel flow would have to be adjusted periodically - analogous to a "tune-up".

Question: Are transient pressure effects of the compressor included in the dynamic model?

Answer: It is not known how to define these transient effects on this model until the results of tests on the actual engines with the system are available. These effects may be significant, so this information should be very helpful.

Question: How long does it take for the variable nozzle to move after control actuation is started?

Answer: First movement of the actuator is in less than 50 milliseconds.

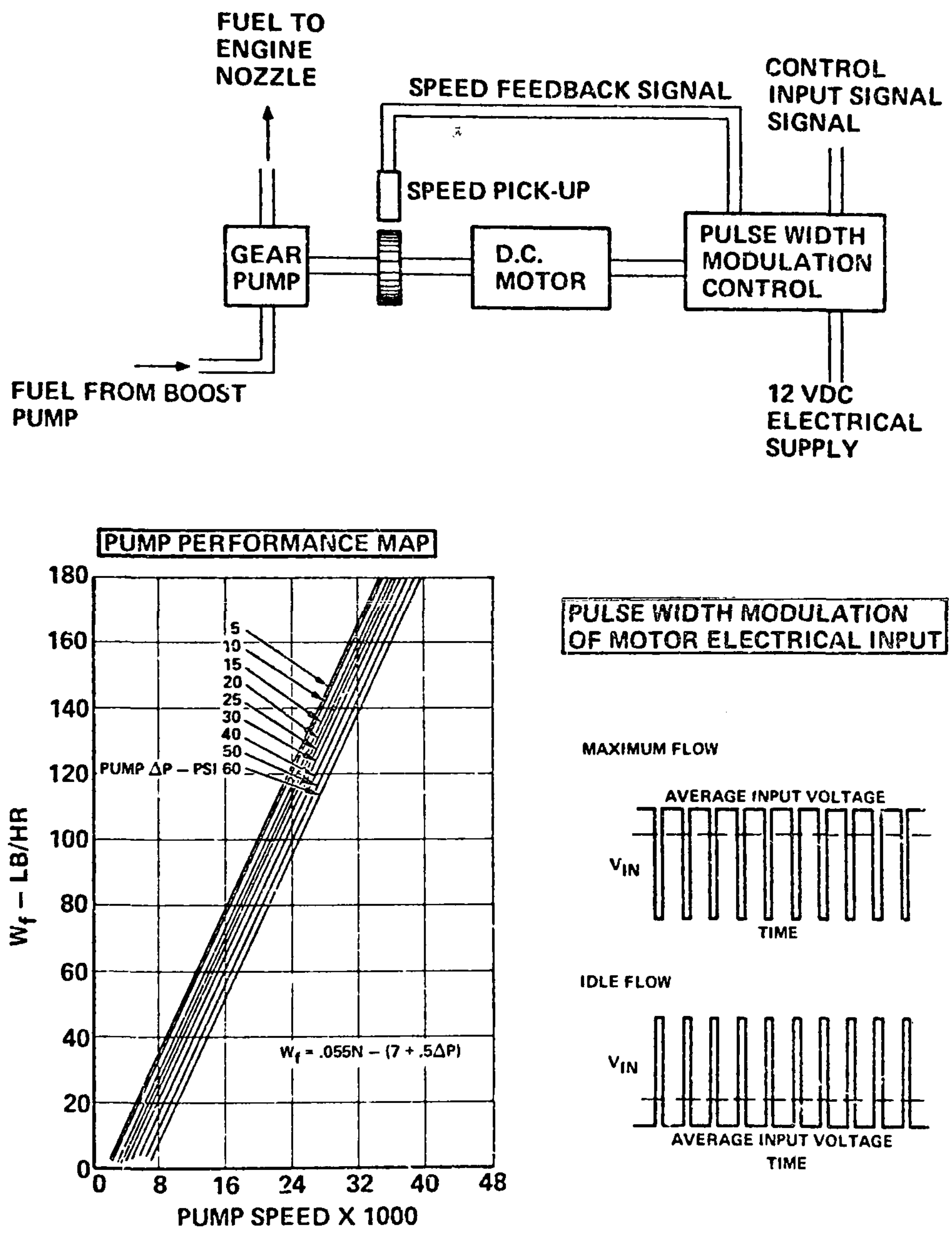


Fig. 61 Motor-Driven Fuel Pump - Chrysler Automotive Gas Turbine Integrated Control System

E. Low Cost Turbine Wheel Manufacturing Process, by Marvin Allen, Pratt & Whitney Aircraft Corp.

The Florida Research and Development Center is under contract to EPA to demonstrate the feasibility of low cost production of automotive turbine rotors by the Gatorizing process.

The general objectives of the two-phase program are:

Phase I

- Design and fabricate the dies and experimentally demonstrate low-cost, mass-production manufacturing techniques for automotive turbine disks.
- Estimate the tooling and manufacturing cost for a representative automotive turbine disk for production rates of one million turbine disks per year.

Phase II

- Produce, evaluate, and deliver compressor turbine disks using the recommended manufacturing process for demonstration in the EPA Baseline Gas Turbine Engine.

The current contract authorizes only the first phase, as shown in Fig. 62.

The program was initiated 26 April 1973 and is comprised of five major tasks:

- Task 1 - Baseline Process Demonstration
- Task 2 - Process Parameter Evaluation
- Task 3 - Generation of Design Data
- Task 4 - Definition of Manufacturing Process
- Task 5 - Manufacturing Cost Estimate

The Task 1 basic process demonstration involves the procurement of the program material, the designing and fabrication of preform forging dies, and the GATORIZING of the initial preform for Baseline mechanical properties. The selected processing parameters for the raw material, the GATORIZING parameters, and the heat treatment were currently used to produce the wrought IN100 components for the F100 engine (the F100 engine powers the F-15 air superiority fighter).

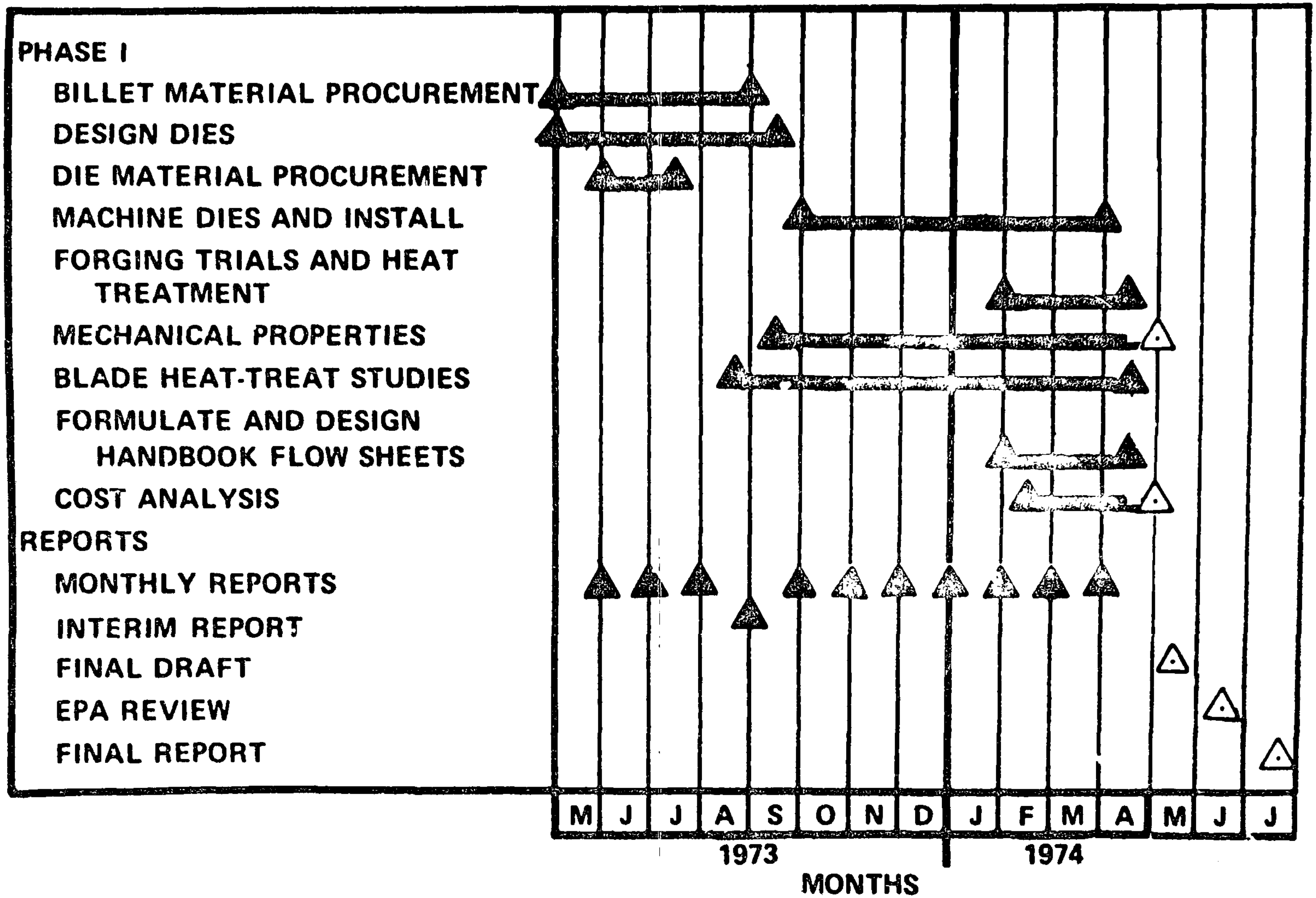


Fig. 62 Phase I Program Schedule

The parametric evaluation, Task 2, involves the evaluation of additional forging parameters and heat treatments. The alternate processing will be designed to create the most favorable structure in the preform for subsequent finish forging and to establish a thermal process, which produces mechanical properties consistent with Chrysler's design requirements. The final part of Task 2 is the forging and evaluation of GATORIZED, integrally bladed rotors.

The design data generation, Task 3, involves the establishment of complete design curves for the short-time, long-time, and cyclic properties. It was anticipated that the optimum heat treatment for the disk portion of the wheel (LCF consideration) might not be adequate for the blades (stress-rupture consideration). Therefore, additional thermal cycles aimed at producing higher properties in the blade operating temperature range (1700 to 1800^{o}F) will be evaluated.

The Task 4 Manufacturing Process Definition actually describes two separate tasks. The first is the preparation of detailed process sheets for the manufacture of the finished rotor; the second is the preparation of design data sheets to identify trade-offs in rotor design and performance versus producibility and cost.

In Task 5, a detailed Manufacturing Cost Estimate for producing the wrought turbine rotor in quantities of 100,000, 1,000,000 and 10,000,000 pieces annually will be prepared. The processing sequence will follow that prepared in Task 4 and identify additional research and development, fixed and variable costs, and the impact of the alternate production rates.

By April 1974, Tasks 1, 2 and 4 had been completed. The bladed rotors for the Task 3 design data have been forged and heat treated and are currently being cut up for test specimens. Finally, the Manufacturing Cost Estimate, Task 5, will be completed by 30 May 1974.

A two-step forging sequence was selected to GATORIZE the rotors. The first step produced a nonbladed oversized preform, which has a twofold purpose: (1) to ensure proper metal distribution for forging the bladed rotor; and (2) to further enhance the forgeability of the material. The second step reduces the disk area to final dimensions and fills the blade die insert cavities.

The final bladed rotor design was completed and the tooling fabricated. A cross section of this tooling is shown in Fig. 63. The cavities for the 53 blades are formed by simple split inserts. The finished machined tooling is shown in Fig. 64.

Eight forging mults 44.45 mm (1.750 in.) in diameter by 85.85 mm (3.38 in.) high were machined from the extruded stock. The mults, after being coated with a boron nitride lubricant, were GATORIZED to the preform configuration. In the as-forged configuration the preform exhibited a uniform, fully recrystallized fine-grained structure (ASTM 8 to 10 when viewed at 1000X).

These preforms were used for the Task 1 and portions of the Task 2 evaluation as summarized in Fig. 65. The test specimens for the mechanical property and/or structural evaluation were located within and machined from the forgings as shown in Fig. 66. The depicted cut-up diagram was used for both the preform and bladed rotor evaluation.

The remaining preforms were used to determine the effect of forging temperature and solution temperature on microstructure and mechanical properties. Mechanical properties did not vary significantly with forging temperatures in the 1038°C (1900°F) to 1093°C (2000°F) range. Room temperature tensile properties are shown in Fig. 67. The reasons for the variation in tensile ductility have not been fully explained. Elevated tamperature tensile strength was insensitive to forging temperature over the entire range investigated. Again a degree of inconsistency in ductility was noted. The elevated temperature tensile data are presented in Fig. 68.

Two preforms were used to establish the effects of alternate heat treatments. Gradient bars cut from one of the preforms were used to determine the effect of heat treatment on microstructure. The second preform was cut in half, and each half given a heat treatment selected from the gradient bar evaluation. The purpose of this evaluation was to establish a heat treatment (primarily modified solution temperature) to produce a coarser grained structure, which would exhibit mechanical properties commensurate (primarily stress-rupture)

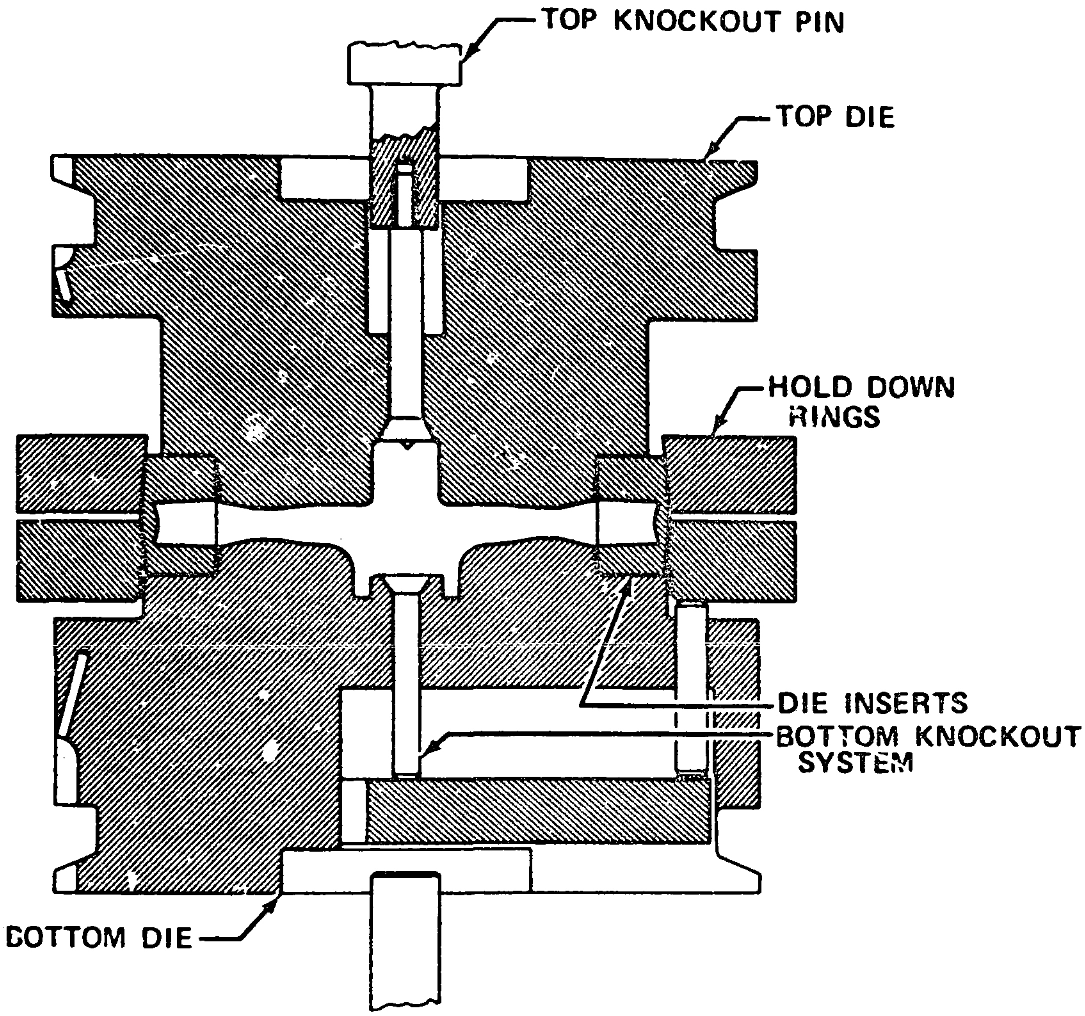


Fig. 63 Tool for Phase I -- Task 2 Bladed Rotor

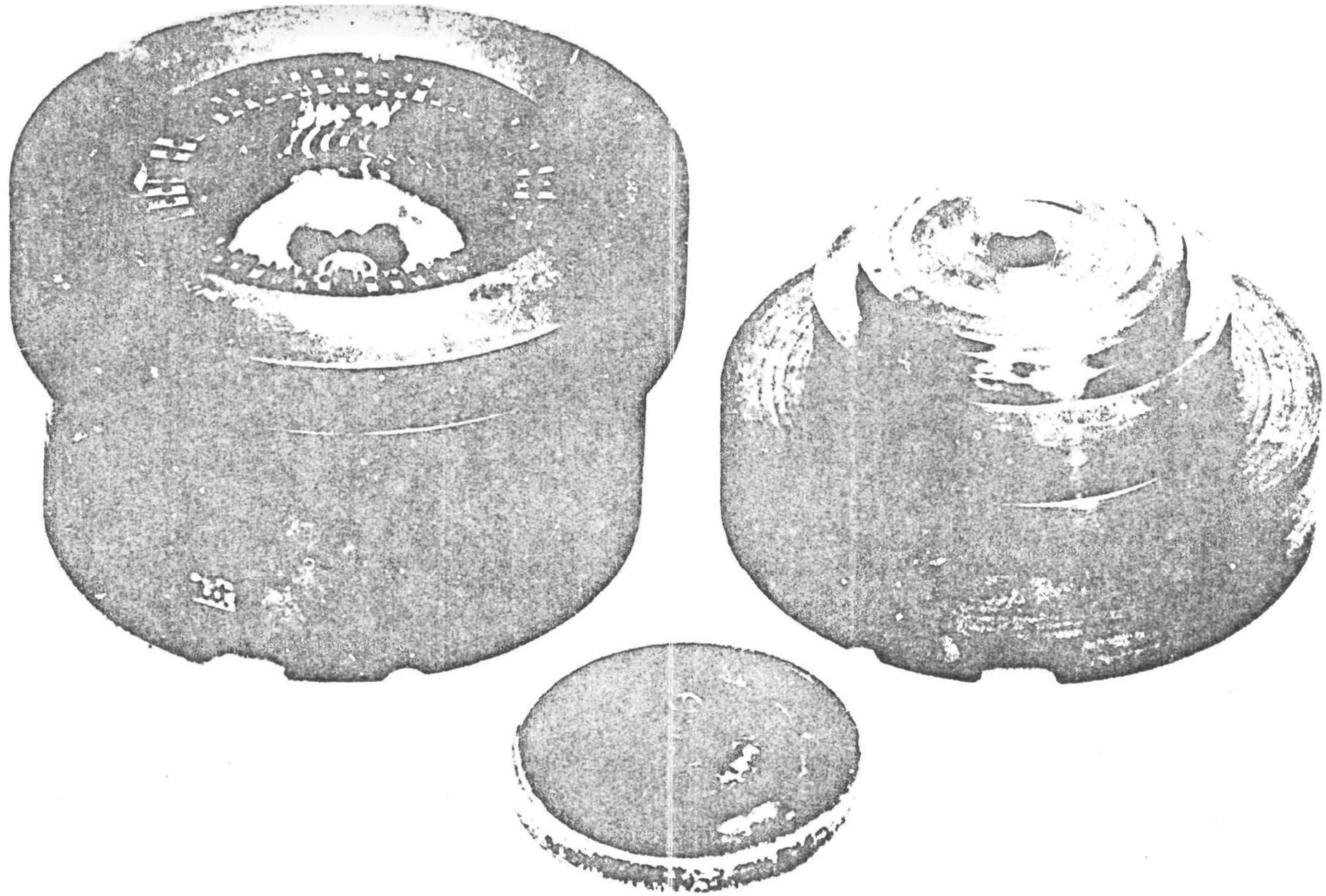


Fig. 64 Finish Machined Bladed Rotor Tooling and Preform

PROFORM S/N	FORGE TEMPERATURE °C	°F	HEAT TREATMENT	PROGRAM USE	ASTM GRAIN SIZE PREDOMINATE	OCCASIONAL
2-3	1010	1850	BASELINE:	FORGE TEMPERATURE STUDY	10.5 - 13.5	10.0
2-4	1038	1900	1121°C (2050°F) SOLUTION, OIL QUENCH	BASELINE DATA	10.5 - 13.5	10.0
2-5	1038	1900	871°C (1600°F) AIR COOL	BASELINE DATA	10.5 - 13.5	9.5
2-8	1066	1950	982°C (1800°F) AIR COOL 649°C (1200°F) AIR COOL	FORGE TEMPERATURE STUDY	11.5 - 13.5	
2-7	1093	2000	760°C (1400°F) AIR COOL	FORGE TEMPEATURE STUDY	9.5 - 12.5	13.5
2-2A	1038	1900	1163°C (2125°F) SOLUTION, AIR COOL + BASELINE	BLADE PROPERTY CHARACTERIZATION	4.0 - 6.0 AND 8.0 - 13.5	
2-2B	1038	1900	1177°C (2150°F) SOLUTION, AIR COOL + BASELINE	BLADE PROPERTY CHARACTERIZATION	3.0 - 4.0	6.0 - 8.0
2-6	1038	1900	VARIOUS	GRADIENT BAR STUDY		
2-6B	1038	1900	1177°C (2150°F) SOLUTION, AIR COOL + BASELINE	BLADE PROPERTY CHARACTERIZATION	2.0 - 4.0	5.0 - 10.0

Fig. 65 Summary of Preform Evaluation

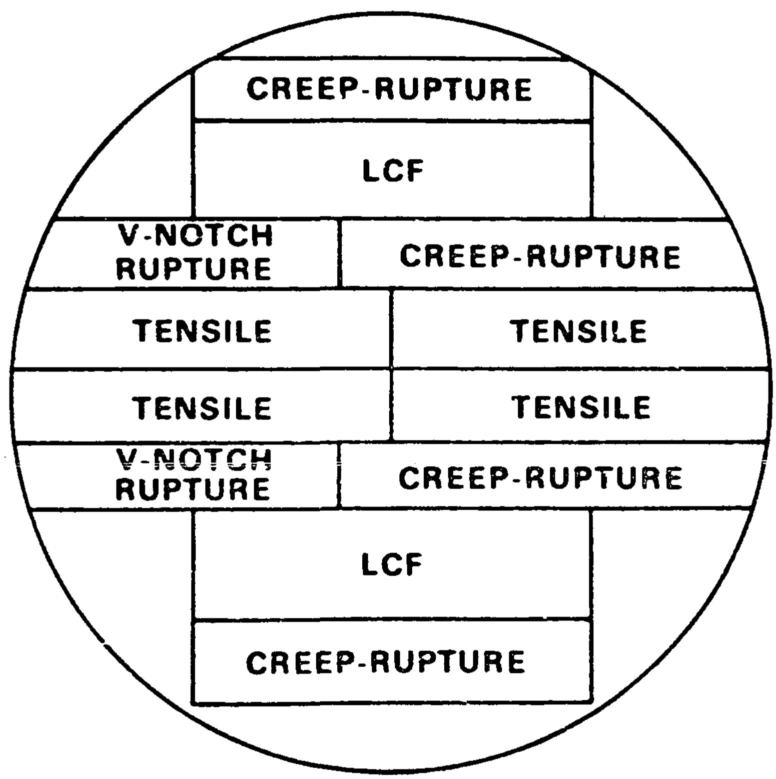


Fig. 66 Cut-Up Diagram

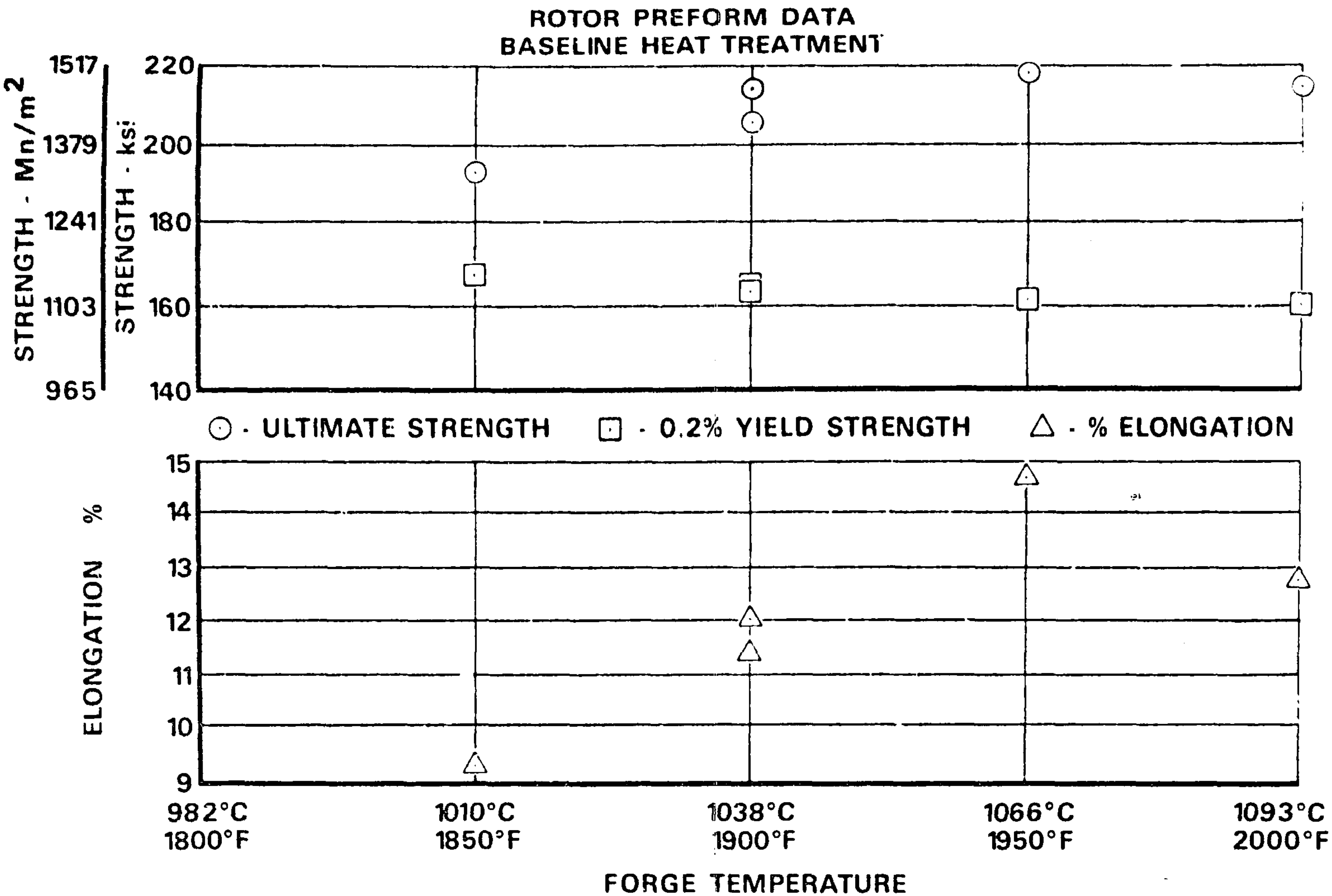


Fig. 67 Room Temperature Tensile Properties vs. Forging Temperature

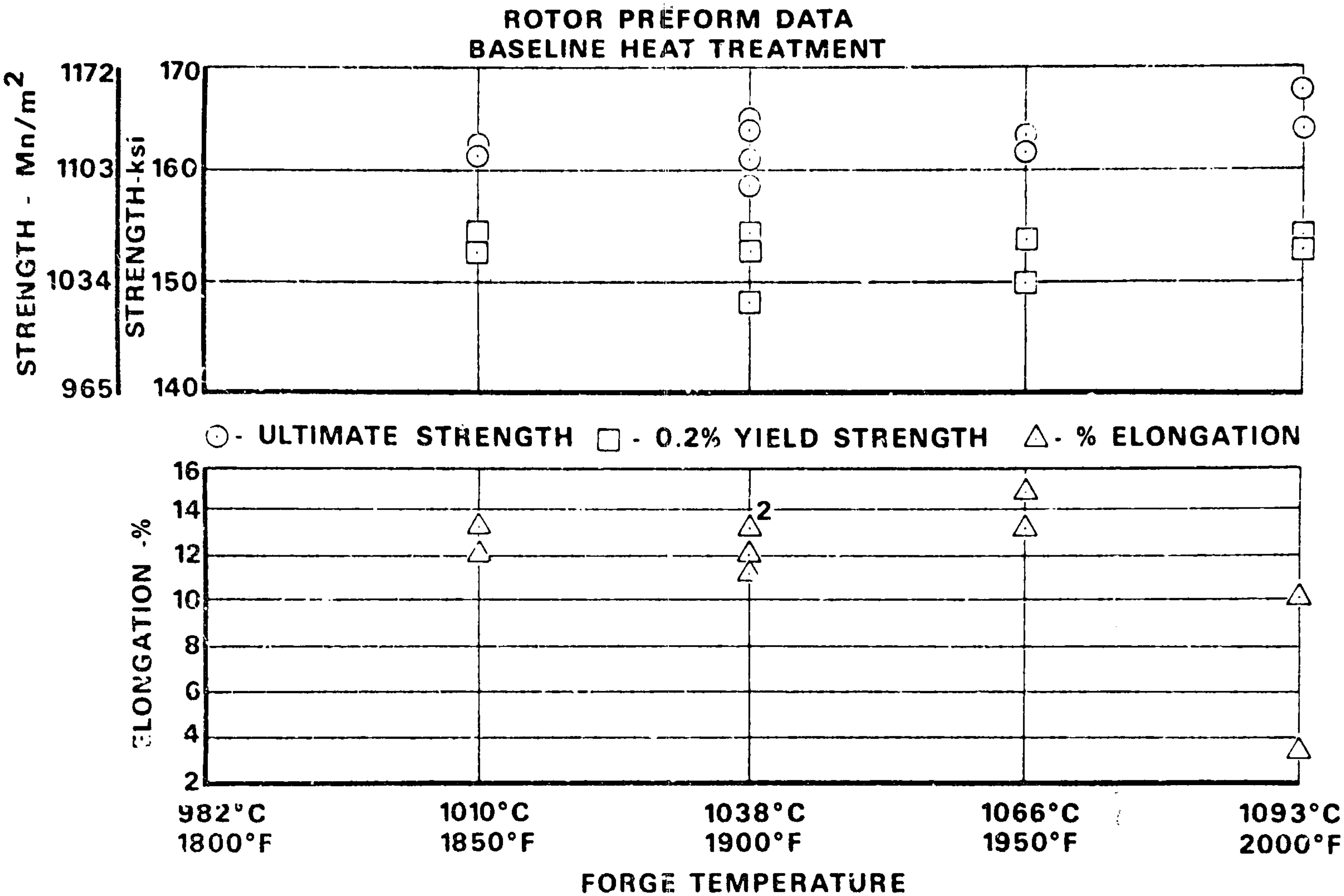


Fig. 68 760°C (1400°F) Tensile Properties vs Forging Temperature with blade operating temperatures. These halves were subsequently cut up for mechanical property evaluation. The effect of these heat treatments on tensile strengths is shown in Fig. 69. As expected the coarser grained material exhibited a loss in tensile strengths. However, a significant increase in creep-rupture life was achieved (Fig. 70). The data referred to as baseline represent material forged at all four forging temperatures and given the baseline heat treatment.

Four preforms were used for the initial bladed rotor forging trials. Because it was determined during the preform evaluations that forging temperature had no significant effect on mechanical properties, these and subsequent forgings were produced at a temperature commensurate with optimum forgeability. The first bladed rotor forging trial resulted in the partially bladed rotor. The lack of blade fill was attributed to the degree of taper in the airfoil thickness (root to tip). The blade cavities were opened up 0.010 to 0.020 in. to minimize the frictional forces. The resulting modified blade cross sections are shown in Fig. 71. The first forging attempt with the modified blade inserts resulted in a fully bladed rotor as shown in Fig. 72. Two additional bladed rotors were subsequently forged. The four rotor forgings (one with underfilled blades) were heat treated, cut-up and evaluated to complete the Task 2 and Task 3B evaluations. A summary of the bladed rotor evaluations is given in Fig. 73. The results of this evaluation established the processing parameters for the rotors used to generate design data. Forging at alternate strain rates in the range of 0.6 to 1.0 in./in./min. had no effect on mechanical properties or microstructure.

Two additional variations of the heat treatment used to produce a coarse grained structure were evaluated. The aim was to achieve the highest LCF capability commensurate with the coarse grain size. Figures 74, 75 and 76 show that, while sacrificing tensile strength (compared to baseline), one of the alternate heat treatments resulted in the highest LCF capability and maintained the desired level of stress-rupture strength. This heat treatment was, therefore, selected for the Task 3 - Design Data.

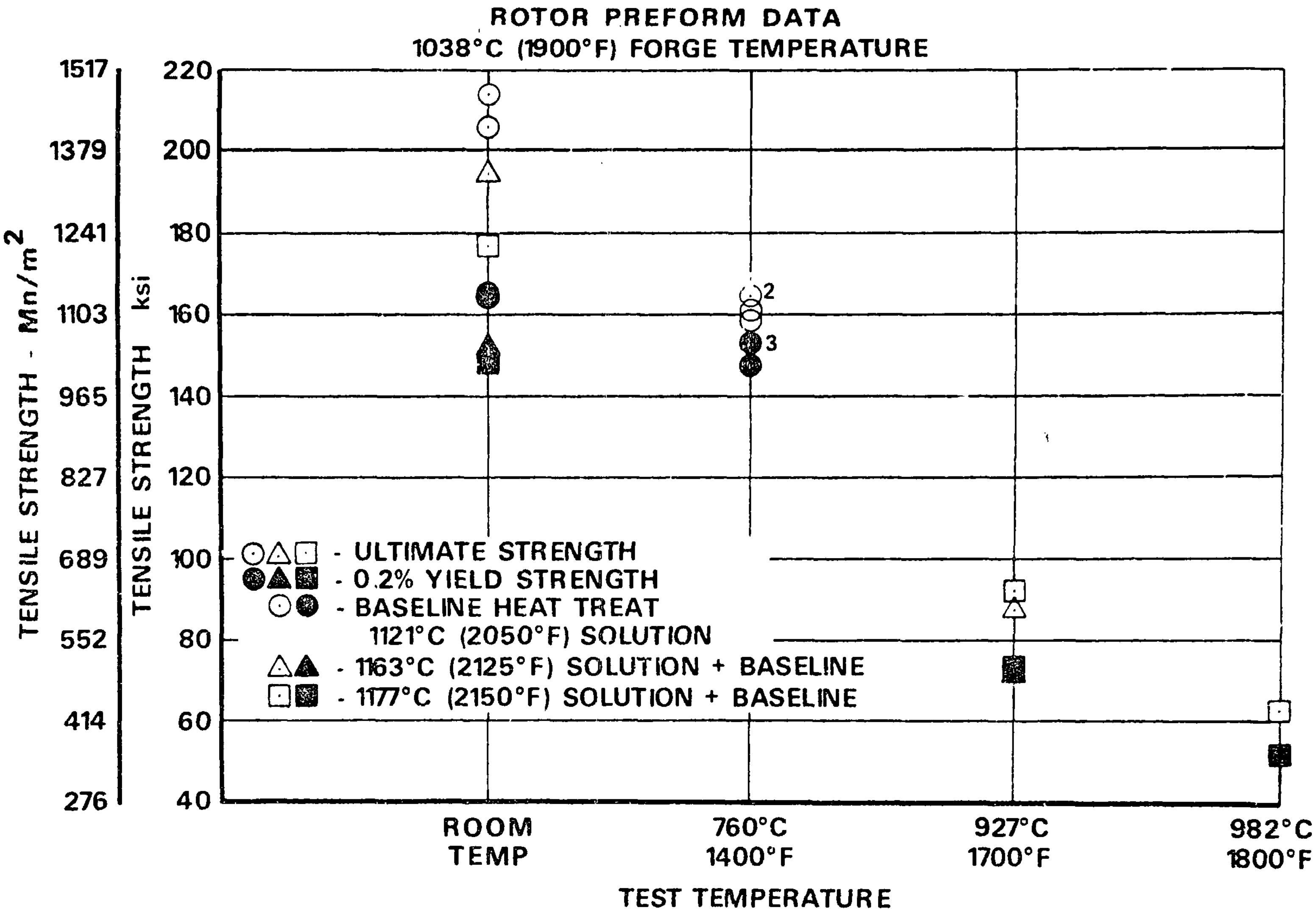


Fig. 69 Tensile Properties vs Solution Temperature

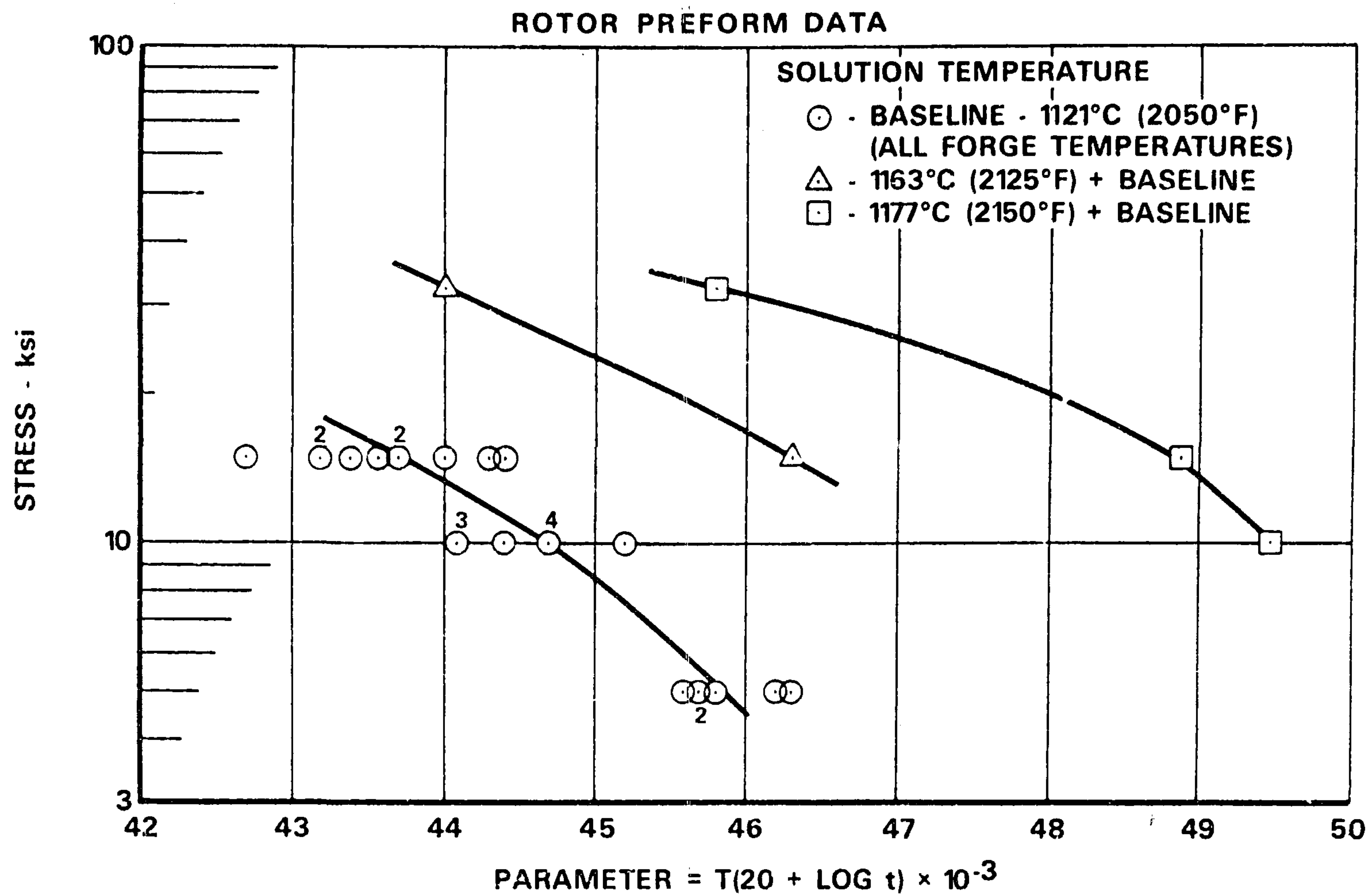


Fig. 70   Stress Rupture Capability vs Solution Temperature

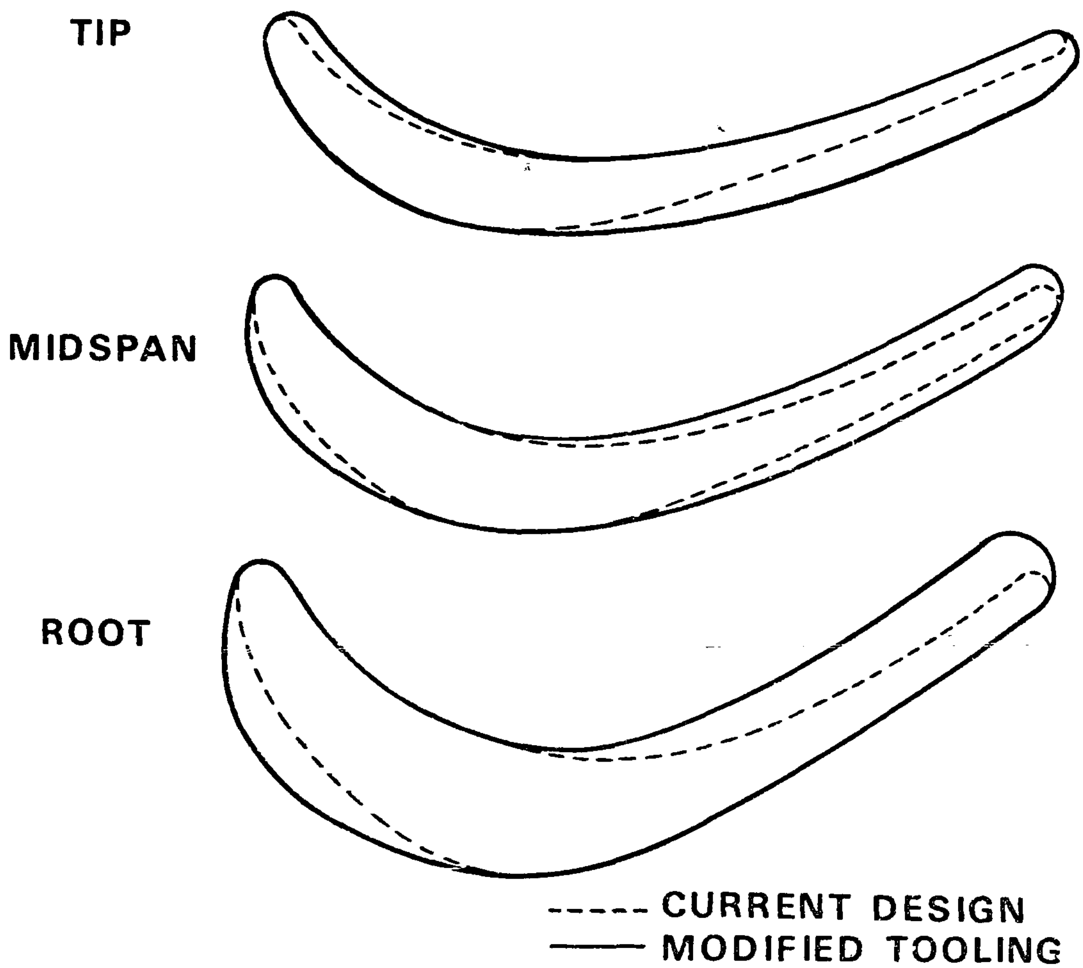


Fig. 71 Modified Blade Cross-Section

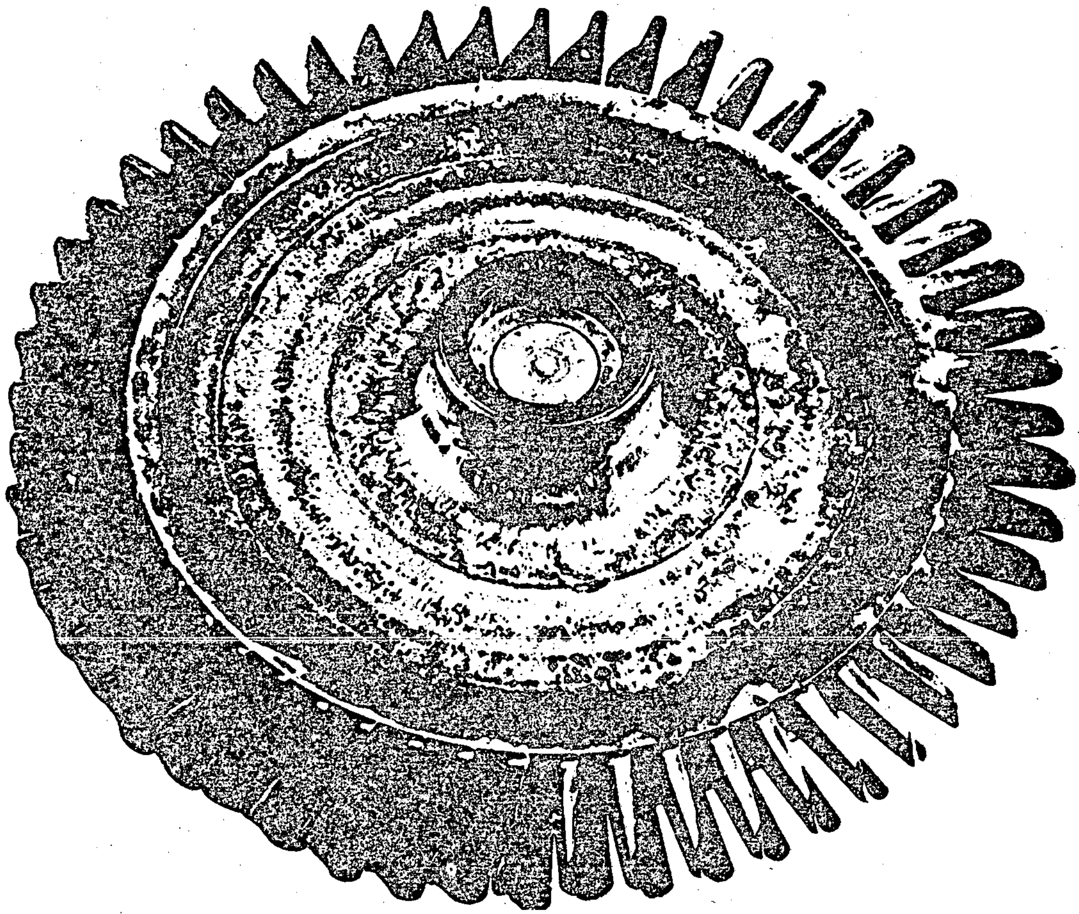


Fig. 72 Fully Bladed Rotor Forging

ROTOR S/N	FORGE TEMPERATURE PREFORM °C	PREFORM (°F)	ROTOR °C	ROTOR (°F)	HEAT TREATMENT	PROGRAM USE	ASTM GRAIN SIZE PREDOMINATE	ASTM GRAIN SIZE OCCASIONAL
2-9	1038	1900	1093	2000	BASELINE	ALTERNATE STRAIN RATE STUDY	11.5 - 13.5	
2-10	1038	1900	1093	2000	1177°C (2150°F) SOLUTION, AIR COOL + 1121°C (2050°F) SOLUTION, AIR COOL + BASELINE STABLIZATION AND AGE	ALTERNATE HEAT TREAT STUDY	3.0 - 4.0	7.0 - 10.0
2-11	1038	1900	1093	2000	1177°C (2150°F) SOLUTION, AIR COOL + 1066°C (1950°F) SOLUTION, AIR COOL + BASELINE STABILIZATION AND AGE	ALTERNATE HEAT TREAT STUDY	4.0 - 6.0	7.0 - 8.0
2-12A	1038	1900	1093	2000	1163°C (2125°F) SOLUTION, AIR COOL + BASELINE	BLADE PROPERTY CHARACTERIZATION	3.0 - 4.0	6.0 - 10.0
2-12B	1038	1900	1093	2000	1177°C (2150°F) SOLUTION, AIR COOL + BASELINE	BLADE PROPERTY CHARACTERIZATION	4.0 - 6.0	6.0 - 8.0

Fig. 73 Summary of Bladed Rotor Evaluation

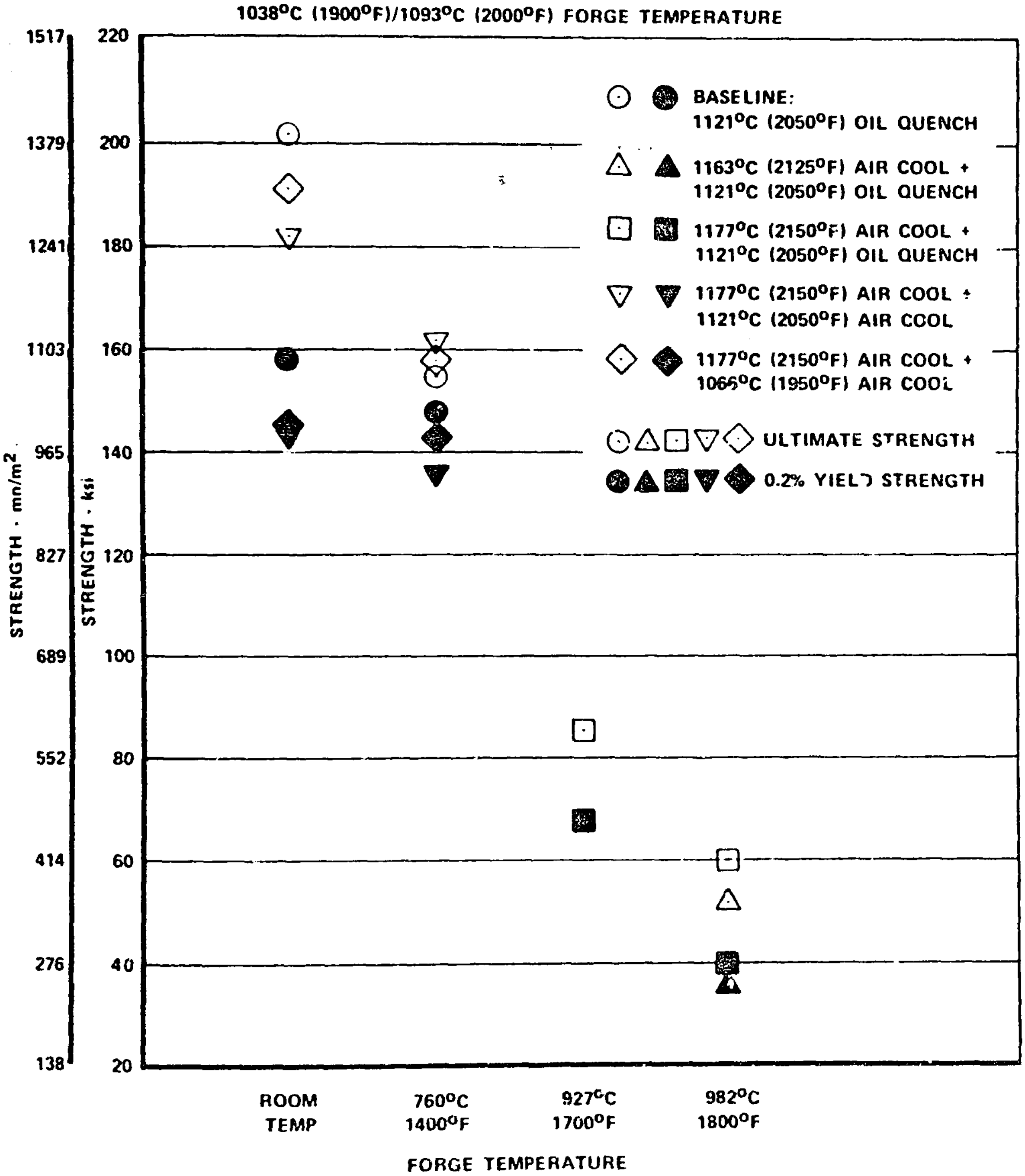


Fig. 74 Tensile Properties vs Heat Treatment - Bladed Rotor Data

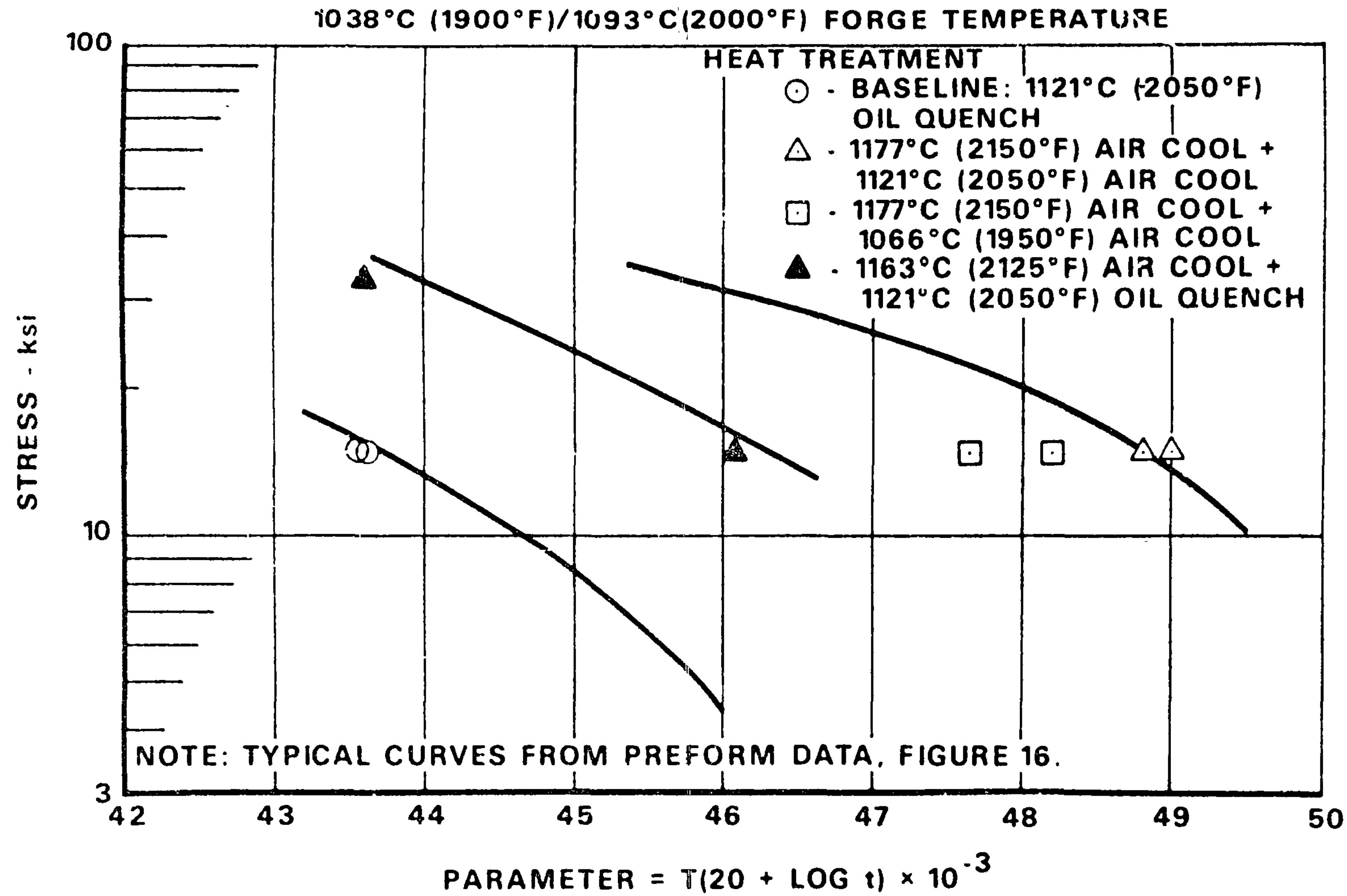


Fig. 75 Stress Rupture Capability vs Heat Treatment - Bladed Rotor Data

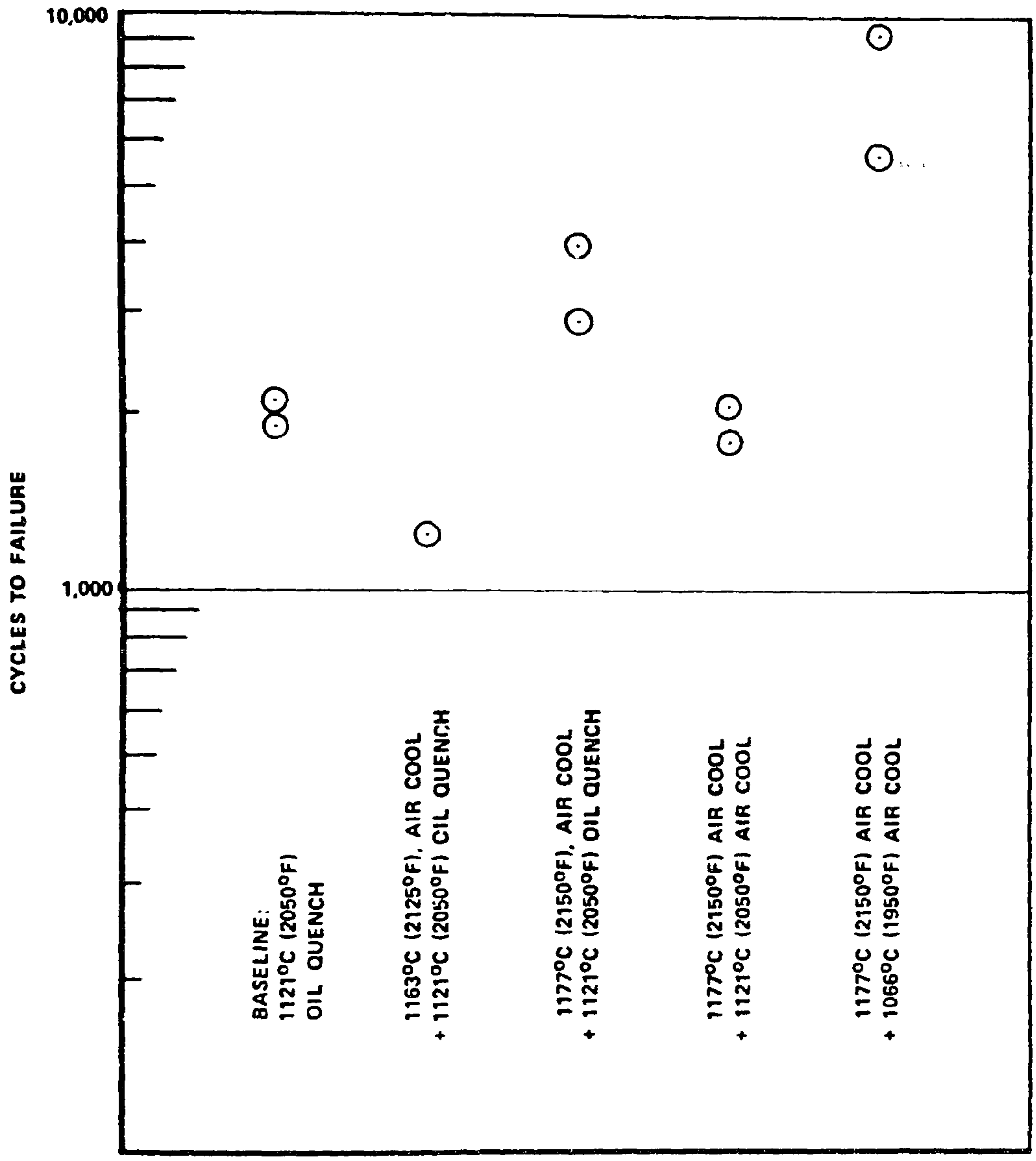


Fig. 76 927°C (1700°F) LCF Capability vs Heat Treatment - Bladed Rotor Data-Constant Strain Testing (Strain Range 0.5%)

An important conclusion is that preferential heat treatment of the blade area is not necessary to maximize stress-rupture and LCF strength.

The remaining effort on the Phase I program includes:

- Complete design data: tensile, creep-rupture and LCF.
- Complete the "Manufacturing Design Handbook".
- Complete the production cost analysis.

Questions and Comments

Question: It appears that trailing edge thickness of the blades and disk thickness are about twice that in current engines. What about loss in aerodynamic performance and reduced acceleration of the wheel?

Answer: The disk dimensions are the same as the current engine design except for the pockets under the blade roots. These were not necessary to demonstrate the fabrication process. In Phase II the web thickness will be reduced almost 2/3 without sacrificing strength and giving an even lighter wheel. Although trailing edge thicknesses can be reduced to 0.018 to 0.020 inch, it probably will not be possible to get down to the present 0.012 inch. It is being suggested that comparative tests be run in Phase II to measure the loss in performance. Similar experiences with aircraft engines have shown that the small losses predicted analytically often do not show up as a measurable degradation in engine performance.

Question: How long does it take from receipt of the billet to the forged product including the aging?

Answer: Using a single forge practice, the forging time is 7 minutes. Heat treatment and aging could be as long as 26 hours. There are some techniques whereby this time may be reduced.

F. Gas Turbine Low Emission Combustion System, by D. J. White, Solar, Division of International Harvester

The present low emission combustor program at Solar is the culmination of several years of intensive research in this field; i.e., combustor concepts developed and proved in previous programs have been further expanded to ensure practical application to an automotive gas turbine engine. The overall objective of the program is to develop a low emission combustion system for installation and demonstration in the EPA/AAPS Baseline Gas Turbine Engine.

Three specific program goals have been defined:

- The combustor should be capable of operating over the entire engine cycle.
- The combustor should meet one-half or less of the original 1976 Federal Automotive Emission Standards:

NOx (as NO_2)	- 0.20 gm/mile
CO	- 1.70 gm/mile
UHC (as $CH_{1.85}$)	- 0.21 gm/mile

- The combustor/actuating mechanism should meet the engine interface requirements.

In the initial phase of the program test optimization of models of the key combustor components was accomplished. Design, based on these various components such as the variable geometry port and the ignition system, was then integrated into a full-scale prototype combustor.

This combustor (Figs. 77, 78, and 79) includes all necessary wall cooling devices and a fully modulating variable area port and actuating mechanism system.

At present the combustor is still on the test stand undergoing mechanism development and final emissions evaluation. Control of the variable area ports on the test rig is manual through a remote, electrical actuator. Cold lightoff is achieved using a torch igniter mounted on the side of the primary zone body. A spark ignition system is used, in addition, to provide hot relights.

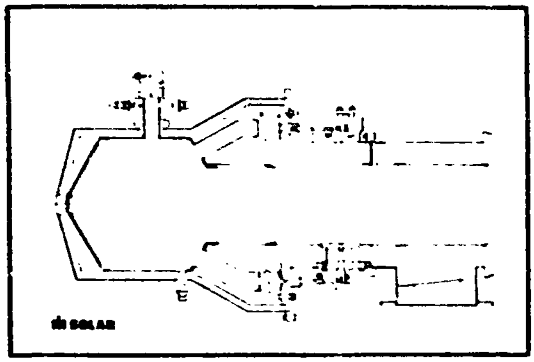


Fig. 77 Layout of Phase II JIC-B Combustor

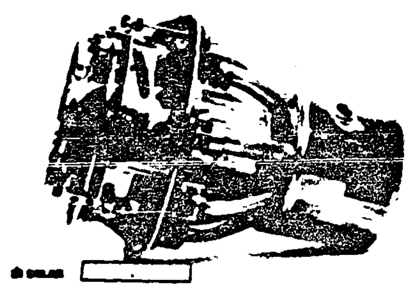


Fig. 78 JIC-B Variable Geometry Low Emission Combustor

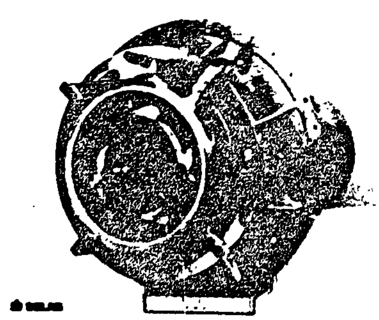


Fig. 79 JIC-B Variable Geometry Low Emission Combustor

Emission levels obtained during testing over the Simulated Federal Driving Cycle, indicate the feasibility of meeting one-half of original 1976 Emission Standards (see Figs. 80, 81, 82, 83, 84, and 85). Problems of mechanism reliability still exist. The mechanism design criteria require the mechanism to be capable of:

- Operating in an oxidizing environment up to 1200°F
- Moving the ports from full open to full closed positions in 1/20th of a second
- Operating reliably with minimal actuation forces and minimal movement
- Operating without significant air leakage

Problems which have come up include:

- Failure of graphite bushings (seals for actuating rods)
- Misalignment of actuating cam rings
- Rotation of actuating rods and cam follower mechanism

Solutions to these mechanism problems will involve:

- Positive cam ring centering system
- Longer and more effective bushings
- Cam follower arrangement that does not rotate or is insensitive to rotation

Obviously, further development will be needed before such a combustor/engine combination can be used to power a vehicle. However, it can be concluded that the original 1976 Emission Standards can be satisfied with this burner if Point 2 on the FDC will permit 8 pounds per hour fuel flow (see Fig. 86). The mechanism works over the full operating range of the engine, but its life is unknown. Integration with the control system is required for activation.

<u>Questions and Comments</u>

<u>Comment</u>: Prime effort on this combustion system has been focused on achievement of low emissions; relatively little effort has been devoted to

V_f (mph)	P_4 (psig)	T_4 (°F)	T_5 (°F)	w_a (lb/sec)	TIME (%)	TIME (Sec)
(decel)	10	1150	(decel)	0.90	6.41	88
6	6	1150	1300	0.75	11.44	157
10	6	975	1220	0.75	29.67	407
15.5	10	1150	1470	0.90	37.90	520
25.5	17	1150	1560	1.15	8.75	120
57.[illegible]	13	1150	2220	1.00	5.83	80
					100.00	1372

Overall mileage 8.347 mpg on 7.5 miles

SOLAR

Fig. 80 Simulated Federal Driving Cycle Mode

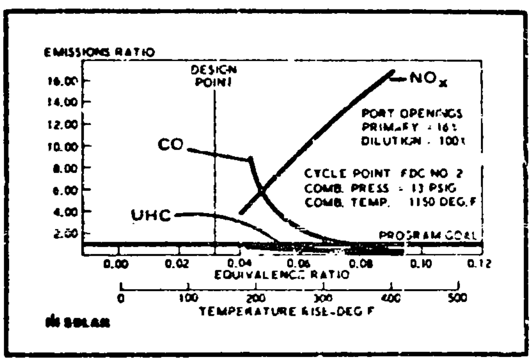


Fig. 81 Simulated Federal Driving Cycle Emissions

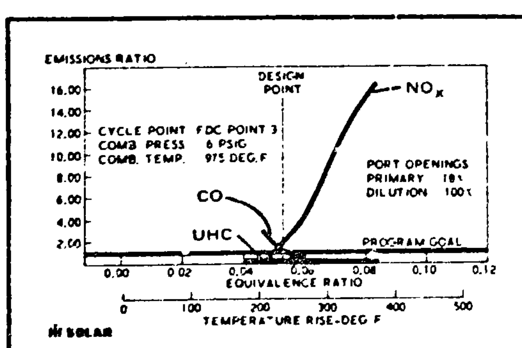


Fig. 82 Simulated Federal Driving Cycle Emissions

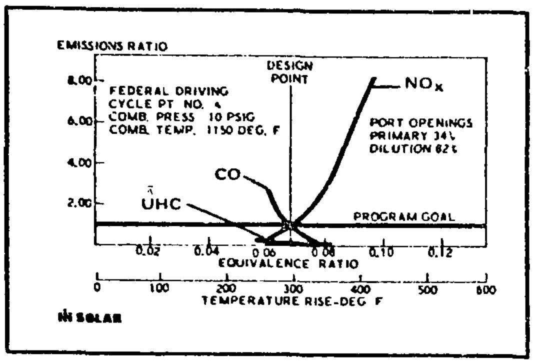


Fig. 83 Simulated Federal Driving Cycle Emissions

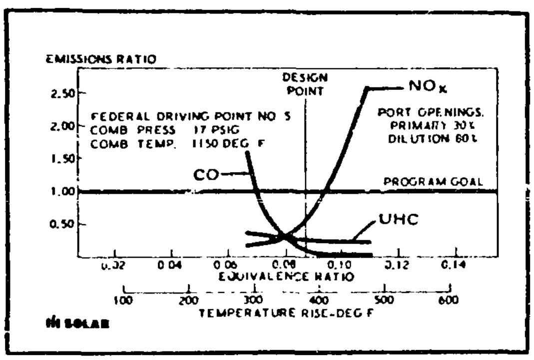


Fig. 84 Simulated Federal Driving Cycle Emissions

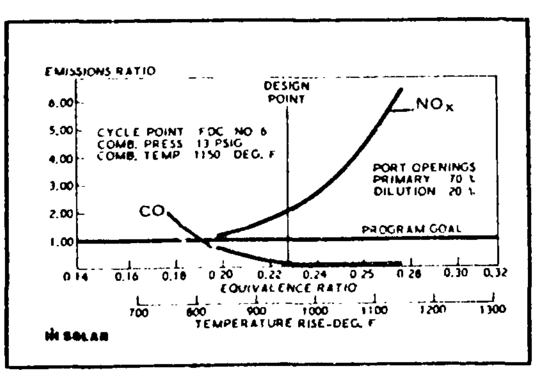


Fig. 85 Simulated Federal Driving Cycle Emissions

	ORIGINAL 1976 STANDARDS	PROGRAM GOALS	RESULTS
NO_x (AS NO_2) -	0.4 gm/mile	0.2 gm/mile	0.34
CO -	3.4 gm/mile	1.7 gm/mile	3.379
UHC (AS $CH_{1.5}$) -	0.42 gm/mile	0.21 gm/mile	0.155

*BASED ON ESTIMATES FOR POINT 2 AT 8 LBS/HR AND POINT 6.

SOLAR

Fig. 86 JIC-B Combustor Integrated Federal Driving Cycle Emissions mechanical development and packaging. The program requirements have changed in the course of the program; increasingly difficult goals have been established.

Question: Does the Point 2 data represent a flashback or normal operating condition?

Answer: Point 2 data represents a normal operational mode. Monitoring thermocouples in the port indicate when flashback occurs. Also, CO emissions suddenly increase very rapidly.

Question: Have you measured the effect on emissions of step changes in fuel flow and variable geometry?

Answer: Attempts have just recently been made to make step changes from Point Number 2 to Point Number 6. This is difficult to do with three manual controls to operate (2 controlling variable geometry and one for the fuel valve). Also it is difficult to integrate the emission traces. Data from these attempts are being processed now, and will be reported subsequently. Also such tests will be run on the Chrysler engine.

G. Oxide Recuperator Technology Program, by K. R. Kormanyos, Owens-Illinois Corp.

The project objective is the investigation of low expansion glass-ceramic materials for the fabrication of low cost recuperators for automotive gas-turbine engines. The program is divided into six complementary tasks dealing with specific aspects of recuperator design and fabrication inherent to the use of a glass-ceramic material:

- Task 1 - Parametric design analysis
- Task 2 - Sample fabrication to establish manufacturing feasibility
- Task 3 - Conceptual design
- Task 4 - Core fabrication and testing
- Task 5 - Seal development
- Task 6 - Trade-off evaluation and cost estimates

The work through Task 3 has been completed and previously reported. The sample core fabrication and testing, Task 4, are discussed here. Objectives for the next period are suggested.

Single pass crossflow test cores were fabricated using Cer-Vit^R C-126 glass-ceramic material. The test cores were 5-inch cubes using 0.025 inch ID tubes with a 0.002-inch wall (Fig. 87). Each of the cores was leak tested measuring cross circuit leakage as a function of pressure (Fig. 88); the results indicated that it would be possible to successfully fabricate low leakage recuperators and that the current fabrication technique requires refinement to achieve consistent leakage properties.

A pressure burst test on one of the cores showed that the core survived 11 atmospheres absolute at room temperature, implying that a glass-ceramic recuperator should be able to withstand operating pressures expected with an acceptable safety margin.

A thermal cycle test rig was fabricated and tested. It allows hot and cold air to be alternately passed through one flow path while ambient temperature air is continuously passed through the other path to approximate the temperature transients of an engine start-up. Fracture of a core tested in the rig following one thermal cycle (Fig. 89) indicates that the thermal properties of the material system in matrix form require additional investigation. The importance of an operable metal-ceramic interface system has been reinforced.

In view of the observed cross-leakage data scatter between individual samples, a contract extension has been proposed, the direction of which is to refine the existing fabrication process to the point that test cores can be fabricated with consistently low cross circuit leakage. The fabrication effort being considered will include counterflow as well as crossflow test cores since the probability exists that a counterflow unit will be the final design requirement. Also matrix property characterization is needed including such critical factors as ultimate matrix strength, heat transfer properties, etc.

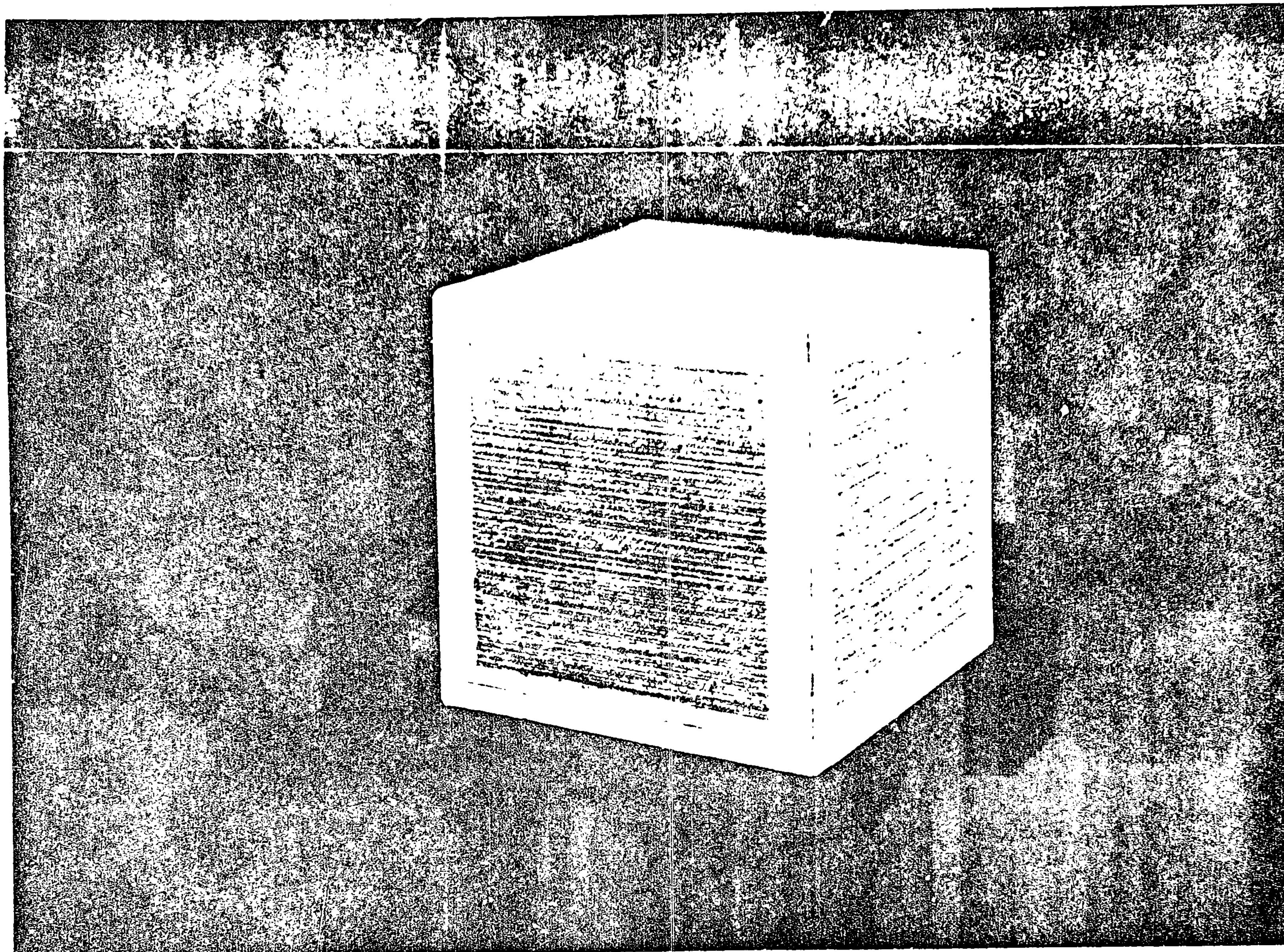
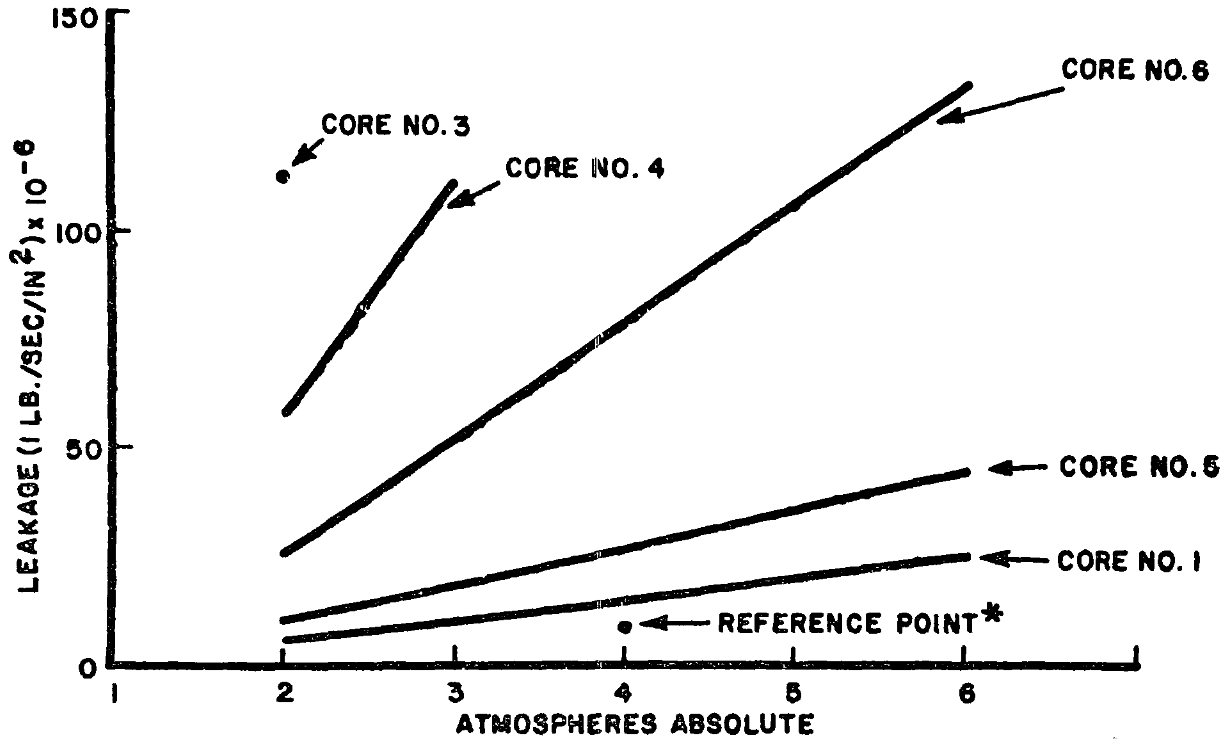


Fig. 87 Typical 5-Inch Glass Ceramic Test Core



*REPRESENTS 0.5% LEAKAGE BASED ON A TASK III SIZED RECUPERATOR FOR A 4:1 COMPRESSOR RATIO AND 1 LB./SEC FLOW

Fig. 88 Test Core Leakage Rates

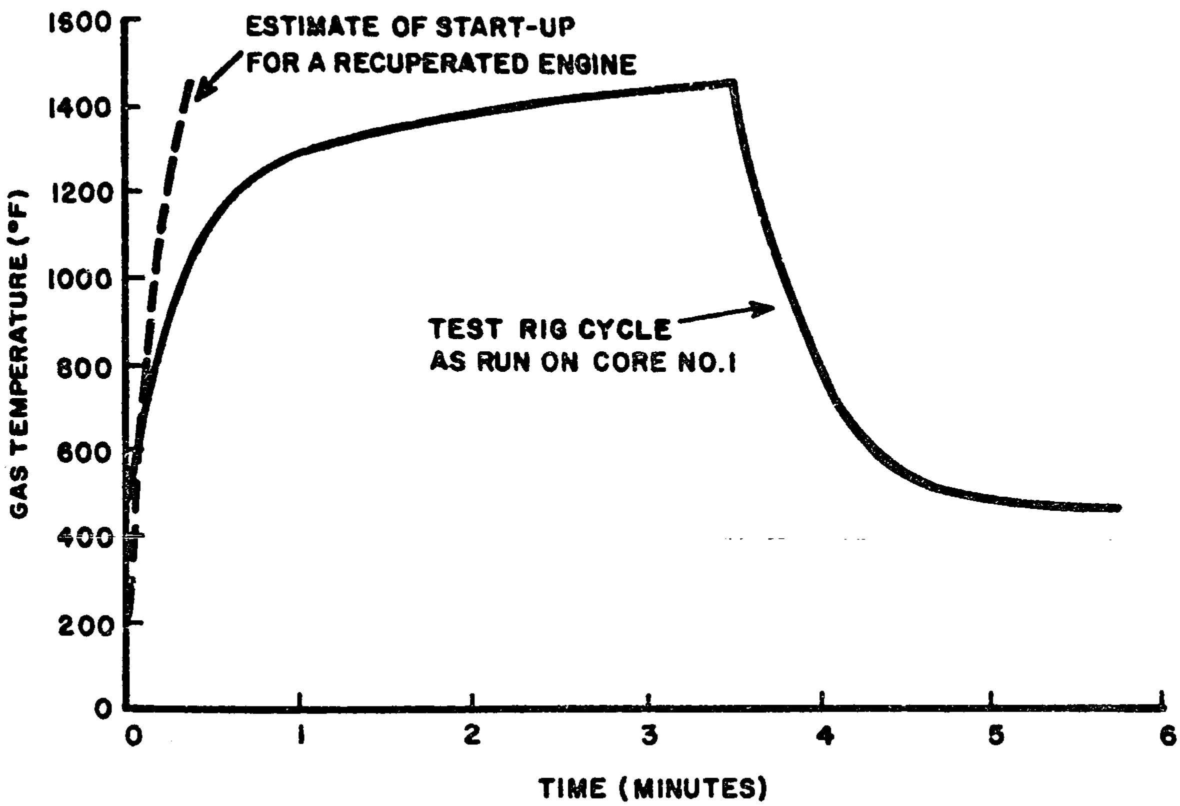


Fig. 89 Test Rig Thermal Cycle

Questions and Comments

Question: Has consideration been given to the configuration that might be used with the Baseline Engine?

Answer: Results of Task 3 indicate that a minimum volume single pass, cross-flow, rectangular configuration should be suitable - about 34-inch high (no flow side), 6-inch gas flow length, and 8-inch air flow length. Hydraulic diameter is about 0.025-inch in both flow directions. It would be mounted on the side in a manner similar to the present Baseline Engine regenerator.

Question: What about the problem of plugging without the benefit of alternating reverse flow as in the regenerator?

Answer: Clean combustion is required.

Question: Why are ceramic materials chosen for the heat exchanger?

Answer: The trend in engine development is toward higher operating temperatures to achieve lower fuel rates. Ceramic materials should be able to withstand these higher temperatures at a lower cost than the more exotic high temperature metals.

Comment: The size of the single pass, cross flow heat exchanger quoted above is for equivalent thermal effectiveness and pressure drop of a regenerator.

Question: Was the burst test run over an extended period of time? Has possible stress corrosion been examined?

Answer: Stress corrosion has not been investigated. Pressure was increased in a series of plateaus to 11 atmospheres, the limit of the test rig.

Comment (Tom Sebestyen, EPA): It was pointed out that the original intent of the present program is to demonstrate the fabrication technology so that overall development is still in the very early stages.

Comment (Representative from Climax Molybdenum): The ceramics versus metal heat exchanger controversy has been of interest for a number of years. Some new stainless steel alloys have been developed which have about twice the creep-rupture strength of 430 stainless. They should be good, economical candidate materials for heat exchanger applications up to 1400 or 1500°F. It is doubtful if the ceramic materials discussed above would be suitable for long-term applications in the 1750°F range.

Comment (Tom Sebestyen, EPA): These are still points of discussion and controversy. The intent of the technology programs is to develop information and know-how for advanced engines which may require heat exchangers in the 1800 and 1900°F range on a relatively near-term basis.

H. Ceramic Regenerator Reliability, by Chris Rahnke, Ford Motor Company (Guest Presentation)

EPA is negotiating a program with Ford Motor Company to develop a ceramic regenerator which will satisfy the requirements of the EPA Chrysler automotive gas turbire; i.e., up to 800°C (1475°F inlet temperature) and have a B-10 life of 3500 hours when operating on a passenger car duty cycle with diesel fuel No. 1, No. 2, and/or unleaded gasoline.

Ford has been running regenerators in engines for several years accumulating more than 100,000 hours of operation on a large sample of lithium-aluminum-silicate (LAS) cores from two different suppliers. This operating experience has shown the major causes of failures to be: excessive thermal stresses and chemical attack on the matrix material.

Because the periphery is surrounded by relatively cold compressor discharge air and the center part by hot exhaust gas, tensile stresses are set up around the rim and compressive stresses are set up in the center part of the core. When high enough, these stresses cause cracks in the matrix and ultimate failure of the core. A 100°F rise in regenerator inlet temperature will cause a 25% increase in stress. Hence, high inlet temperatures are a major cause of failures.

The source of chemical attack is sodium, potassium, and sulfur from fuel impurities, and ingested road salt. Sodium and potassium attack the hot side; sulfur in the form of sulfuric acid attacks the cold side leaching the lithium out of the matrix material thereby increasing its thermal coefficient of expansion and causing mechanical failure of the core.

Corrective measures include:

- Mechanical design techniques to relieve thermal stress and regenerator drive loads at the rim of the core.
- Coatings to protect LAS material from exposure to deleterious chemicals.
- Low expansion materials which are impervious to chemical attack such as magnesium-aluminum-silicates (MAS). The major effort is being expended on this approach.
- Fabrication methods and matrix geometries which would result in superior and more consistent material quality.

The EPA/FORD program includes three phases as follows:

Phase One: Summary report on previous experience, data and state-of-the-art with ceramic regenerator cores at Ford Motor Company. This will include: description of failure modes, thermal stress, analytical techniques and calculation of regenerator safety factors, and laboratory and engine operating experiences.

Phase Two: Laboratory and engine durability tests on new regenerator materials, fabrication techniques and coatings. Tests will be conducted on the Ford 707 engine; correlating factors will be established so that durability data can be applied to the EPA Chrysler automotive turbine and other engines. Between 10,000 and 20,000 hours of dynamometer testing will be conducted (corresponds to 20,000 to 40,000 core hours) on a large sample of cores this year.

Phase Three: A report will be submitted providing the design method and specification needed for a passenger car regenerator system which will meet EPA durability objectives. Completion date is April 1, 1975.

Questions and Comments

Question: To what extent is the EPA/Ford Program a mutual effort as compared to a more conventional contracted effort?

Answer: Ford is providing a report summarizing extensive test and development background. Design work done earlier this year on new design techniques to reduce rim stress and new drive techniques will be reflected in the test cores of Phase Two which will be made of MAS and coated LAS materials. Cores will be supplied by: Corning Glass, G.T.E. Sylvania, Coors Porcelain, and W. R. Grace.

Question: Are seals included in the program?

Answer: Seals are excluded. Just the regenerator, its mount, and its drive are included.

Question: Have tests been run with atmospheric pressure on both sides of the disk with the outside pressurized to improve the stresses?

Answer: This configuration has not been run. However, failures have been correlated with calculated stresses at given temperatures. This constitutes a calculation of the structural strength.

Question: What are the stresses under transient as compared to steady-state conditions?

Answer: Analysis shows that the transient stresses under start-up (worst condition) are about 10% higher than steady-state stresses.

Question: What are current acceptable temperature levels for the core inlet? What diameters were you working with?

Answer: Temperature tolerance varies widely with stress relief in the rim and the duty cycle. Some cores have operated without failure for brief periods at 1750°F with a stress relieved rim. A 28.5 inch O.D. core was used, but the stress does not seem to vary much with the size of the core provided the radius ratios of the seals are about the same.

I. Ceramics for Turbines, by Dr. E. M. Lenoe, U.S. Army Materials and Mechanics Research Center (Guest Presentation)

The Army Materials and Mechanics Research Center(AMMRC) is engaged in participative monitoring of a "Brittle Materials Design, High Temperature Gas Turbine" program. This program, funded by Advanced Research Projects Agency, Westinghouse, and Ford, aims at building a gas turbine entirely from ceramic materials. Specific tasks are to demonstrate:

- Ceramic vanes operating at 2500°F in a 30-Mw central station turbine
- An all-ceramic 100 to 500 hp class engine including rotors, stators, ducting, regenerators, combustors and nozzles.

The ARPA program is at mid-point; considerable progress has been made. Primary ceramic materials have been identified, ceramic component design iterations have been completed, and process development has led to the fabrication of ceramic parts which have been tested with encouraging results. A technology base to utilize uncooled high temperature ceramic components has been established. This is the key to increasing gas turbine operating temperatures so that significant improvements is specific fuel consumption and specific power can be realized.

This briefing:

- Briefly reviews the status of the ARPA project
- Discusses AMMRC supporting in-house studies
- Describes a planning study recently contracted between the Environmental Protection Agency and the AMMRC-Planning Directorate

2500°F Target for Propulsion and Power Systems: It is widely known that propulsion and power generation represents a most promising area for using high temperature, high strength ceramic materials. Several of the more apparent advantages of ceramics are:

- Increased turbine inlet temperature
  (Lower fuel consumption/hp or kw)
- Enhanced erosion-corrosion resistance
- Multiple fuel capability (all volatile hydrocarbons)
- Lower cost than superalloys and no strategic materials
- Elimination of cooling

Another major reason for the increasing interest in ceramic gas turbines is because of their beneficial impact on problems of energy, air pollution and materials resources. Considering the fuel and oil consumption of passenger cars, it is imperative that fossil fuels be more efficiently utilized. Obviously, one can reduce the size of cars and develop an alternate power plant with improved fuel economy, lighter weight and multifuel capability.

In assessing and comparing engine performance it is important to choose a representative driving cycle. Recently, Ford Motor Company compared estimated ceramic gas turbine and piston engine fuel consumption on a basis of:

25% city driving
38% suburban driving
37% driving at 50 mph

Figure 90 suggests in a general way that the potential improvement in fuel utilization is of the order of 30%.

As for power generator applications, by 1990 the demand for electrical energy is expected to increase by more than a factor of 3. Coal and nuclear energy will remain as significant fuel sources. Consequently, there is great incentive to develop a power generating system which will most effectively use coal. Of the current fossil fueled power plant systems, the combined gas turbine and steam plant is the most efficient with a conversion of 42%. This can be raised to more than 50% by improving the gas turbine system efficiency through higher inlet temperature. The importance of ceramics is that they provide the only direct materials approach to reaching inlet temperatures of 2500°F and higher, where gains are greatest. Other approaches such as metal cooling have an anticipated limit in the region of about 2150°F because of the necessity for using residual instead of clean distillate fuels.

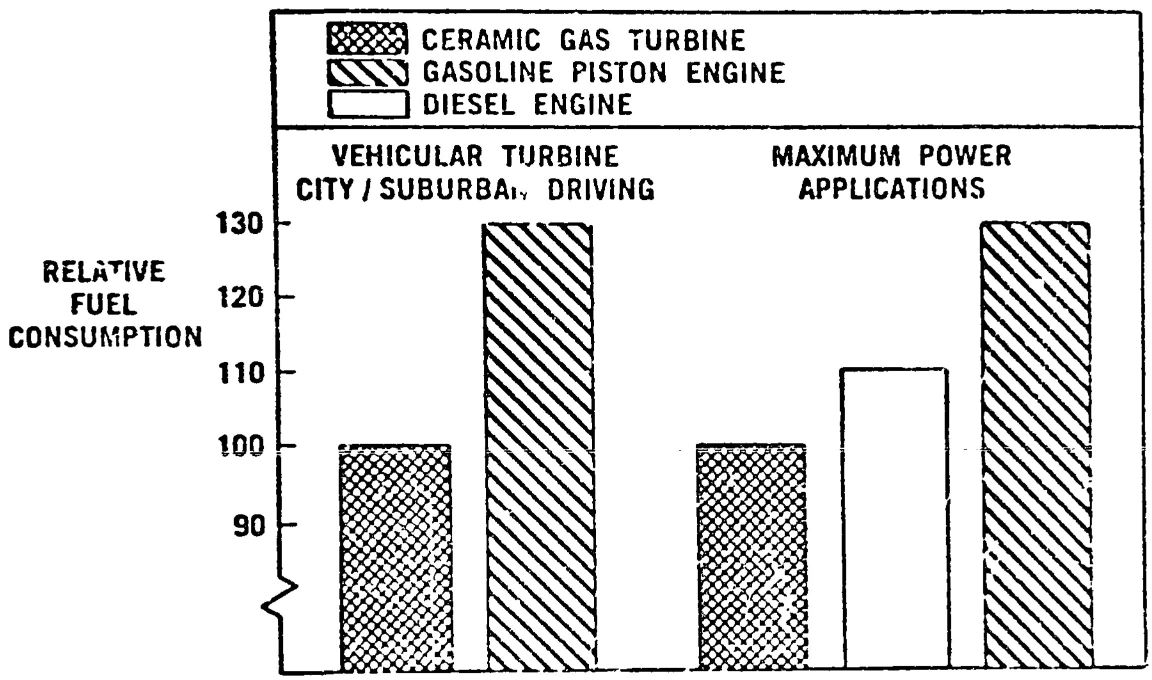


Fig. 90 Ceramic Gas Turbine/Piston Engine Fuel Economy Comparison

In tests to date, ceramic components have shown potential strength and corrosion resistance to meet an uncooled 2500°F turbine goal by the 1980's. Note that the operation of large power generating turbines with only the vanes uncooled, at 2500°F would also yield 20% more power with the same fuel input (Fig. 91).

To attain 2500°F turbine inlet temperatures without cooling in engines of Army interest, means that ceramic materials will have to be employed in the hot flow path (combustors, nozzles, vanes, rotors, shrouds and ducting). In addition, it appears that ceramic materials can offer improved performance of bearings and seals in high temperature or unlubricated environments. The use of ceramics in both large and small military gas turbine engines should lead to the following advantages:

- Reduced weight and more efficient field power generators
- Reduced weight engines for craft and vehicles with:
  - greater range
  - greater payload
  - enhanced air mobility
- Reduction in weight with increased efficiency for:
  - aircraft engines
  - auxiliary power units
  - primary power plants for limited life applications
- Strategic advantage of reduced dependence on foreign hydrocarbon fuels

In addition to these, there is a logistic advantage in less fuel to be transported, handled, and stored, as well as a multifuel capability. Viewed against the background of a national fuel shortage, the goal of a 20% decrease in specific fuel consumption is particularly attractive. Similarly, reducing dependence on chromium and nickel based superalloys appears to be prudent based on projected estimates of materials availability and domestic resources.

The ARPA program has caused a world-wide flurry of activity in ceramic materials development. Currently more than eighteen turbine manufacturers have tested or

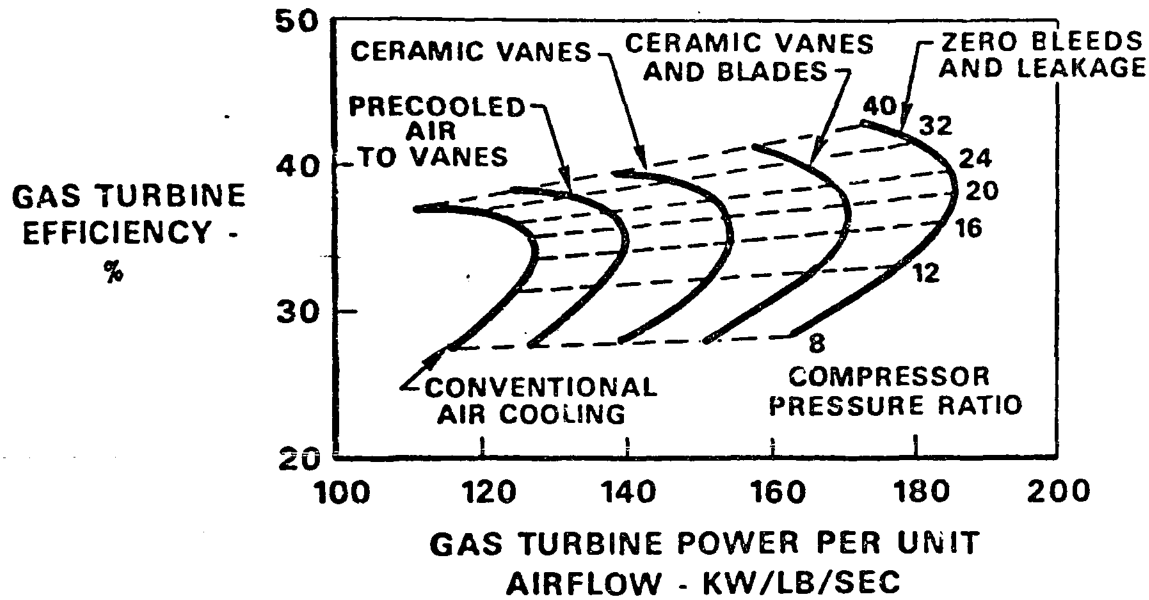


Fig. 91 Gas Turbine Performance at Turbine Inlet Temperature = 2400 F

fabricated ceramic hardware in the United States, Great Britain, Germany and Japan. Thus it is appropriate to accelerate utilization of high temperature, high strength ceramics in energy conversion systems.

Some Current Engine Results: Results to date have demonstrated that the stationary hot flow path components can go through an actual engine test (2000°F with metal rotors) and still be serviceable after a testing sequence of: (1) cold static testing; (2) hot static testing, including 50 light-ups; and (3) hot dynamic testing at 55% maximum design speed for 25 hours. (These components will be subjected to further testing.)

On the basis of these tests, it is now apparent that stationary reaction bonded silicon nitride components have demonstrated performance capability for application to non-man rated, short-lived engines, such as target drones, RPV's, or GT powered missiles. An example of how design iterations are leading to increased component life and reliability can be seen from the improved reaction bonded silicon nitride (RBSN) component performance shown in Figs. 92, 93, and 94).

Shown in Fig. 95 is a so-called duo-density rotor concept employing injection molded, reaction bonded silicon nitride hub. Such parts have been successfully spin-tested at more than 57,000 rpm.

During the project, numerous materials and processing techniques have been studied. Thus a technology base has been established which involves techniques to produce high temperature ceramic parts at low cost and with little or no machining, depending on the production techniques. Slip castings, injection molding, chemical vapor deposition and glass forming methods certainly result in lower strength materials, but they offer the advantage of economy of production.

In the hot pressed materials, on the other hand, the machining and finishing requirements have been thoroughly investigated so that cost estimates can now be made on a more realistic basis. Furthermore, in order to minimize machining, hot pressing to shape of silicon nitride and silicon carbide has been explored.

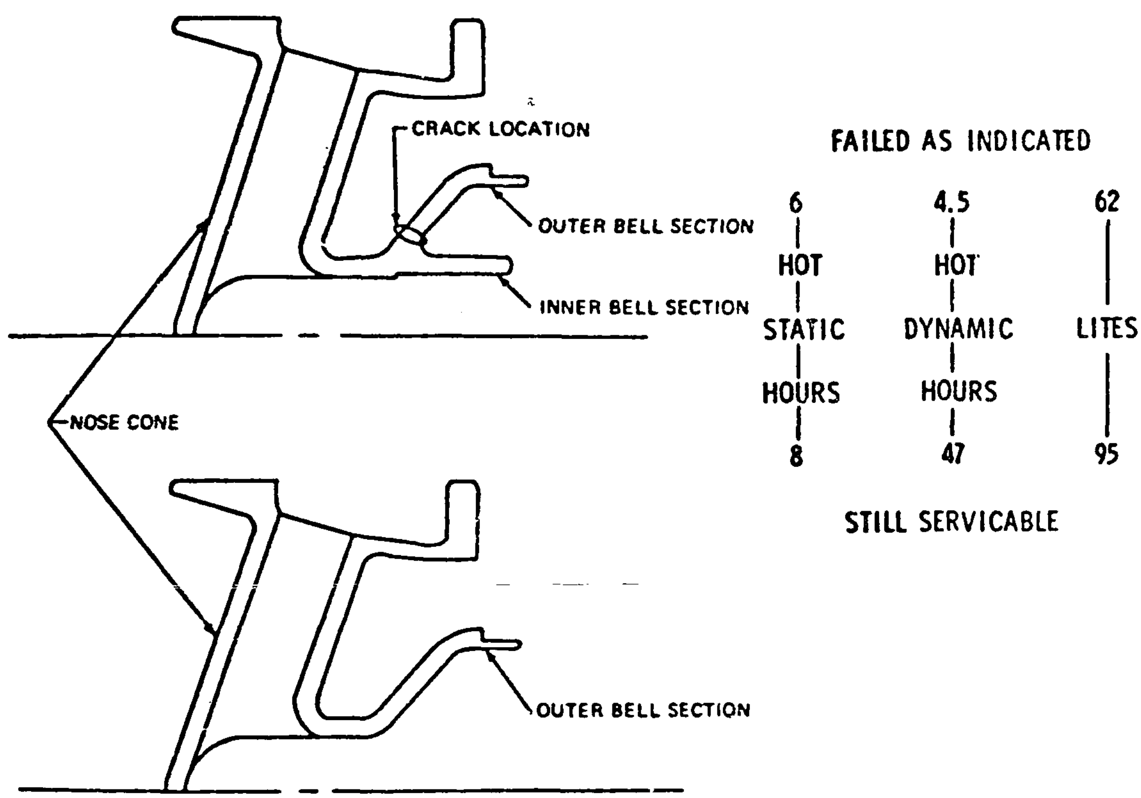


Fig. 92 Design Modification Leading to Improved Nose Cone Performance

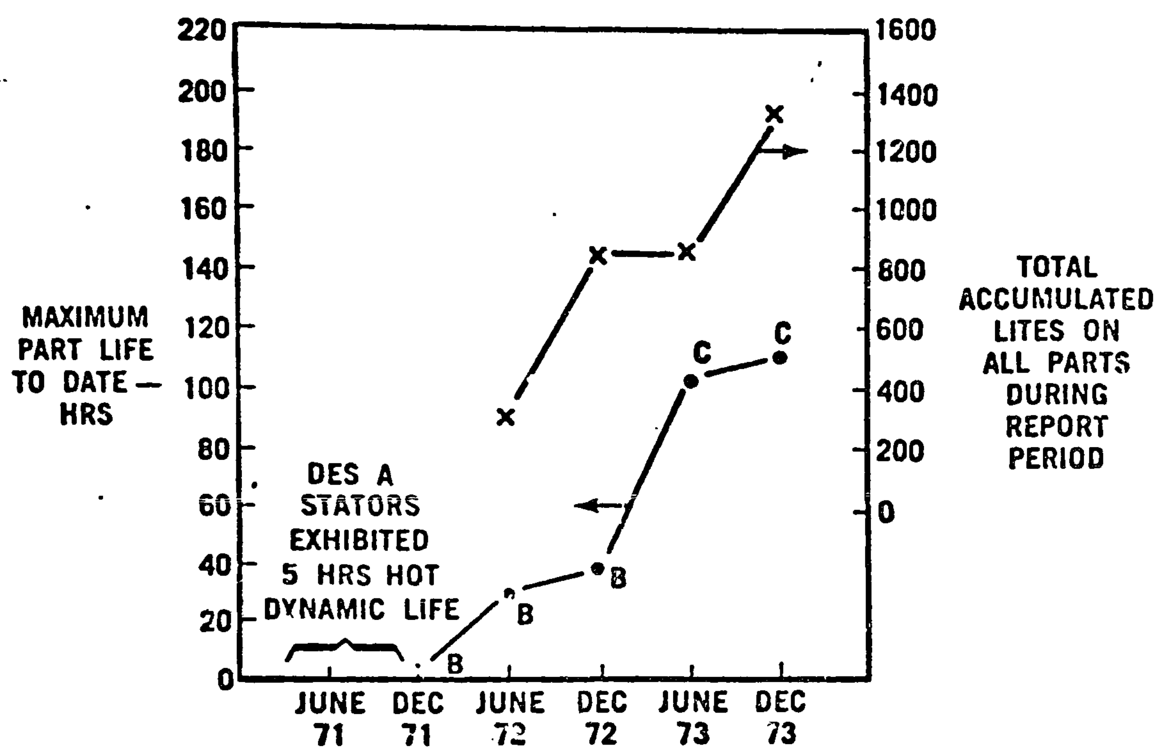


Fig. 93 First Stage Stator Testing

Design	Number of Stators Tested	Total Hours	Total Lights	Total Number of Broken or Cracked Blades	Average Hours Per Failure	Average Lights Per Failure
B	9	151	356	60	2.5	5.9
C	7	212	611	7	30.3	87.3

- AN ORDER OF MAGNITUDE IMPROVEMENT
- MATERIALS PROPERTIES AND PROCESSING HISTORY CONSTANT

Fig. 94 Design Iteration Results for First Stage Stators

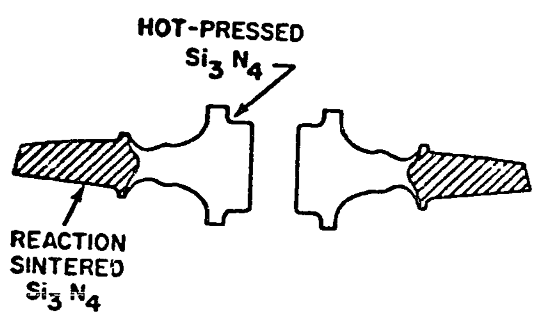


Fig. 95 The Duo-Density Rotor Concept

It is possible to produce high quality hot pressings with compound curvatures. The rotor hub in the duo-density rotor wheel, for instance, has been successfully produced in a single hot pressing with minimum machining required.

As for progress on the Westinghouse stationary turbine, a full scale model of a stator vane assembly has been constructed. Twenty vane assembly components have been completed and a vane assembly has been successfully tested at 2200°F. A 2500°F test rig for vane component testing is under construction and further elevated temperature, full scale vane tests will be completed. In addition, during the past two years, Westinghouse has measured engineering properties of silicon nitride and silicon carbide ceramics at temperatures up to 2500°F. A first-design study iteration of a first-stage rotor blade for a 30Mw gas turbine has been completed. The results are encouraging as the maximum predicted tensile stress (38,000 psi) is within the capability of current materials.

Current technology levels indicate a number of immediate opportunities for Army application of ceramics in propulsion and power generation:

- Nozzle guide vanes for APU's
  - Increased erosion resistance demonstrated
  - Benefit - reduction of maintenance
- Ceramic roller bearings
  - Increased fatigue life
  - Non-lubricated operation
- Limited life engines
  - Stationary hot flow path
  - Components for drones, RPV's, and missiles

Work in these areas is being pursued both in the ARPA program on design, specific materials and processing improvement; and in-house on a more general basis. AMMRC's role in these areas has been to provide an in-depth technology base and to address critical problems which might otherwise be ignored.

AMMRC Support: In addition to monitoring the program AMMRC has provided support in numerous areas including:

- Critical review and analysis of program
- Critical review of reports
- Technical assistance to contractor in radiography failure analysis, nitriding kinetics, neutron activation analysis, etc.
- Information dissemination to gas turbine and materials industries (Technology transfer)
- Organizing conferences on ceramic turbines

In addition to Army sponsored studies of basic processing technology in silicon nitride and silicon carbide, under ARPA funding, AMMRC has been conducting investigations into design, analysis, and mechanical properties characterization procedures for high performance structural ceramics. In the area of properties measurements, a variety of stress states have been studied. This includes flexure tests on various sizes of beams and two types of tension experiments. Conventional contoured tension configurations as well as thinning hydroburst tests have been completed on several types of silicon nitride and silicon carbide. Ring tests have been conducted on hot pressed silicon nitride (HS-130) and chemical vapor deposited silicon carbide.

In the area of probability based analysis, reliability equations have now been programmed to treat all types of statistical distributions, including empirical probability data. The treatment is based on numerical integration techniques and transformation equations. Emphasis of the work in probability theories will now be on the algebra of non-normal functions and application of various approximate solution techniques to problems of fracture, creep and combined stress failure. Future properties characterization will deal with high temperature materials properties.

Figures 96, 97, and 98 indicate current in-house studies, outline the general program and indicate missing design information in our Mechanics of Brittle Materials studies.

Most recently EPA has requested that AMMRC prepare a planning document relating to ceramics technology.

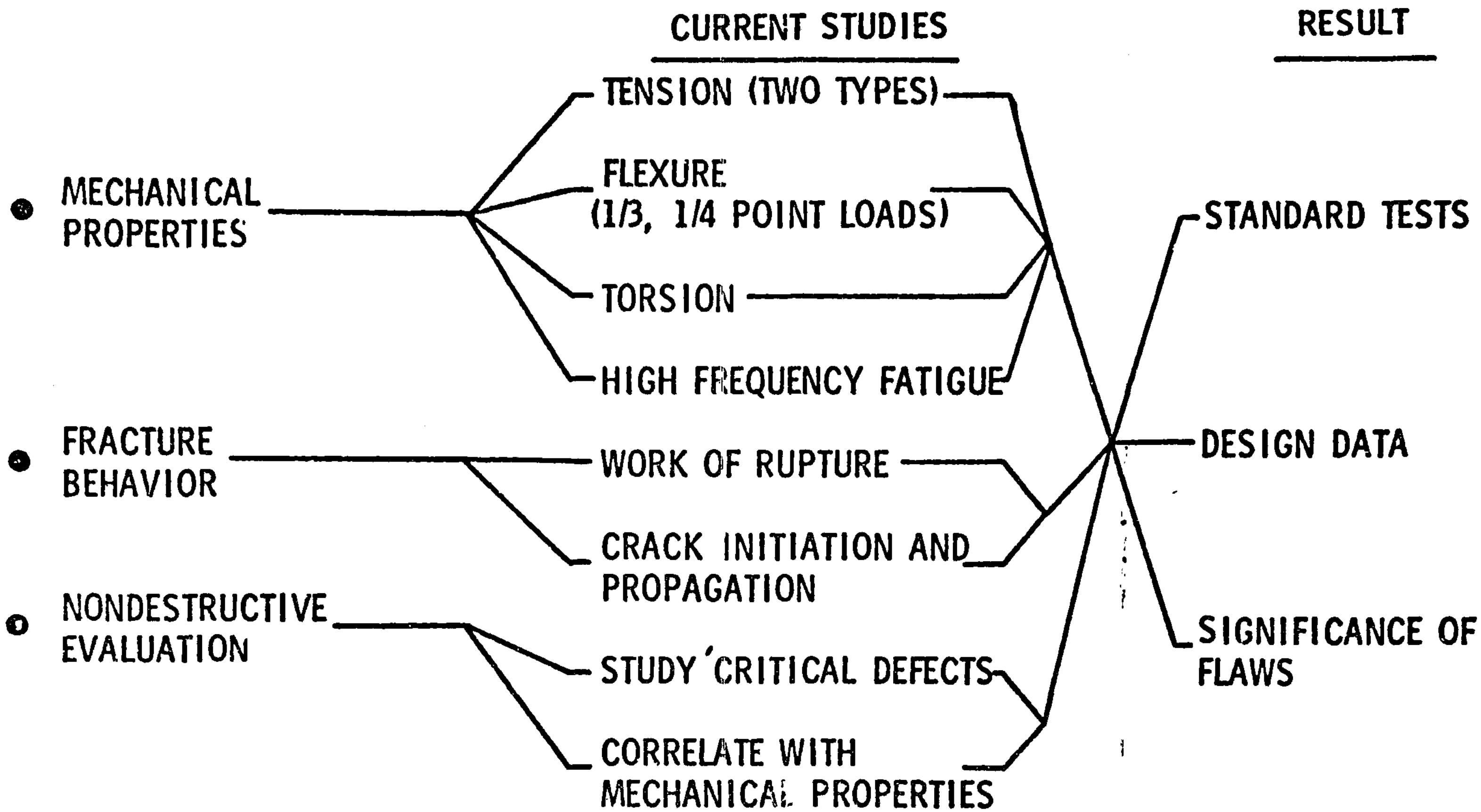
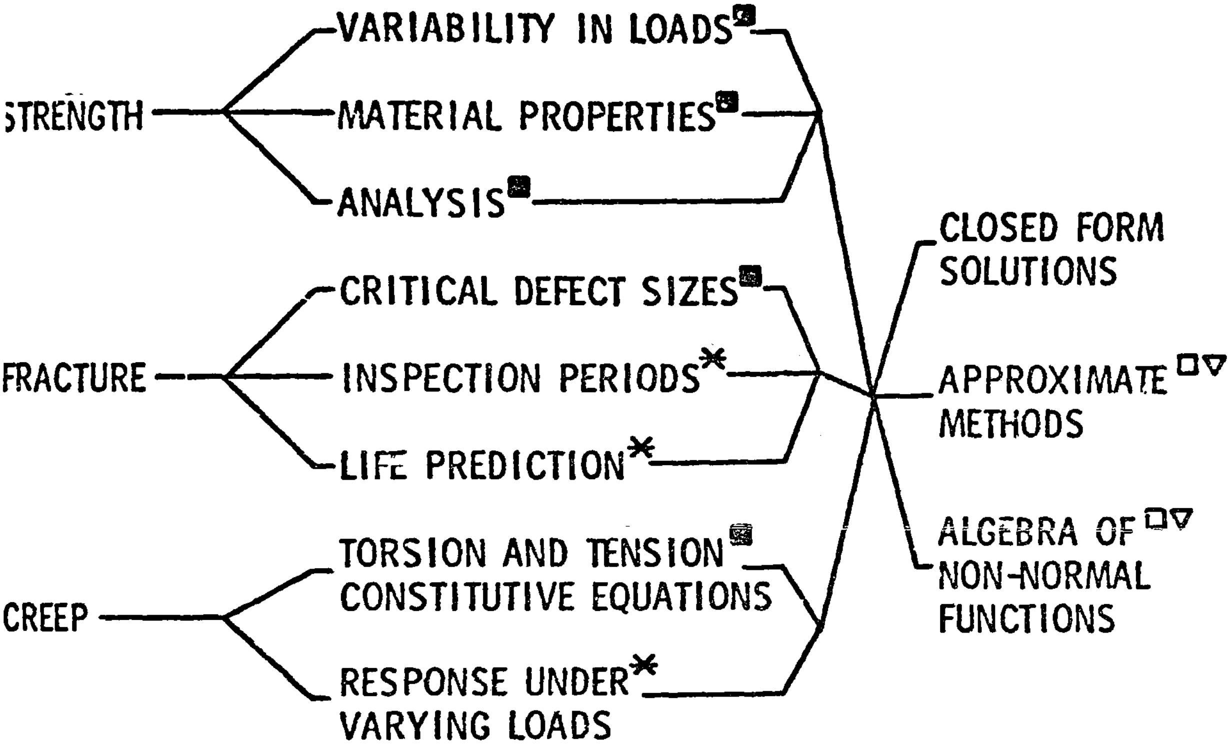


Fig. 96 Statistical Evaluation of Ceramics



■ Currently planned in ARPA Program
* Not currently addressed by ARPA Program
□ R&D capabilities known to exist elsewhere
▽ R&D capabilities at AMMRC

Fig. 97 Design and Analysis of Brittle Materials AMMRC Probability Based Analysis

- FAILURE THEORY FOR COMBINED STRESS □▽
- CREEP LAWS (TENSION, TORSION, COMPRESSION) □▽
- FATIGUE CRACK PROPAGATION - FRACTURE MECHANICS PREDICTION □▽

□ R&D capabilities at AMMRC
▽ R&D capabilities known to exist elsewhere

Fig. 98 Missing Data

Analysis of the Potential for Ceramics in Automotive Gas Turbine Engines: The objective of the survey is to prepare an in-depth critical assessment and planning document aimed at delineating the technology developments required to ensure expeditious and efficient application of ceramics materials to alternate automotive power sources. This document will address: potential applications, available materials, pacing materials problems, current status of ceramic component development and testing, pacing processing and producibility problems, and design approaches for maximizing reliability. Specific research and development tasks and suggested vendors, as well as materials supply, engineering, and manufacturing sources and deficiencies will be enumerated. Priorities and costing for the suggested program will be provided. The program will consider the time frame between the present and five years hence. It is anticipated that copies of the document will be distributed in July 1974.

Contents of the study are illustrated in Fig. 99 through 102. The potential applications, materials, problems, available ceramics and current status of component development will be described (Fig. 99). Pacing materials problems will be identified on a component-by-component basis (Fig. 100). Materials and processes with approximate temperature limitations (Fig. 101) will be documented. A summary of the general content of the document is illustrated in Fig. 102. It is anticipated that the survey will be of interest to the gas turbine industry; the opportunity to participate in this work is appreciated.

Questions and Comments: None

J. Continuously Variable Transmission Program, by Dyer Kenney, EPA

Proposals are being evaluated for the first phase of a possible two phase program. A recent study for EPA by Mechanical Technology Incorporated and Sundstrand, Inc. concluded that it is possible with present technology to build continuously variable transmissions which could improve fuel economy by 25 to 30%. Also, the most viable types are the hydromechanical and the traction. Two contractors (one for each type) will be selected for Phase I.

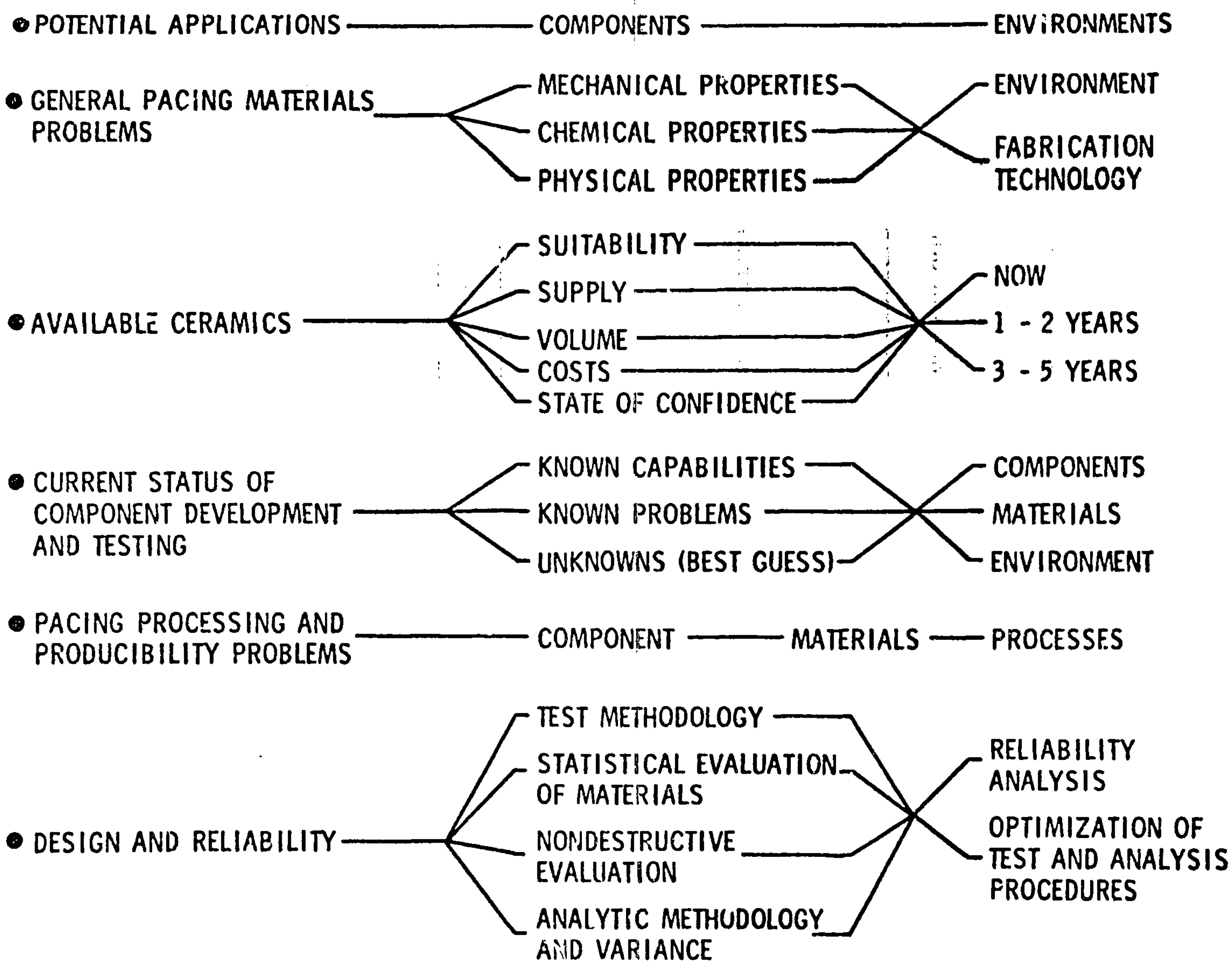


Fig. 99 Ceramics for Small Gas Turbine Applications

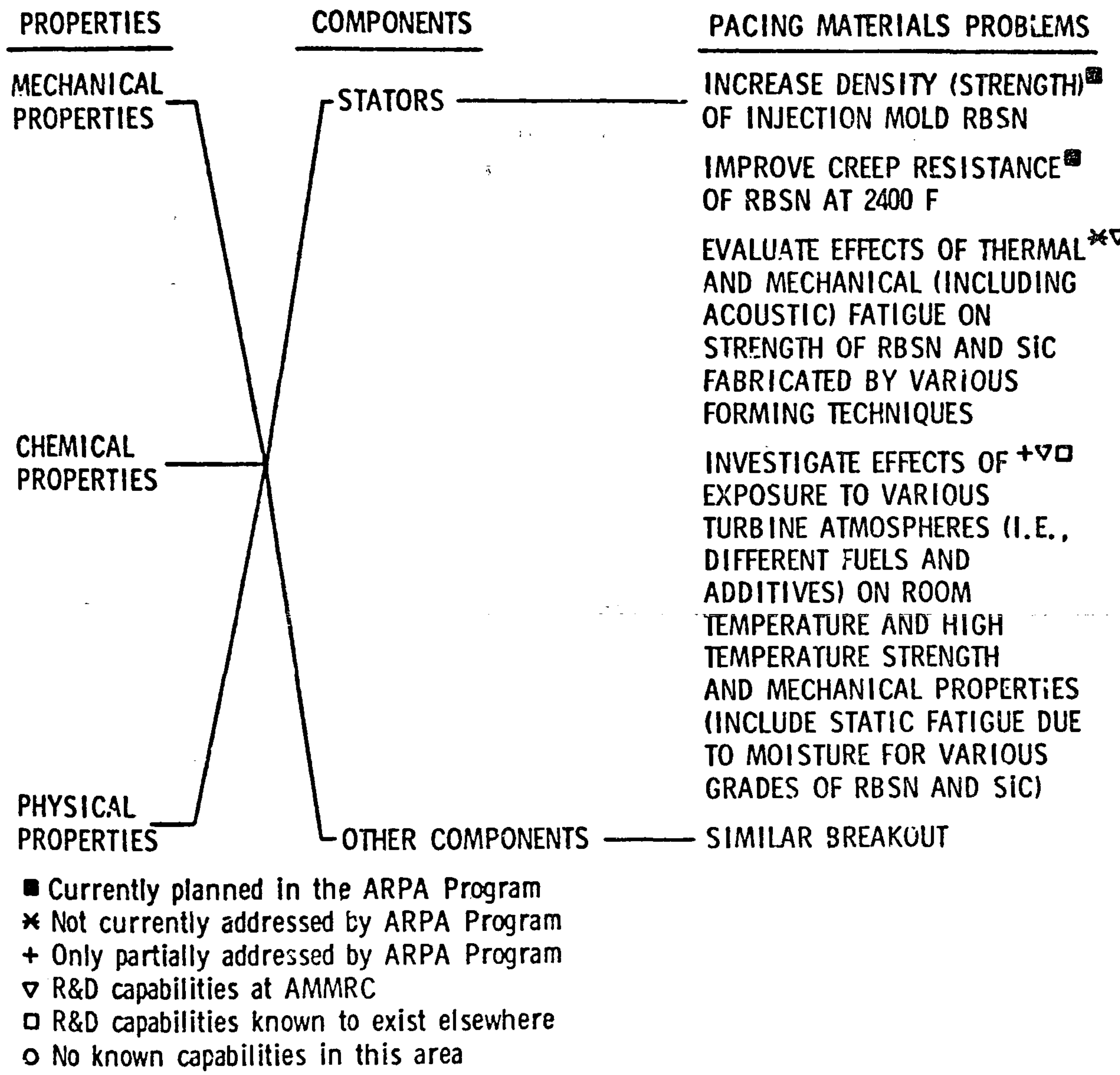


Fig. 100 "Spiderchart" for Pacing Materials Problems

CERAMIC COMPONENT	MATERIAL				PROCESS						
	MAX. PART TEMP. °F	Si_3N_4	SIC	L.A.S	COLD PRESSING	SLIP CASTING	INJ. MOLDING	HOT PRESSING	CHEM. VAP. DEP.	PAPER WRAPPING	GLASS FORMING
1ST STAGE STATOR	2400	√				√	√				
2ND STAGE STATOR	2100	√				√	√				
1ST STAGE ROTOR	2300	√	X			√	√	√	X		
2ND STAGE ROTOR	2000	√	X			√	√	√	X		
1ST STAGE SHROUD	2300	√			√	√					
2ND STAGE SHROUD	2000	√			√	√					
INLET NOSE CONE	2500	√					√				
COMBUSTOR	3000		X			X					
REGENERATORS	1800			0						0	0
MATERIALS SOURCES											

Data from Mr. A. F. McLean

Fig. 101 Materials and Processes for Ceramic Components for Ford Ceramic Engine Operating at T.I.T. of 2500°F Uncooled

ANALYSIS ↓ / APPLICATIONS →	STATORS	ROTORS	SHROUDS	COMBUSTORS	DUCTING	REGENERATORS	RECUPERATORS	SEALS AND BEARINGS	INSULATION
CRITICAL PROPERTIES	• HIGH TEMPERATURE CAPABILITY • THERMAL SHOCK AND THERMAL FATIGUE RESISTANCE • CORROSION-EROSION RESISTANCE IN TURBINE ATMOSPHERE • EASE OF FABRICABILITY					• HIGH TEMPERATURE CAPABILITY • LOW THERMAL EXCURSION • THERMAL SHOCK RESISTANCE	• HIGH TEMPERATURE CAPABILITY • THERMAL SHOCK RESISTANCE		
IMPORTANT PROPERTIES	• LOW THERMAL EXPANSION • IMPACT RESISTANCE • STRENGTH > 40,000 PSI					• CORROSION RESISTANCE Na, S, Pb OR OTHER FUEL ADDITIVES	• CORROSION RESISTANCE Na, S, Pb OR OTHER FUEL ADDITIVES		
CANDIDATE CERAMICS	• RBSN • SIC CRYSTAR SINTERED • SI ALONS • Al N • GLASS CERAMICS (AT LOWER TEMPERATURES)					• LAS • MAS • Al-TITANATE • RBSN	• LAS • MAS • Al-TITANATE • RBSN • SIC		
AVAILABLE MANUFACTURING TECHNIQUE	• RBSN INJECTION MOLD SLIP CAST BISQUE FIRE AND MACHINE ISOSTATIC PRESS PROPRIETARY METHODS • SIC SINTER SLIP CAST AND SINTER								
COSTS	RBSN $2/STATOR IN LOTS OF 200,000 (AME ESTIMATE)								
SOURCES	FORD MOTOR COMPANY NORTON COMPANY AME LIMITED								
STATUS OF CURRENT DEMO. PROGRAMS - LOCATION	RUN @ 2000 F T.I.T. * ~100 HR STATIC ~ 30 HR DYNAMIC ~270 LIGHTS FORD MOTOR COMPANY								
PLANNED EFFORTS									
SUGGESTED PRIORITIZED ADDITIONAL R&D PROGRAMS									

Fig. 102 Ceramics for Small Gas Turbine Applications

Phase I is scoped as a 6-month, 8400 man-hour effort to do a preliminary design for an I.C. engine and for the AAPS candidate engines. It is hoped that one transmission can be designed which can do the job, with minor modifications, for both the I.C. engine and the alternate engines. Then a final design will be made, probably for the I.C. engine, because an I.C. engine will be used for subsequent tests.

Phase II (optional depending on Phase I results) will be a 12-month effort to (1) fabricate and (2) test two of the transmissions on dynamometer--both steady-state and transient tests will be compared against an automatic transmission on an I.C. engine. Task 3 is to test the transmission in a vehicle to verify performance and fuel economy. Baseline tests will also be run with a vehicle and an automatic transmission. Task 4 will be a cost estimate for 1,000,000 units per year of a continuously variable transmission. Deliverable items are two transmissions, critical spare parts, final report with log books and analyses, and vehicles purchased.

The contract is to be awarded before the end of this Fiscal Year.

K. Potential Health Hazard of Nickel Compound Emissions from Automotive Gas Turbine Engines Using Nickel Oxide Base Regenerator Seals by R.Schulz, EPA

The EPA National Environmental Research Center surveyed the toxicologic literature on the carcinogenicity of NiO (Reference 1 - Appendix D). The principal concerns found over the release of additional NiO to the atmosphere were as follows:

- The compound porduces muscle sarcomas when injected into rats.
- Nickel oxide may function as a cocarcinogen when introduced into the lungs with a known carcinogen.
- Low level (100-150 $\mu g/m^3$) nickel oxide exposure may result in histological changes in bronchi and alveoli.
- Nickel oxide is cleared relatively slowly from the respiratory tract.
- Cigarette smoking may impair clearance of nickel oxide and potentiate tissue damage.
- Nickel oxide has been implicated by association in the higher incidence of nasal and lung cancer observed among nickel workers.

Estimates of NiO emission rates from gas turbine powered autos have been made on the basis of wear rate calculations and from preliminary testing of a prototype gas turbine car with NiO based regenerator seals. From these estimates it appears that an emission factor of 0.003 to 0.005 grams NiO per mile could be expected. While further seal development and testing of other prototype gas turbine vehicles might result in lower NiO emission rates, it seemed worthwhile to determine if emissions of NiO from automobiles at a level of approximately 0.005 grams NiO/mile pose an unacceptable risk.

The industrial threshold limit value (TLV) for nickel and its soluble salts is 1000 $\mu g/m^3$ for 8 hours per day. The present urban ambient nickel concentrations are as follows:

- National 1968 arithmetic average — 0.036 $\mu g/m^3$
- 1968 maximum — 1.300 $\mu g/m^3$
- 1969 maximum quarterly — 0.330 $\mu g/m^3$

NiO exposures were estimated (Reference 2 - Appendix D) based upon the extensive projections developed by the EPA Office of Research and Development which modeled sulfate exposures from oxidation catalysts. The projected exposures were made for NiO on and near major arterial throughways, assuming 25% of vehicle miles with turbine engine vehicles, and NiO emissions are 0.005 gm/mile from the turbine engine vehicles and zero from the remaining vehicles. The estimated incremental exposures for worst meteorological conditions are:

- 1 hour peak — 12.4 $\mu gm/m^3$
- 24 hour average — 1.45 $\mu gm/m^3$
- Incremental 24 hour — 0.88 $\mu gm/m^3$

It is concluded that the emission of NiO from automotive turbine engines of 0.005 grams/mile and the attendant exposure of the public to the incremental increases of this metal oxide is an unnecessary risk. Evidence against nickel oxide is sufficient to warrant development of alternate materials for use in automobile turbine engine rubbing seals. Since urban ambient levels of nickel are relatively high at present, due consideration should be given to any sources likely to increase these levels.

While it is probably safe to assume that we will not have 25% of the light-duty motor vehicles mileage attributable to turbine powered vehicles for a decade, at least, it is appropriate to identify the emission levels of non-regulated pollutants from all alternate power systems early in the development stages in order to properly assess the total environmental impact of their potential use. NiO emissions from turbines is but one example of this concern, and it should encourage emissions characterization of the other alternate powerplants currently under intensive development.

It is recommended that the following be pursued by industry and government as part of their automotive gas turbine development programs:

- Consider alternate seal materials that do not pose a health hazard or make design changes to minimize or reduce nickel emissions.
- Identify the form of nickel compounds emitted.

It is further recommended that EPA expand the non-regulated emissions characterization program relative to automotive gas turbines and other alternate powerplants. Also, the National Academy of Science should be advised of this study by EPA so that they may consider this issue within the perspective of their study on nickel.

Questions and Comments

Question: What was the source of the 1968 maximum and the 1969 maximum quarterly concentrations?

Answer: These concentrations were encountered in Portland, Maine and New York City, but the source of the pollutants is not known. EPA is on the alert for any sort of contaminant which represents a health hazard. Any marked increase in a known pollutant is investigated as to source and cause.

Question (Paul Reynolds, Jet Propulsion Laboratory): Has anyone identified a problem with fuel catalysts used with stainless steel in the exhaust system?

Answer: The pollution could be in the form of particulates or a compound like nickel carbonyl (very toxic) which can be produced by carbon monoxide in contact with nickel particles. However, this is not believed to be a problem with gas turbines because the exhaust temperatures are far above the 100 to 120^{o}F dissociation temperature. This has not been investigated.

Question: Have nickel emissions been measured around airports where aircraft turbine engines have been running?

Answer: EPA has a network of stations measuring various pollutants in the air; some of these are undoubtedly near airports. No correlation in the vicinity of airports has been reported or investigated as far as is known at this time.

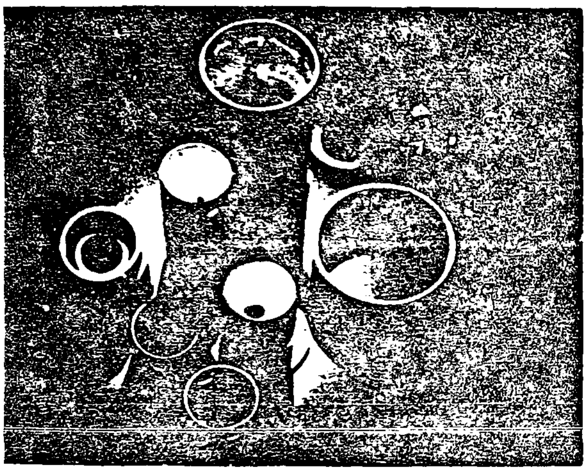
L. Ceramic Materials Development, by John Egenolf, Advanced Materials Engineering, Ltd., England (Guest Presentation)

In the three and a half years since it was organized, AME has focused primarily on the processing and fabrication techniques for the practical application of reaction bonded silicon nitride. One of the major application areas is power systems where overall economics is of prime importance. Some of the early vanes and a nozzle ring are shown in Fig. 103. The nozzle ring (for Plessey) is 6 to 7 inches outside diameter. Using the fabrication characteristics of silicon nitride, the molded blades are bonded to the outer and inner shrouds (cut from a solid) during the nitriding process. RBSN is not being recommended for rotating components.

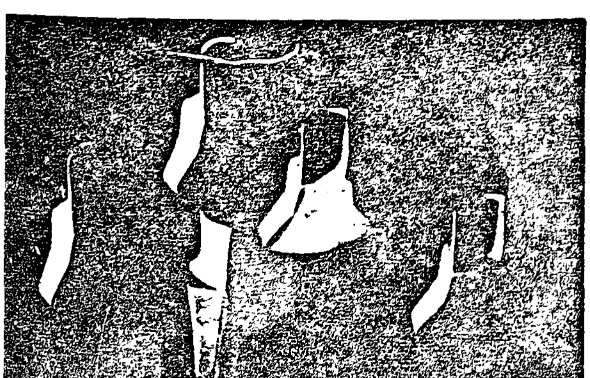
Also shown in Fig. 103 are typical burner liners in which thin film and bandage wrapping techniques, developed earlier for heat exchangers, have been applied.

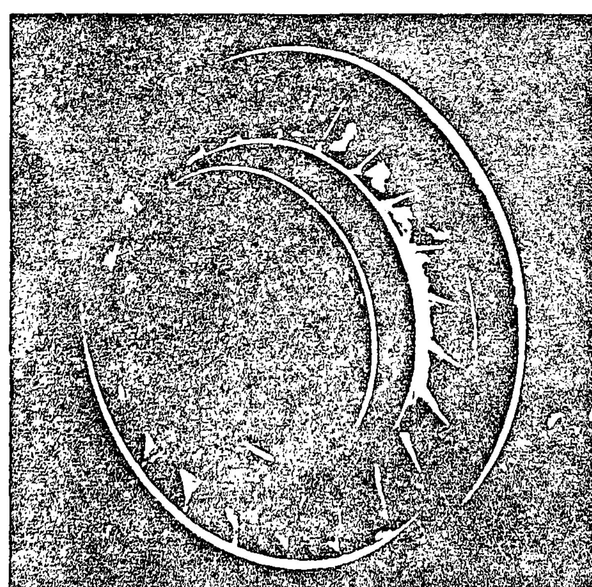
Much of the early thin film technology was developed in conjunction with British Leyland requirements for regenerator disks. Early disks were single pieces, 15-inch OD. Interest in recuperators also focused attention on reducing the permeability of the ceramic materials. This led to work on alloying silicon nitride and densifying or sealing the material. By matching the thermal coefficients of expansion of both the densifying agent and the silicon nitride, some of the thermal shock loss in the material property was restored.

Some of the later, modular designs of regenerators and recuperators aimed at mitigating thermal stress and repair cost are shown in Fig. 104. Also indicated is a foam matrix, as well as the extruded honeycomb matrix, which can be combustion chamber liners



nozzles and blades





Plessey Co. Ltd., M.T.U., M.A.N. and other customers for the kind use of photographs.

Fig. 103 Typical Ceramic Components

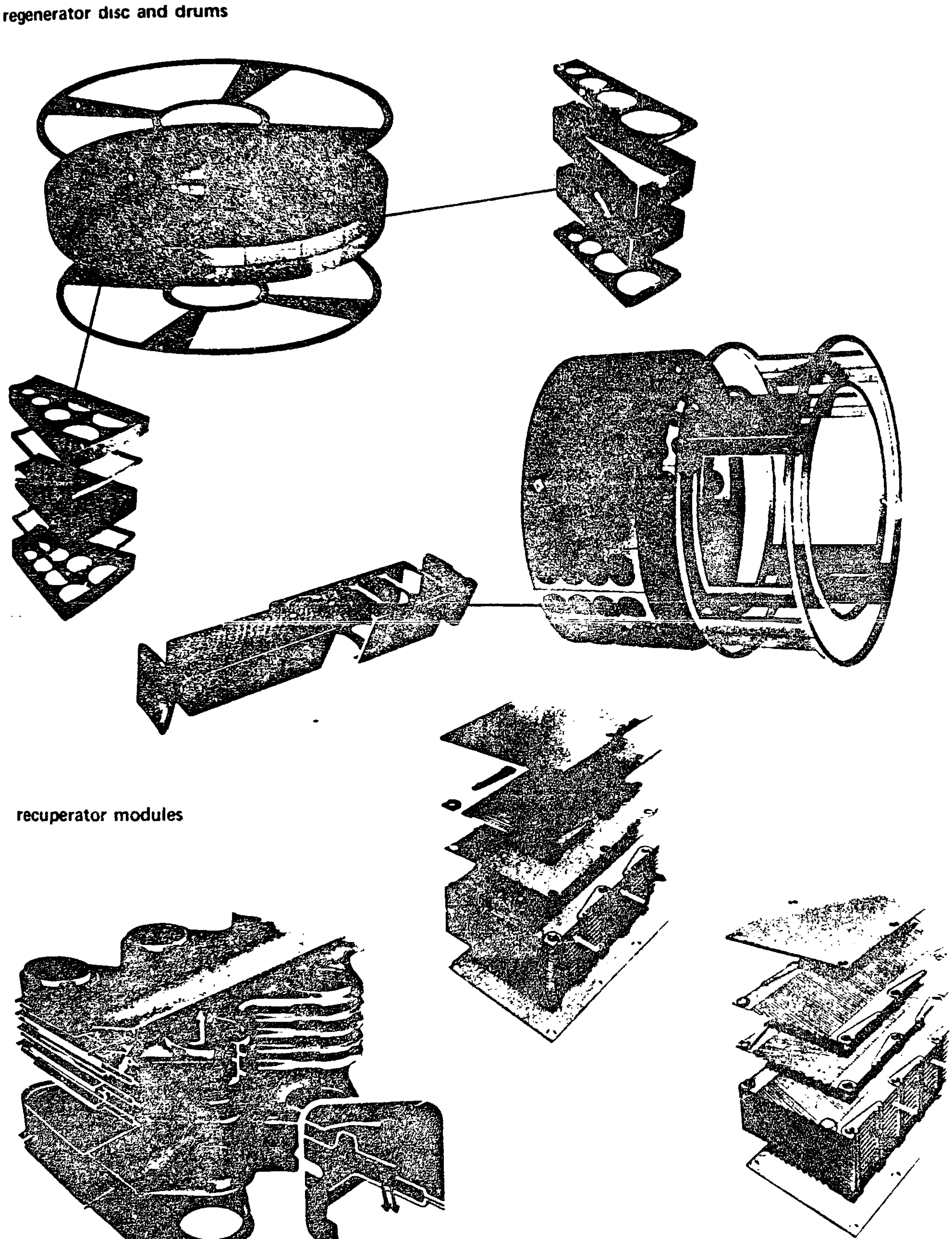


Fig. 104 Heat Exchanger Models

used not only for regenerator segments but also for high temperature insulation systems. It is believed that silicon nitride has an important role to play in future heat exchangers.

Questions and Comments: None

M. General Purpose Programmable Analog Control - by D. Court, Ultra Electronics, Inc., England (Guest Presentation)

Electronic analog control systems have been used successfully to control gas turbine engines for industrial and vehicular applications. Their initial introduction arose largely from the need to control engine temperature accurately for both economic and durability reasons. The ability of electronic controllers, however, to accept readily any input as a control parameter and use it as the basis of control in a particular mode of operation has meant that in many cases, an electronic controller currently offers the most economic control for a given application.

A typical automotive gas turbine engine control system achieved electronically is shown in Fig. 105. Input signals on the left-hand side: from the accelerator pedal; the gas generator speed, N_G; the intake air temperature, T_A; the turbine entry temperature, T_T; and the output shaft speed, N_O; are converted into voltage signals. These are used as inputs to an electronic analog computer which computes the correct fuel flow and nozzle actuator position from these inputs. Electrical outputs to drive the fuel metering valve and the nozzle actuator are shown on the right-hand side of Fig. 105.

Controllers of this type possess two major characteristics, their low cost and their flexibility. The low cost has arisen because the basic blocks in Fig. 105 are largely constructed from semi-conductor integrated circuits. During the last few years, the overall market for these circuits has greatly increased in volume, and extremely low unit costs have resulted. The second advantage, flexibility, is particularly desirable and economical during the development of a control, because, as with an electronic analog computer, changes in control schedules can be achieved with modest changes in the electrical interconnections between the hardware.

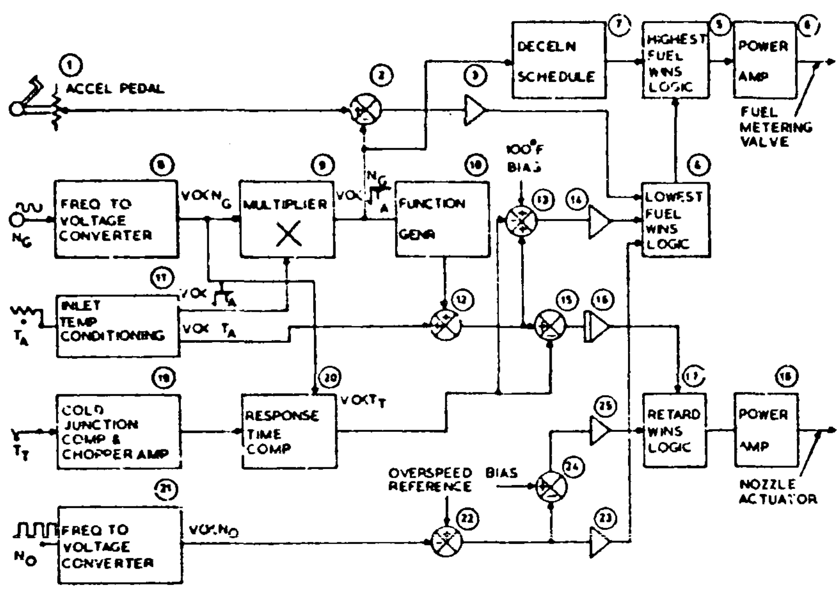


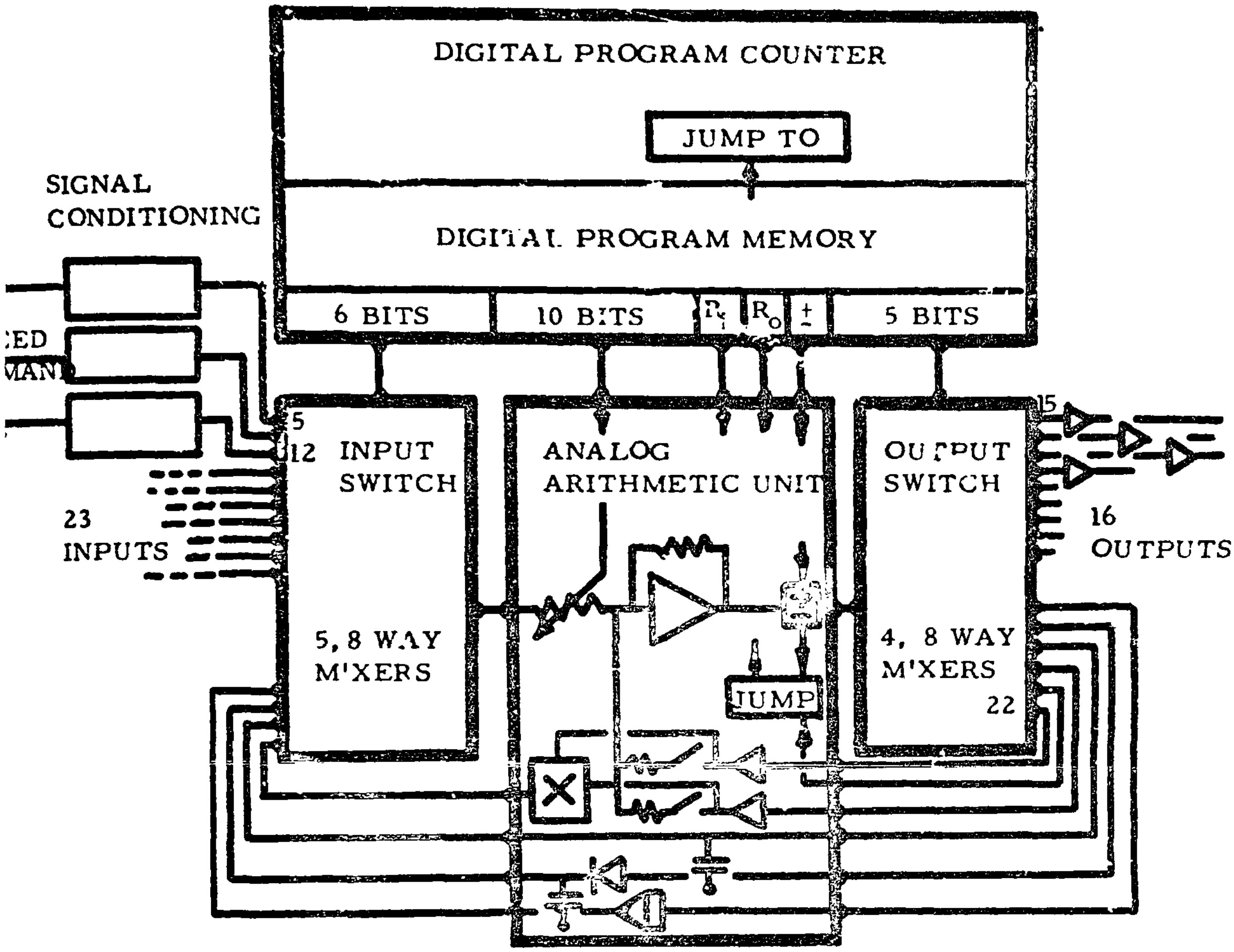
Fig. 105 Basic Electronic Analog Control System

During the last few years, however, there have been further developments of electronic controllers with the two objectives of: (a) reducing their cost, and (b) increasing their flexibility. The approach that has generally been adopted to achieve these ends is that of "programmability" and sequential operation of the computational elements. Instead of performing the control calculations simultaneously and in parallel using a large number of computational elements as shown in Fig. 105, a single computational element is used which is under the control of a stored program. This performs each of the required calculations, stores the intermediate results, and finally produces the required fuel flow and nozzle actuator position. The sequence of calculations is performed repetitively at high speed, so that the fuel flow and nozzle position are updated at intervals much shorter than the response times of the engine being controlled.

An approach like this has the ability to achieve the two objectives for the following reasons. First, a single computational element is "time-shared" between the various control loops, and, for fairly complex control systems, this can lead to a decrease in the overall volume of electronics. Secondly, the control laws are completely defined by the stored program; thus, by changing the stored program, the control laws can be completely changed. Within the constraints of the sensor inputs and actuator outputs provided initially, the flexibility is unlimited.

A schematic of the general purpose programmable analog control is shown in Fig. 106. This control system provides the following:

- The optimum solution to the twin problems of control capability and low cost.
- Calculations performed directly on sensor signals in analog form to provide analog signals that can be used directly to drive the system actuators. The basic element of this system is an analog computer which is programmed from a stored digital program.
- A programmable system a control engineer can understand immediately and operate within hours.
- A final system, the size, cost and reliability of which is attractive.

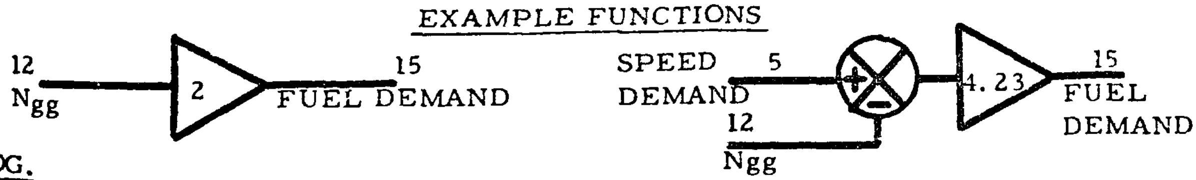


24 BIT INSTRUCTION WORD

INPUT						GAIN										OUTPUT							
32	16	8	4	2	1	512	256	128	64	32	16	8	4	2	1	16	8	4	2	1	R_o	R_i	±

[MAX GAIN (1111111111)= 10.23]

EXAMPLE FUNCTIONS



PROG.																								
1.	0	0	1	1	0	0	0	0	1	1	0	0	1	0	0	0	0	1	1	1	1	0	0	0
2.	0	0	1	1	0	0	0	1	1	0	1	0	0	1	1	1	1	0	1	1	0	0	0	1
3.	0	0	0	1	0	1	0	1	1	0	1	0	0	1	1	1	0	1	1	1	1	1	0	0

Fig. 106 General Purpose Programmable Analog Control

For more detailed description r information see (1) "Developments in Programmable Analog Control Systems" by J. R. Dent and A. .. Bergman, Ultra Electronics, Ltd., 36 Mansfield Road, Western Avenue, Acton, London N30RT, England, this is A.S.M.E. Paper No. 74 GT 117, presented at 1974 Gas Turbine Conference and Products Show in Zurich.

Questions and Comments

Comment (T. Sebestyen, EPA): This system has been used in a number of practical control applications including gas turbines and industrial chemical processes.

IV. RANKINE ENGINE PROGRAMS

A. Overview of Trends, Objectives, and Status, by Steve Luchter, EPA

As indicated in Fig. 107, the Rankine Program was initiated with a broad base of technology and system contractors. Four preprototype system developments (covering water-base fluid reciprocating and turbine; and organic fluid reciprocating and turbine approaches) were carried essentially through January 1974. In February 1974, approximately in accordance with the schedule in Fig. 108, decisions were made:

- To pursue the water base, reciprocating system through the prototype system evaluation with Scientific Energy Systems, Inc.
- To use the organic, reciprocating system as a back-up with Thermo Electron Corporation.
- To evaluate the prototype system in a "compact" car rather than the standard vehicle as originally planned.

Since the last Coordination Conference (October 1974), activities have focused primarily on two areas:

- Continued testing on preprototype engines to extract the maximum information from them. Emphasis has been on system dynamics and on the valving of the organic engine.
- Design of the Prototype Engine.

Test results continue to show steady-state emission levels well below 1977 Standards. Steady-state fuel economy results are approaching those of spark ignition engines.

Use of the preprototype hardware will continue. The engine will be installed in a vehicle for further development of the control system. Called the Control Development Simulator, it is expected to be operational on a dynamometer by the end of 1974.

Prototype development will continue in parallel.

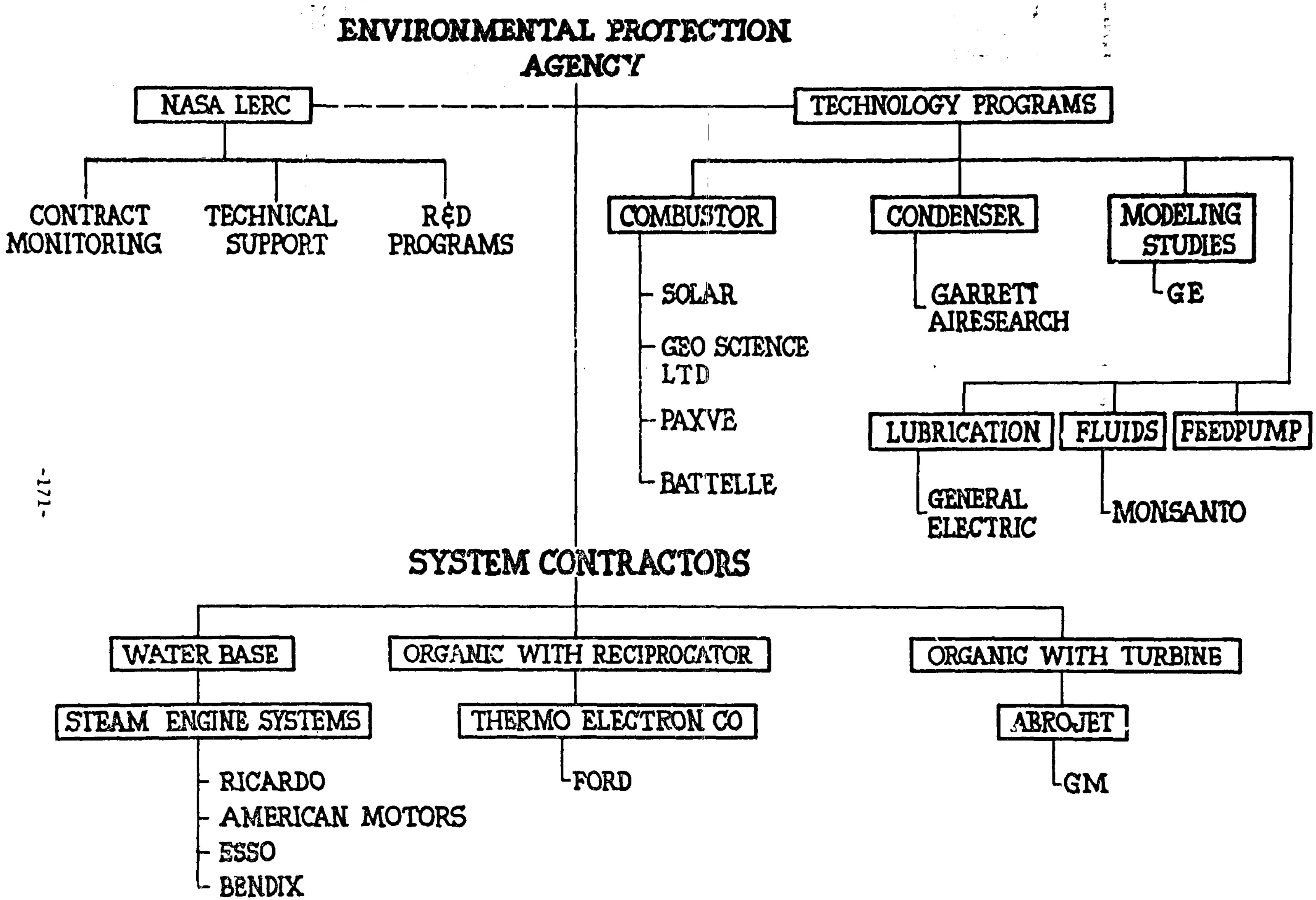


Fig. 107 Rankine System Development Team

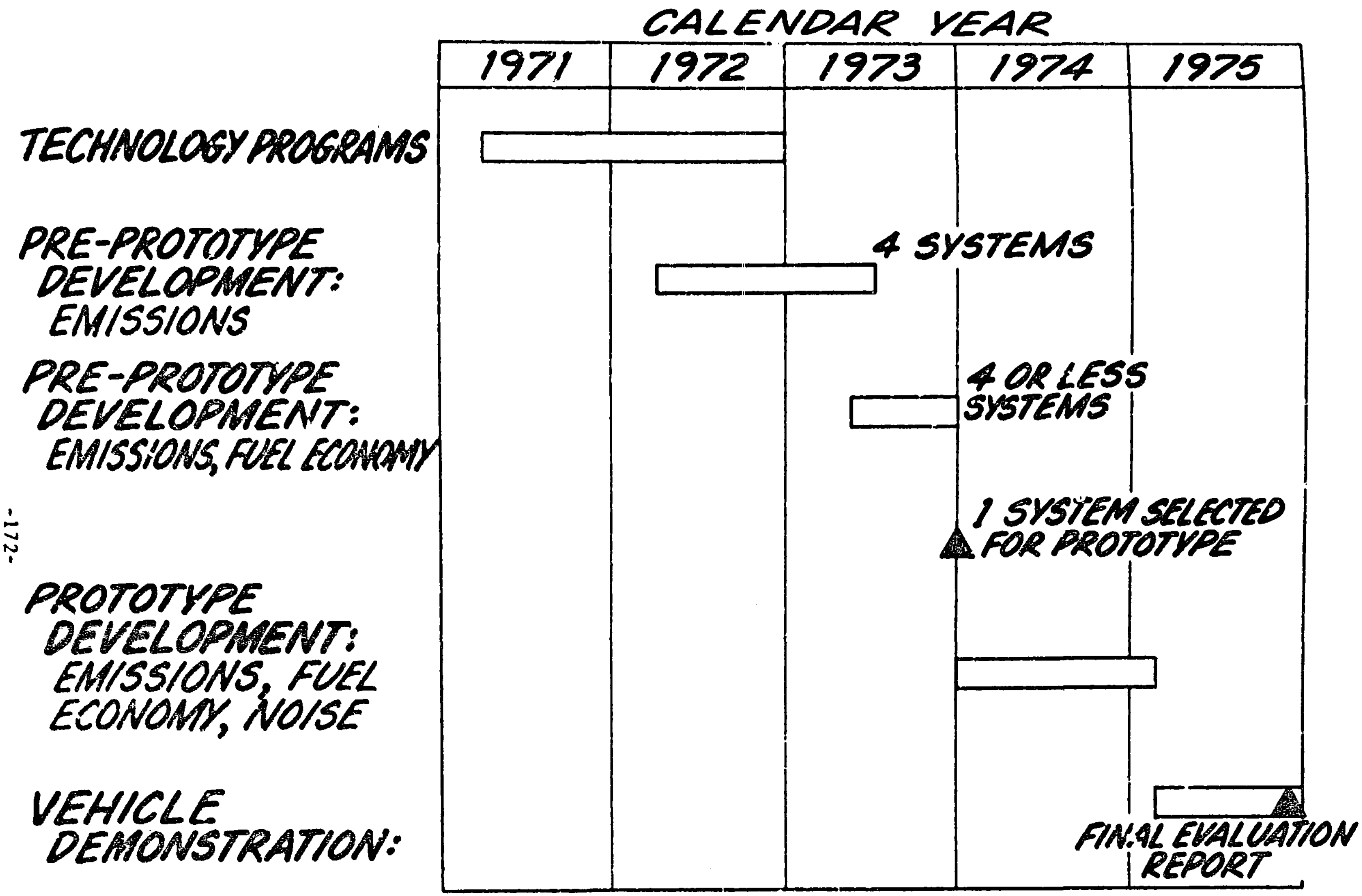


Fig. 108 Rankine System Schedule

B. Water Base Reciprocating System, by Jack H. Vernon and Roger Demler, Scientific Energy Systems, Inc.

Perspective on Rankine Development: Although progress has been made on vehicular steam engines by numerous people and organizations since the early 1900's (Stanley, Doble, White, Besler and GM, to name a few), it is only over the last three years of the AAPS programs, that a concerted effort has been made to bring it all together. By focusing the latest technology on specific goals and requirements in a conscious effort to develop a low pollution Rankine engine, potentially competitive with the I.C. automotive engine, remarkable progress has been made in a short time with nominal investment. The incentives motivating this effort stem from the present environmental laws. Although the present rate of improvement and progress is relatively high, a fully developed, competitive engine is still in the distant future; a large amount of work remains to be done.

Features of SES System: The following lists the principal features of the SES Preprototype System (Fig. 109):

- Working fluid: pure water - 1000°F, 1000 Psig at boiler exit
- Fail-safe freeze protection: working inventory drained to heated sump on shut down - flexible bladder in sump for emergency
- Reciprocating expander: 4 cyl in-line - 135 cu. in. displacement, trunk piston lubricated with natural base-stock oil, uniflow exhaust, variable cut-off control, plain shell type bearings, and cam and tappet valve train
- Design point: EPA/AAPS vehicle specification
  Maximum steam flow = 20 lb./min.
- Maximum expander power: (85°F ambient, high gear)
  Gross hp = 158 @ 1500 rpm
  Net hp into transmission = 138 @ 1500 rpm
- Compact, low emission boiler; 19.5-in. diameter by 18.5-in. long; heat input to water at maximum power = 1.58×10^6 BTU/hr.
- Condenser heat rejection at maximum power = 1.21×10^6 BTU/hr.

Fig. 109 SES Automotive Steam System Mock-Up

- Simple feedwater pump with fixed displacement, direct drive, efficient flow control by inlet valve modulation
- Practical installation with good accessibility, only minor chassis changes, conventional arrangement, good cooling air flow, and conventional seals (not hermetic)

Current Status and Recent Achievements: The data shown in Figs. 110 and 111, based on the best available steady-state laboratory data, show that emissions should be well below statutory 1977 standards. Fuel economy up to 15.45 mpg is shown in Fig. 112. Fuel economy projections, based on steady-state performance, for the Federal Driving Cycle, are shown in Fig. 113.

Cumulative development test hours to date are as follows:

• System Testing (Current Build 115)	391 hours
• Single Cylinder (Over 30 hp 38) (Rated, 40 hp 2½) (Max Single Build 200)	847 hours
• Vapor Generators (Max Single Build 905)	2035 hours
• Prototype Pumps (Max Single Build 600)	3930 hours

Some of the improvements in expander efficiency and auxiliary power requirements are shown in Figs. 114 and 115.

Controls are an important part of the current test and development effort:

- Automatic start-up has been incorporated in the control system
- Idle steam conditions reached in 19 seconds from key "on"
- Flame holder temperature is used for closed loop fuel-air ratio control

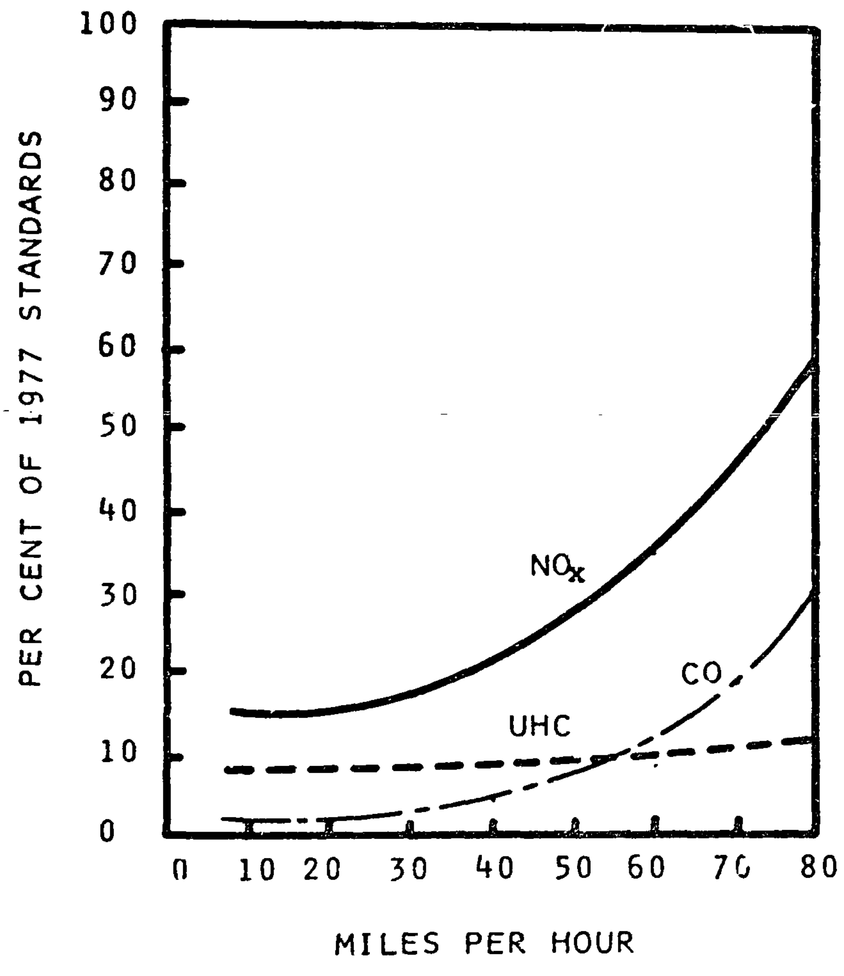


Fig. 110 Steady-State Emissions (Based on Measured Steady-State Emissions and Current System Fuel Economy)

SES PROJECTION	1976 STANDARDS	
NO_x = 0.18	0.40	GRAMS/MILE
CO = 0.43	3.40	GRAMS/MILE
UHC = 0.18	0.41	GRAMS/MILE

COMPUTATION BASED ON MEASURED EMISSIONS FROM PREPROTOTYPE STEAM GENERATOR, 10 MPG AVERAGE FUEL ECONOMY, 25% AVERAGE FIRING RATE. INCLUDES MEASURED UHC OF 0.50 GRAMS ON IGNITION AND 0.25 GRAMS CN SHUT-DOWN.

Fig. 111 Cold Start Federal Driving Cycle Emissions

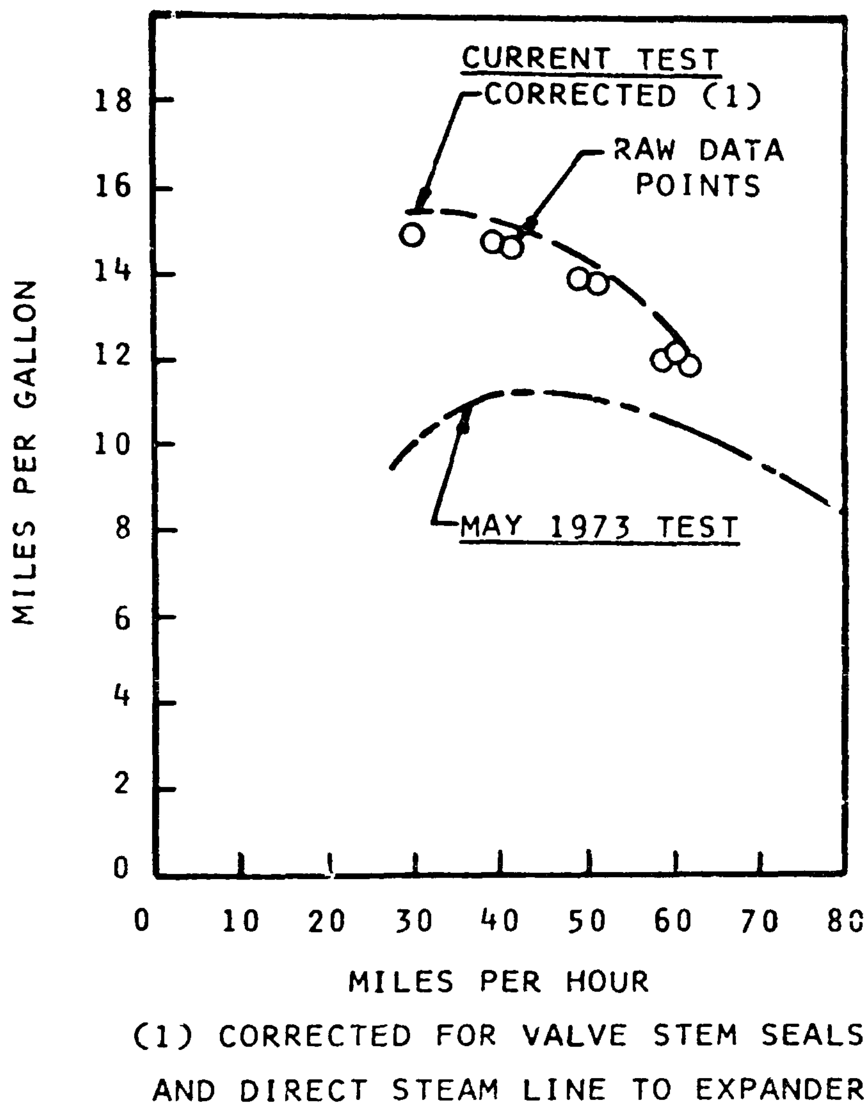


Fig. 112 Steady State Road Load Fuel Economy (4600 Pound Vehicle)

VEHICLE: 4600 LB. TEST WEIGHT, 12. FT^2 DRAG-AREA PRODUCT
SYSTEM: CURRENT PERFORMANCE
DRIVE TRAIN: 3 SP. AUTO TRANS, 11.75" DIAM. TORQUE CONVERTER.
EXPANDER IDLE SPEED: 250 RPM.

	FDC FUEL ECONOMY	
	HOT START	COLD START (1)
ACCESSORY LOAD W/O AIR COND. (2)	10.22 MPG	9.22 MPG
ACCESSORY LOAD WITH AIR COND. (3)	8.64 MPG	8.04 MPG

NOTES: (1) STEAM GENERATOR WARM-UP OF 17 SEC, AT 80% OF FULL FIRING RATE (USING 0.065 GAL. FUEL).

(2) POWER OF 2 HP. AT EXPANDER IDLE SPEED, 5 HP. AT MAXIMUM SPEED AND LINEAR CHANGE WITH SPEED.

(3) POWER OF 4 HP. AT EXPANDER IDLE SPEED, 15 HP. AT MAXIMUM SPEED AND LINEAR CHANGE WITH SPEED.

Fig. 113 Federal Driving Cycle Fuel Economy Projected from Steady State Performance

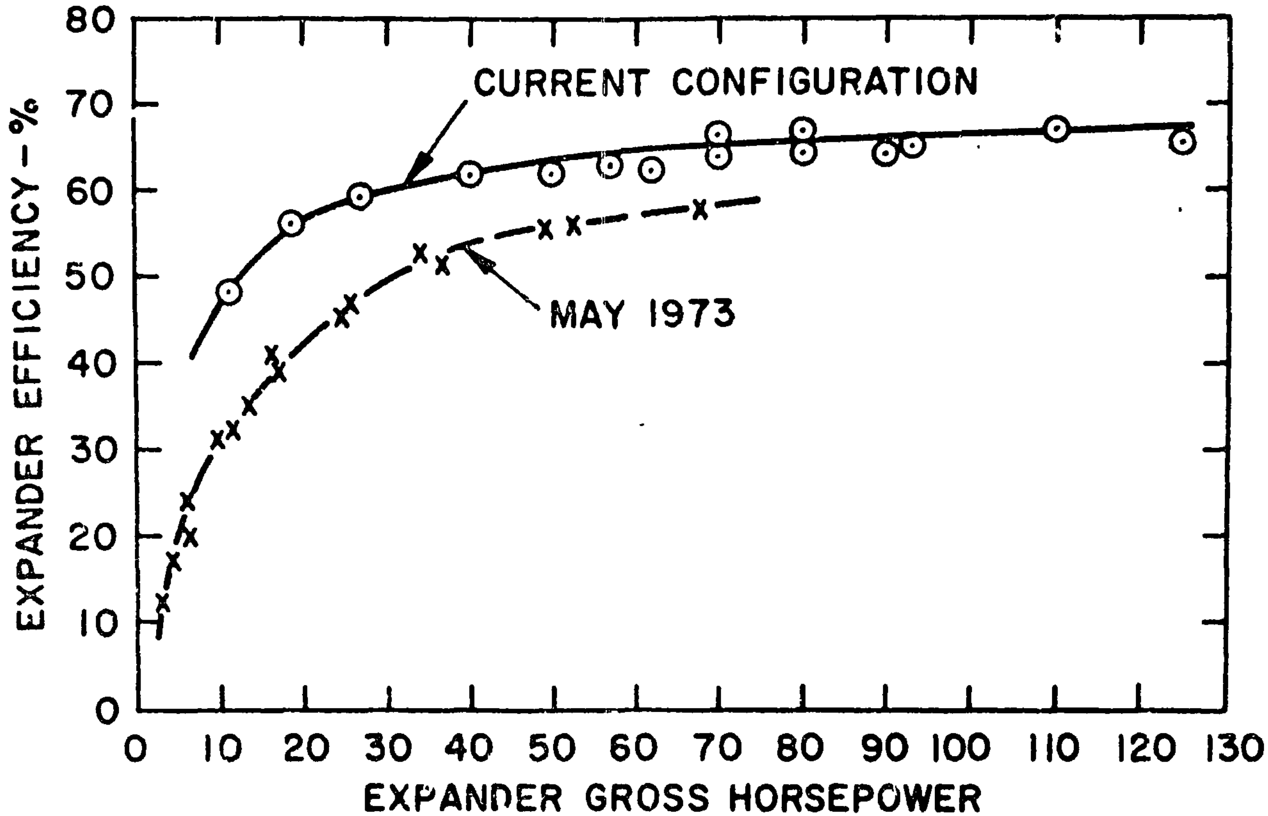


Fig. 114 Expander Efficiency

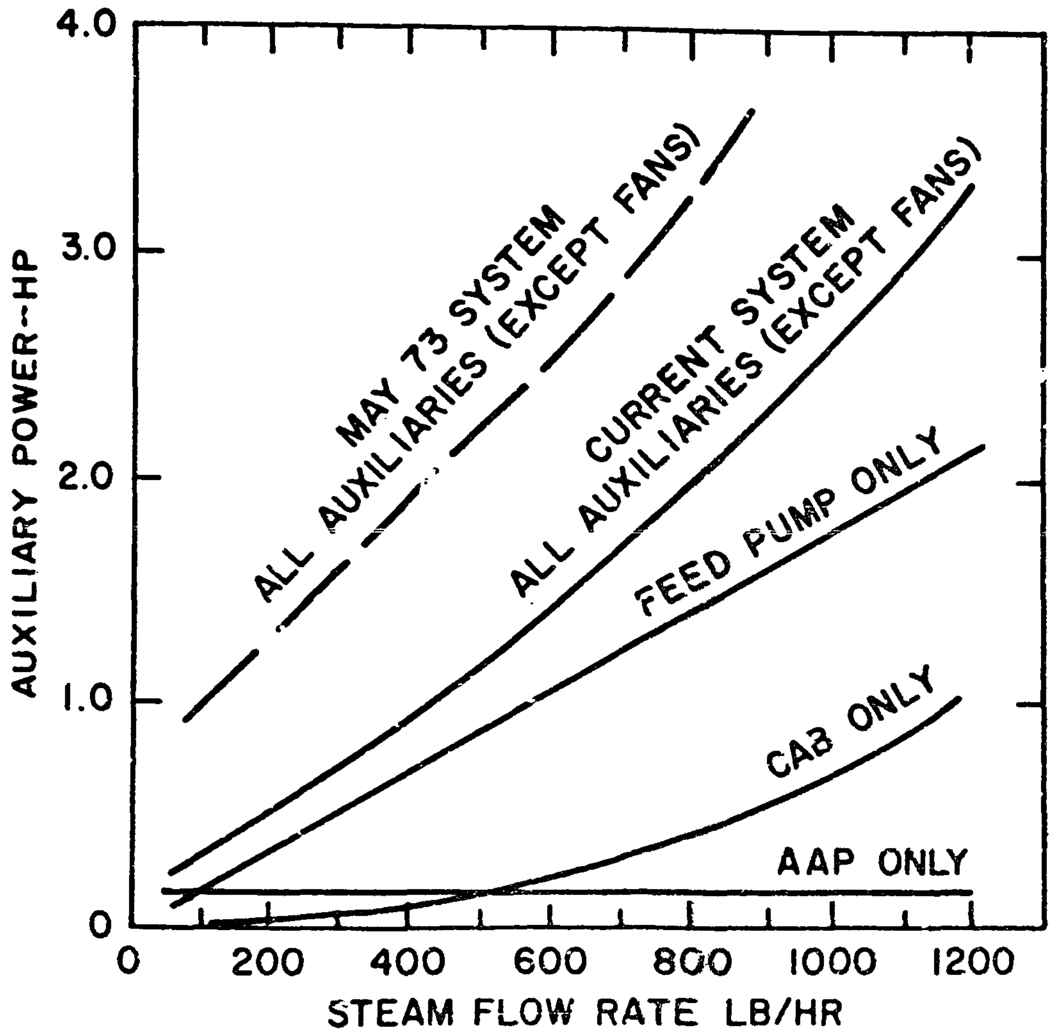


Fig. 115 Auxiliary Power Requirements

- Only two driver inputs
  - Key on/off
  - Power demand (accelerator pedal)
- Automatic cold start enrichment from mixture temperature signal
- Basic control mode is anticipatory with temperature and pressure feedback
- Control options
  - Driver input to expander cut-off or firing rate
  - Active evaporator bypass control
  - Temperature control at superheater inlet or outlet

The preliminary system transient response is too slow. Transient loop tests are in progress incorporating the boiler feed pump, the boiler, the steam throttle and the controls. The key factor determining the response is the metal energy change with load. Secondary factors are: maximum firing rate, firing rate of change, control strategy, and base load (i.e., like a "flight idle").

The strategy for improved boiler response is through energy leveling (by reduced tube weight, revised pass order, and passive evaporator by-pass) and control options (active evaporator by-pass control and variable boiler pressure to level energy change). The following comparison of the current Model 5 with the new Model 7 (see Fig. 116) boiler indicates some of these improvements:

	Model 5	Model 7
• Maximum steam flow, lb./min.	20	20
• Tubing weight, lb.	98	61
• Metal energy change, idle to full load, BTU	1,430	100
• Superheater temperature control point	exit	inlet

Prototype Compact Car: A scaled version of the Preprototype Engine is to be installed and evaluated in a compact car. EPA performance specifications for the compact car are:

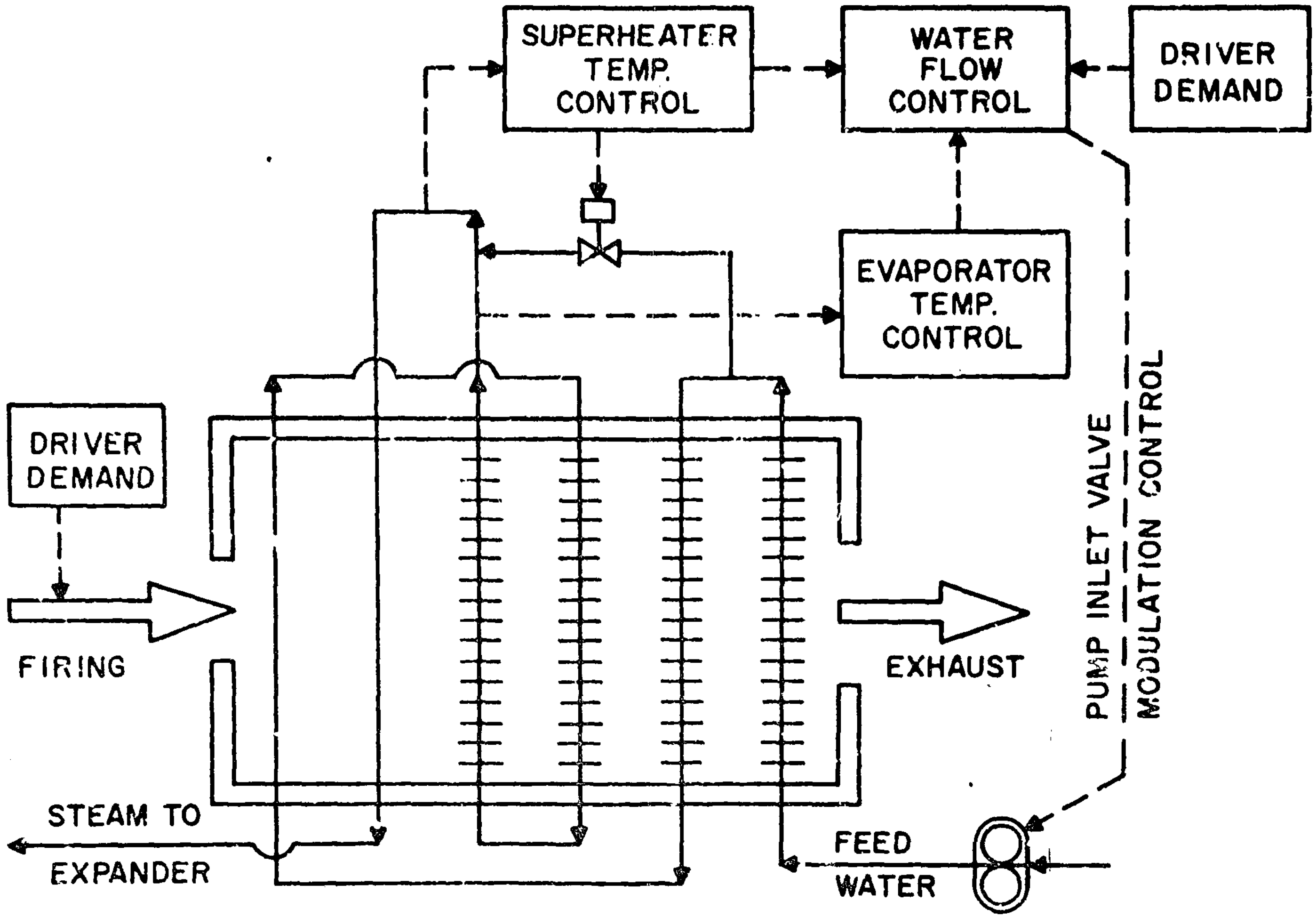


Fig. 116 Model 7 Boiler and Control Strategy

- Emissions to be ½ of 1977 standards
- Standing start: 440 feet in 10 seconds
  60 mph in 17.5 seconds
- Merging traffic - 25 to 70 mph in 20 seconds
- DOT high speed pass in 17 seconds (max 80 mph)
- 30 percent grade at 5 mph
- Fuel economy at 50 mph, 20 mpg
- FDC fuel economy, 15 mpg

The base vehicle is a 1975 Plymouth Valiant. The engine power and configuration will be as follows:

- Gross expander power - 90 hp
- Maximum steam flow of 800 lb. per hour
- Basic engine arrangement and cycle will be scaled from the Preprototype Engine.
- Vapor generator - 17.5 in. diameter by 17 in. long, weight 52 lbs.
- Expander - 4 cylinder, in-line, 65 cu. in. displacement, 4000 rpm, no step-up gear
- Condenser - single fan, aluminum core, 3.8 sq. ft., 4 in. depth, 20 fins per inch on air side
- Feedwater pump - present pump with reduced bore
- Transmission - production 3-speed automatic

A breakdown of projected vehicle weight is as follows:

- Base vehicle without powerplant, W_O = 2131 lb.
- Prototype propulsion system

— Expander	225 lb.
— Condenser & Fan	60
— Vapor Generator	52
— Feedpump	16
— Auxiliary Drives	35
— Working Fluid, 4 gal.	34

— Freeze Protection	18	
— Transmission	180	
— Miscellaneous	80	
— Vehicle Related (Exhaust, propshaft, axle, battery, fuel & tank)	380	
• Propulsion System Weight	W_P = 1080	(Comparable weight for a 6 cylinder production Valiant is 1055 lbs.)
• Curb Weight	W_C = 3211	
• Test Weight	W_T = 3611	
• Gross Weight	W_G = 3911	

Work in Progress

- Continued durability development on preprototype hardware.
- Controls development on chassis dynamometer. Preprototype Engine being installed in Plymouth for the work - called Control Development Simulator.
- Light weight boiler for rapid throttle response (current tube bundle is 98 pounds); light weight tube bundle is 61 pounds; compact car tube bundle is 35 pounds
- Prototype design includes:
  - improved economy with refined expander, valve train refinements, and thermal isolation
  - study of compact and standard car systems
  - car selection and final prototype design in Fall 1974

Questions and Comments

Question (N. Moore, JPL): How does the inlet valve unloading concept work on the feedwater pump?

Answer: The inlet valve on each cylinder is a spring loaded ball valve. Also at each inlet is an electric solenoid with a shaft which holds the valve open when activated. By cycling the three solenoids with the control signal, the flow can be regulated in accordance with the demand of the control.

Question (Dr. J. E. Davoud, D-Cycle Power): Have you considered going to higher cycle temperatures?

Answer: Higher temperatures have been considered, but dropped, because the potential gain of perhaps 1 to 1½ mpg for a 200°F increase does not seem commensurate with the risks of wrecking the engine and getting into a lot of unknowns which would not help the program at this time.

Question (Scott Carpenter, Advanced Power Systems): How were the reductions in the boiler weight (90 lbs. down to 60 lbs.) and the BTU energy loss (1400 BTU down to 100 BTU) achieved?

Answer: The BTU reduction is not a loss, but is the amount of energy which is added to the tube in the course of getting up to the desired steam conditions. The reductions were achieved primarily through smaller tubing in the economizer and the evaporator, aluminum finning on the economizer, and redistribution of the tube passes (for reducing energy change). One of the evaporator passes was put up by the fire.

Question (Paul Vickers, GM Research Center): Why haven't vehicle emissions been measured?

Answer: The engine has not been installed in a vehicle as yet. Equipment for running transient tests will not be ready until next winter. Standard EPA emissions test equipment is installed and will be used.

Question (Comdr. E. Tyrrel, Dept. of Trade & Industry, England): What type of water quality is required for this engine? Are there de-aeration provisions, and what is the boiler tube material? CO_2 corrosion of ferritic materials is a problem over 600°F. What is the thermodynamic efficiency of the cycle?

Answer: Over-all thermal efficiency is 16-17%. City water is run through a demineralizer. No provision is made to measure water quality. Deposits from the demineralized city water have not been observed. The boiler tubing material is stainless steel. No corrosion problems have been identified. Tubes from a boiler which ran 900 hours were cut up. No problems were detected. The condenser pressure is a little over ambient at all times, 20 Psia. A de-aerator valve is set to blow off non-condensable gases when the system is running.

Question (R. R. Stephenson, JPL): Please clarify the time to get up to operating conditions.

Answer: At present it actually takes 19 seconds to get from the turn of the key up to 500 Psig and 500°F idling conditions. EPA, to account for warm-up fuel consumption, asks how long it takes at an 80% firing rate to get up to 1000 Psig and 1000°F. Some of the calculations show 17 seconds. This has not yet been accomplished. At present, it is estimated that another 2½ to 3 seconds are required to get to 1000 Psig and 1000°F.

Question (T. Duffy, Solar): What is the fuel flow at idle and what are pressure and temperature goals in terms of transient limits?

Answer: Idle flow is about 5 pounds per hour (uncertain). It is intended to control pressure within ± 50 Psi and temperature within ± 50°F. The tolerance of the system to such excursions during acceleration and deceleration is not yet clear.

Question (Dr. Max Bentele, Xamag, Inc.): Why do you use an automatic 3-speed transmission when the inherent torque ratio of the steam expander is so good?

Answer: If available, a 2-speed, manual power-shift transmission without a torque converter would be best. To eliminate the transmission or a gear change of some sort completely would probably be impractical because it would lead to an oversize condenser which would in turn be too large for the vehicle.

Question (Dr. F. Paul, Carnegie Mellon University): What are the response times with the controlled and uncontrolled vapor generator?

Answer: Tests are sketchy in this area. Largest step change so far was from idle to 60% power while driving an eddy current dynamometer. Estimates indicate about a 3-second first order time constant on a controlled boiler. This is still very preliminary.

Question (Dr. J. E. Davoud, D-Cycle Power): What is the basis for the road load horsepower versus various speeds (i.e., the basis for the fuel economy curves in Fig. 112)?

Answer: Road load horsepower versus speed figures were established by EPA and take into account wind resistance as well as rolling resistance. This seems to be generally accepted by people such as DOT and others in the industry. Drive train losses at 30 mph were taken as 83%. This then is combined with estimated auxiliary and accessory powers to get power required from the expander and corresponding fuel economy.

Question (Mr. Jack Edwards, Rohr Corp.): What is the cranking time and starter horsepower? Is thermal efficiency of the boiler compromised by reducing the thermal inertia of the boiler?

Answer: It presently takes 19 seconds to get up to idle steam flow. Approximately another 10 seconds might be required to get the expander up to speed to drive accessories, etc. A conventional starting motor, operating at a higher speed, is used. The thermal efficiency of the boiler is compromised about 2% out of 92% at idle as a result of reducing its thermal inertia.

Question (Dr. Douglas Court, Ultra Electronics): Where do you expect to mount the "black box" controls in the vehicle installation?

Answer: No attempt has been made yet at packaging or compacting the control system.

Question (Mr. Tom Duffy, Solar): What are the transient characteristics of the flame holder temperature as these will have an important effect on your feedback control system? Also, what approach is being used for flame detection?

Answer: The automatic feedback system is being used in the starting cycle; it has a 3/4-second smooth response in going from idle to 100% fuel rate; it works very well. A cadmium sulfide cell is used as a flame detector.

C. Organic Reciprocating Engine, by Jack Armstrong, Thermo Electron Corp.

A schematic diagram of the Thermo Electron, Organic Rankine Cycle Engine is shown in Fig. 117. The principal characterics of the Preprototype Engine are as follows:

• Working Fluid	Fluorinol-85 85 mole % CF_3CH_2OH 15 mole % H_2O
• Freezing Point	-82°F
• Lubricant	Commercial Refrigeration Oil (Sun Oil Product)
• Thermal Stability	Capsule tests indicate potential for use to 660°F
• Reference Car and Transmission	1972 Ford Galaxie 500 3-Speed Automatic
• Expander Gross Shaft Power	145.5 hp
• Peak Cycle Temperature	550°F
• Peak Cycle Pressure	700 Psia

Preprototype Engine Program: The program status on the Preprototype Engine is as follows:

- Fluorinol-85 baseline performance has been established. The test range has included cruise speeds from idle to 70 mph (level grade and acceleration), inlet pressures from 400-700 Psia, and maximum

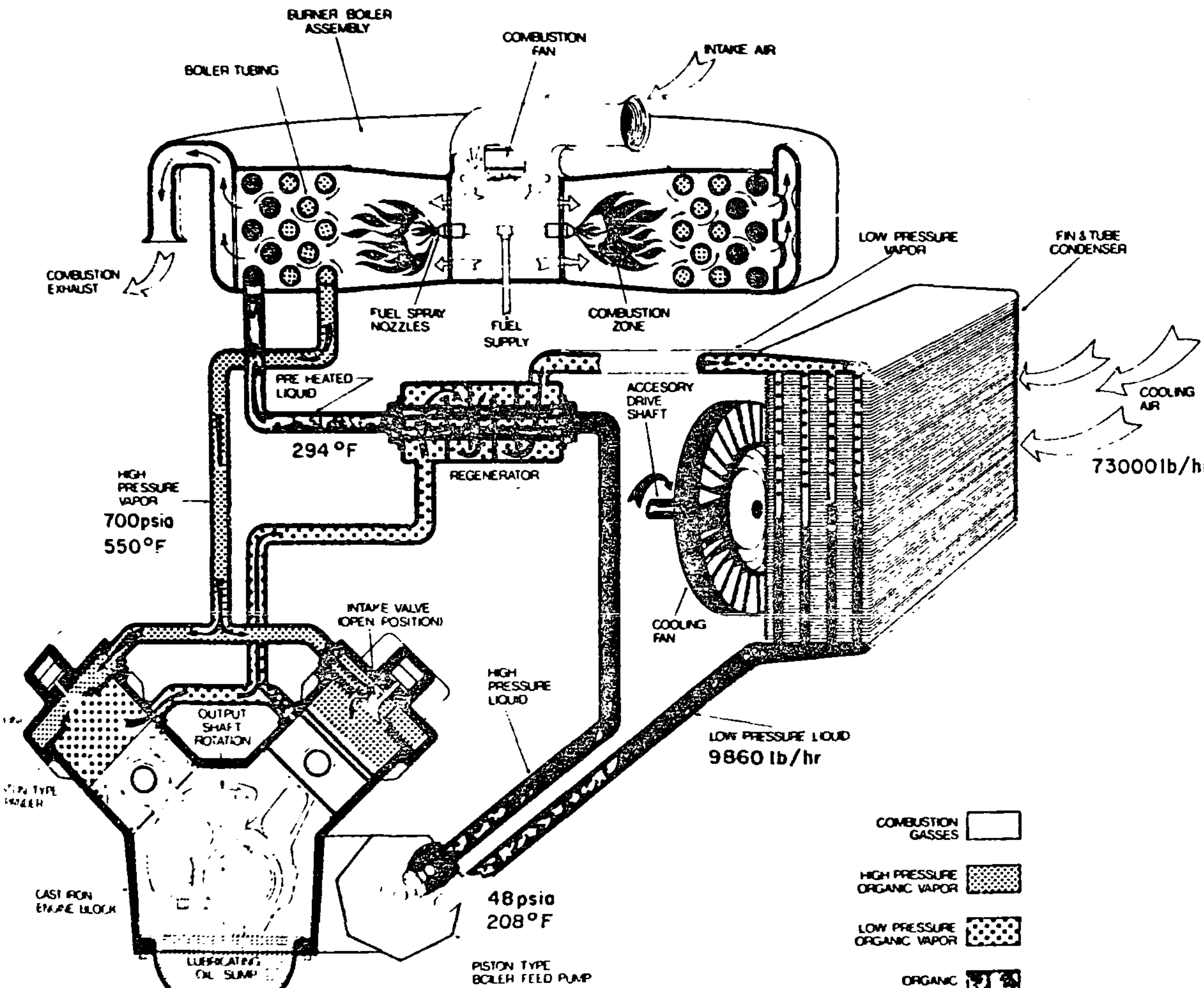


Fig. 117 Thermo Electron Rankine Cycle Engine Schematic Diagram

inlet temperatures to 625^{o}F. Expander driven auxiliaries include: condenser fans, feedpump, lube oil pump, alternator, and hydraulic pump for valves. The test system is close-coupled and arranged as it would be in the vehicle installation. The ram air facility provides realistic system simulation up to 90 mph.

- Up to 50% improvement in fuel economy has been measured (See Fig. 118).
- Emission measurements show pollution levels well below 1976 standards (See Fig. 119).
- The BICERI (British Internal Combustion Engine Research Institute) valve has been demonstrated.
- Idle operation (about 250 rpm) has been simulated.
- Control testing is in progress. This has been done on a component by component basis; the complete control system is to be ready for test by the end of June 1974. It is a "predictive" control; inputs are expander intake valve cut-off set by accelerator positions, and expander rpm. The predictive settings are: blower motor rpm, air/EGR shutter position, fuel pump rpm, and feedpump displacement. Major feedbacks are: organic fluid pressure for feedpump displacement, organic fluid temperature for the corresponding air/fuel setting, and condenser pressure for fan speed control.

Prototype Engine Program: Design of the Prototype Engine for the compact car is based on information generated by the Preprototype Engine. The performance reference is the 1974 Ford Pinto with less than the 1977 Federal Emission Standards.

The program status on the Prototype Engine is as follows:

- Trade-off studies are completed. The resulting system and component characteristics and features are shown in Figs. 120, 121, 122, 123, 124, and 125.
- Compact car design options are developed (See Figs. 126, 127, and 128).

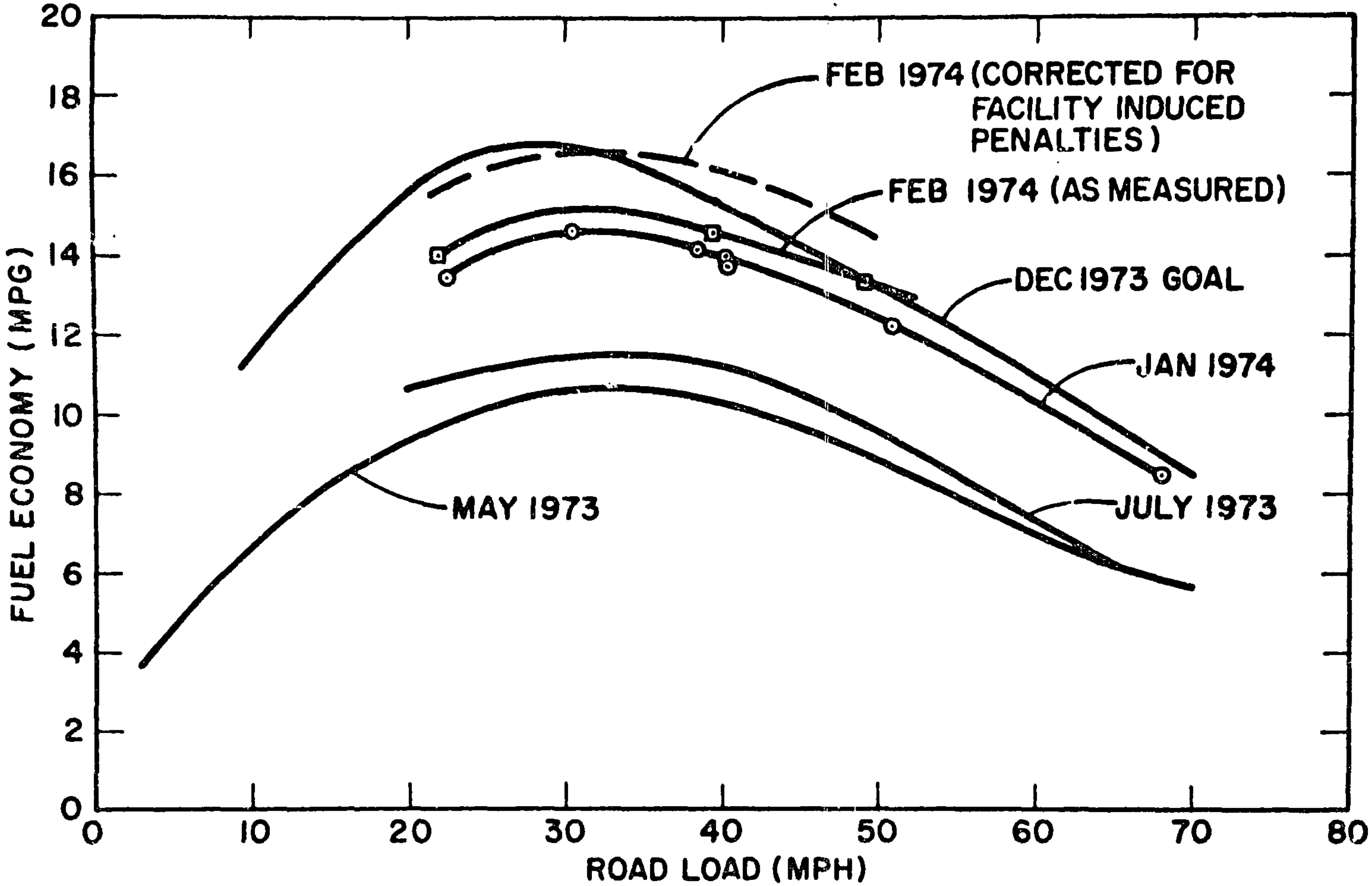


Fig. 118 Preprototype System Fuel Economy - FL-85 Baseline

EMISSIONS FOR FEDERAL DRIVING CYCLE

POLLUTANT	1976 FEDERAL STANDARD [GMS/MILE]	EMISSIONS [GMS/MILE]
UHC	0.41	0.17
CO	3.40	0.21
NO_X	0.40	0.275

1. BASED ON STEADY STATE TEST DATA.
2. INCLUDES 30 SECONDS FIRING AT 58 LBS/HR FOR START-UP SIMULATION.
3. FUEL CONSUMPTION 10.2 MPG FOR FEDERAL DRIVING CYCLE.

Fig. 119 Emissions for Federal Driving Cycle

WEIGHT CLASS	2500-3000 LBS (TEST WEIGHT)
WORKING FLUID	FL-50
MINIMUM PUMPING TEMPERATURE	-28°F
FREEZING POINT	-82°F
PEAK TEMPERATURE	650°F
PEAK PRESSURE	800 PSIA
EXPANDER SHAFT POWER	60 HP
EXPANDER SPEED	2000 RPM
MAXIMUM FIRING RATE	1.06×10^6 Btu/Hr
MAXIMUM FLOW RATE	2370 LBS/HR

Fig. 120 System Characteristics

MAXIMUM FIRING RATE	1.06×10^6 Btu/hr
EFFICIENCY	80%
OUTLET TEMPERATURE	650°F
OUTLET PRESSURE	800 psia
MAXIMUM FUEL FLOW RATE	52.7 lbs/hr
MAXIMUM AIR FLOW RATE	988.3 lbs/hr
COMBUSTION GAS SIDE PRESSURE PRESSURE DROP	9 inches w.c.
WORKING FLUID SIDE PRESSURE DROP	120 psi
BLOWER SHAFT POWER	0.5

FEATURES

- RADIAL COMBUSTOR/VAPOR GENERATOR
- INTEGRATED BLOWER/ROTARY ATOMIZER
- THREE-PASS CROSS PARALLEL, CROSS COUNTER FLOW ARRANGEMENT

Fig. 121 Design Point Characteristics of Combustor/Vapor Generator

CONDENSER	
HEAT TRANSFER RATE	669,000 Btu/hr
EFFECTIVENESS	0.80
CONDENSING TEMPERATURE	212°F
CONDENSING PRESSURE	31.8 psia
AMBIENT TEMPERATURE	85°F
AIR FLOW RATE	27,400 lbm/hr
CORE PRESSURE DROP	3 inches w.c.
REGENERATOR	
HEAT TRANSFER RATE	94,300 Btu/hr
EFFECTIVENESS	0.70

FEATURES

- INTEGRATED CONDENSER-REGENERATOR
- REGENERATOR: TWO PASS CROSS COUNTER FLOW
- CONDENSER: CROSS FLOW
- BRAZED ALUMINUM CONSTRUCTION
- AIR-COOLED
- ENGINE MOUNTED

Fig. 122 Design Point Characteristics of Condenser-Regenerator

TOTAL FLOW	27,400 lbm/hr
INLET TEMPERATURE	85°F
SPEED	2460 rpm
PRESSURE RISE (TOTAL)	2.0 inches w.c.
PRESSURE RISE (STATIC)	1.2 inches w.c.
FAN SHAFT POWER	2.9 hp

FEATURES

- TUBE AXIAL
- CAST ALUMINUM CONSTRUCTION
- ELECTRIC MOTOR DRIVEN
- FRONT MOUNTED

Fig. 123 Design Point Characteristics of Condenser Fan

- CYLINDERS - 2
- BORE - 3.25 INCHES
- STROKE - 3.00 INCHES
- RATED SPEED - 2000 RPM
- INLET VALVING - HYDRAULICALLY ACTUATED
- UNIFLOW EXHAUST PORTING
- FEATURES - VARIABLE CUT-OFF VALVING
  ALUMINUM BLOCK WITH IRON
  LINERS

Fig. 124 Expander Design Characteristics

FLOW RATE	4.6 GPM at 1000 rpm
NUMBER OF CYLINDERS	3 in-line
BORE	1.2 inches
STROKE	0.4 inch (maximum)

FEATURES

- VARIABLE DISPLACEMENT
- INTEGRATED INTO EXPANDER BLOCK
- PUMP DISPLACEMENT AND EXPANDER CUT-OFF CONTROL MECHANICALLY INTEGRATED

Fig. 125 Feedpump Design Characteristics

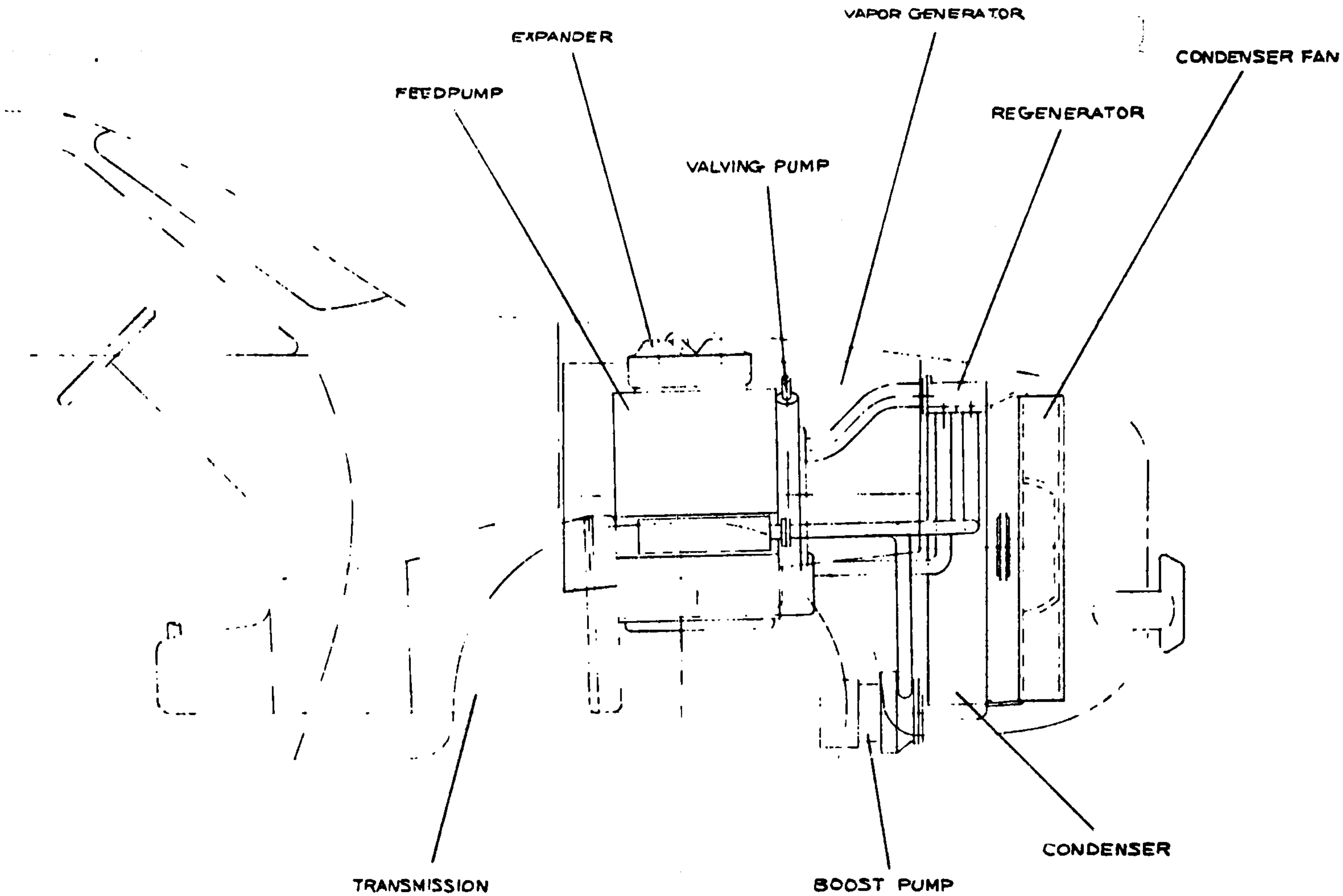


Fig. 126 Organic Rankine Engine (Pinto - Side View)

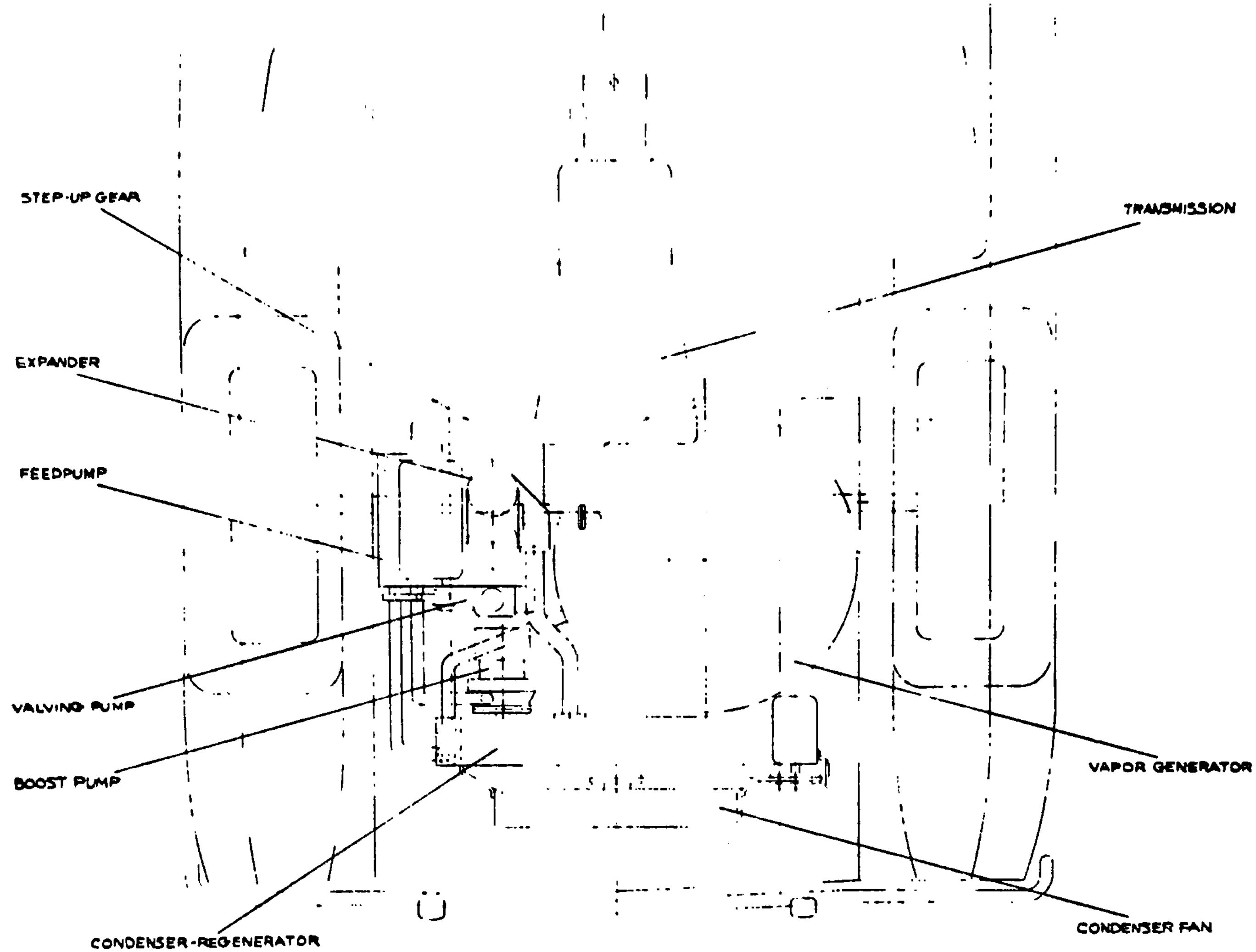


Fig. 127 Organic Rankine Engine (Pinto - Top View)

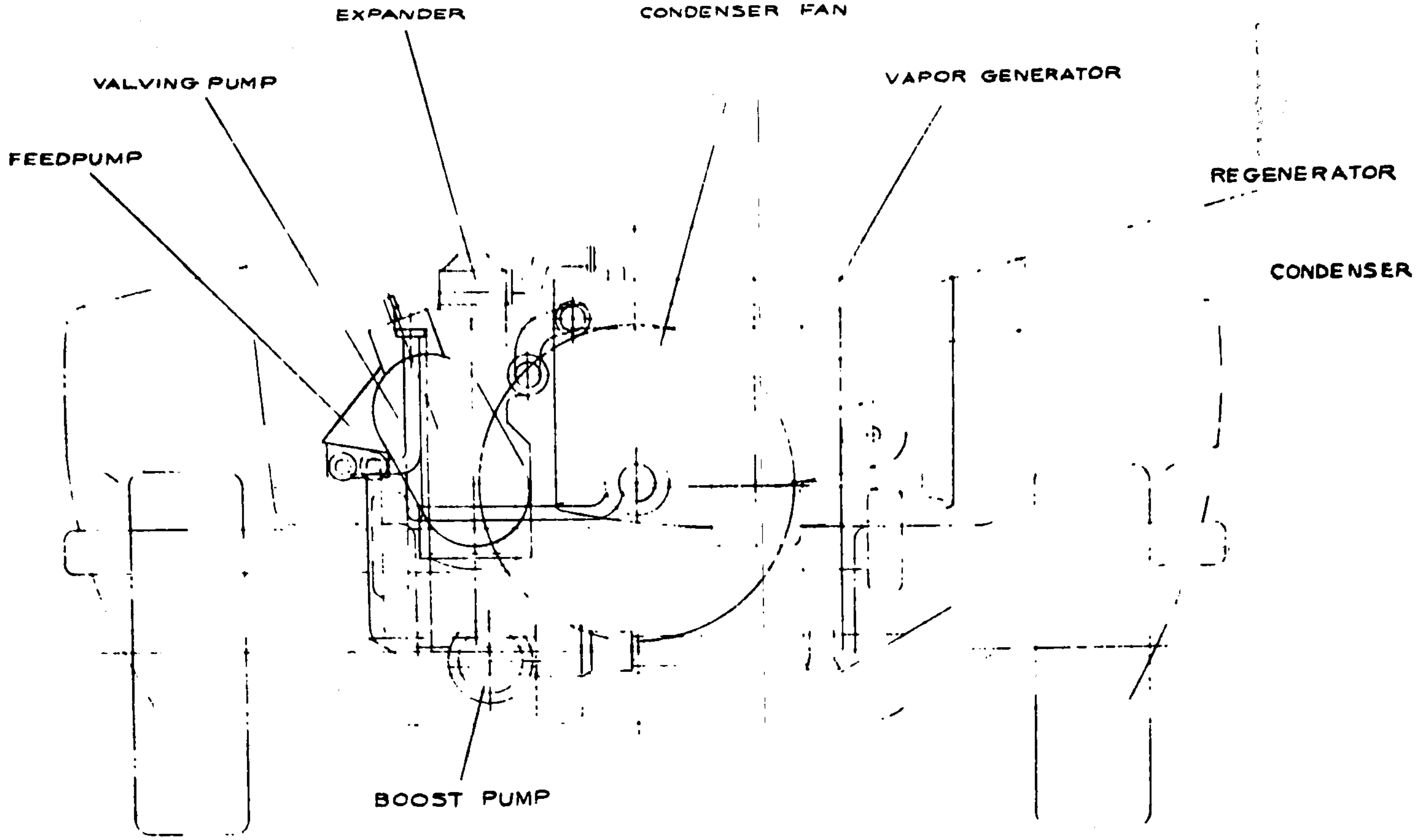


Fig. 128 Organic Rankine Engine (Pinto - Front View)

- Major component layouts and specifications are completed.
- Single cylinder test is in progress.

Calculated fuel economy characteristics for the engine in a Pinto are shown in Fig. 129 for different transmission options. The calculated 0-60 mph acceleration time for the Pinto with a four-speed standard transmission and the organic Rankine engine is 19.1 seconds, whereas for the Pinto with the same transmission and an I.C. engine it is 16.5 seconds.

Improvements of the Prototype Engine relative to the Preprototype system are summarized in Fig. 130.

Questions and Comments

Question (S. S. Miner, Miner Machine Development Co.): How is the cut-off regulation obtained hydraulically on the BICERI valve?

Answer: The hydraulic distributor has a helix cut in a cylinder which is positioned axially by the control. This varies the time that the valve is exposed to hydraulic pressure thus providing a variable cut-off.

Question (H. Moore, Jet Propulsion Laboratory): How does the fuel economy of the organic system compare with that of the steam system?

Answer: Thermal efficiencies and fuel economy values are comparable (about 15-17% thermal efficiency); however, the organic system is operating at a lower peak temperature (600°F versus 1000°F) and pressure (800 Psia versus 1000 Psia).

Question (Dr. J. E. Davoud, D-Cycle Power): Referring to the calculated fuel economy curves in Fig. 129, it appears that 30 mpg at 30 mph exceeds ideal efficiency capability of the organic fluid cycle. How is this explained?

Answer: This is a practical efficiency and does not exceed the ideal. Details of this figure will be discussed separately if desired.

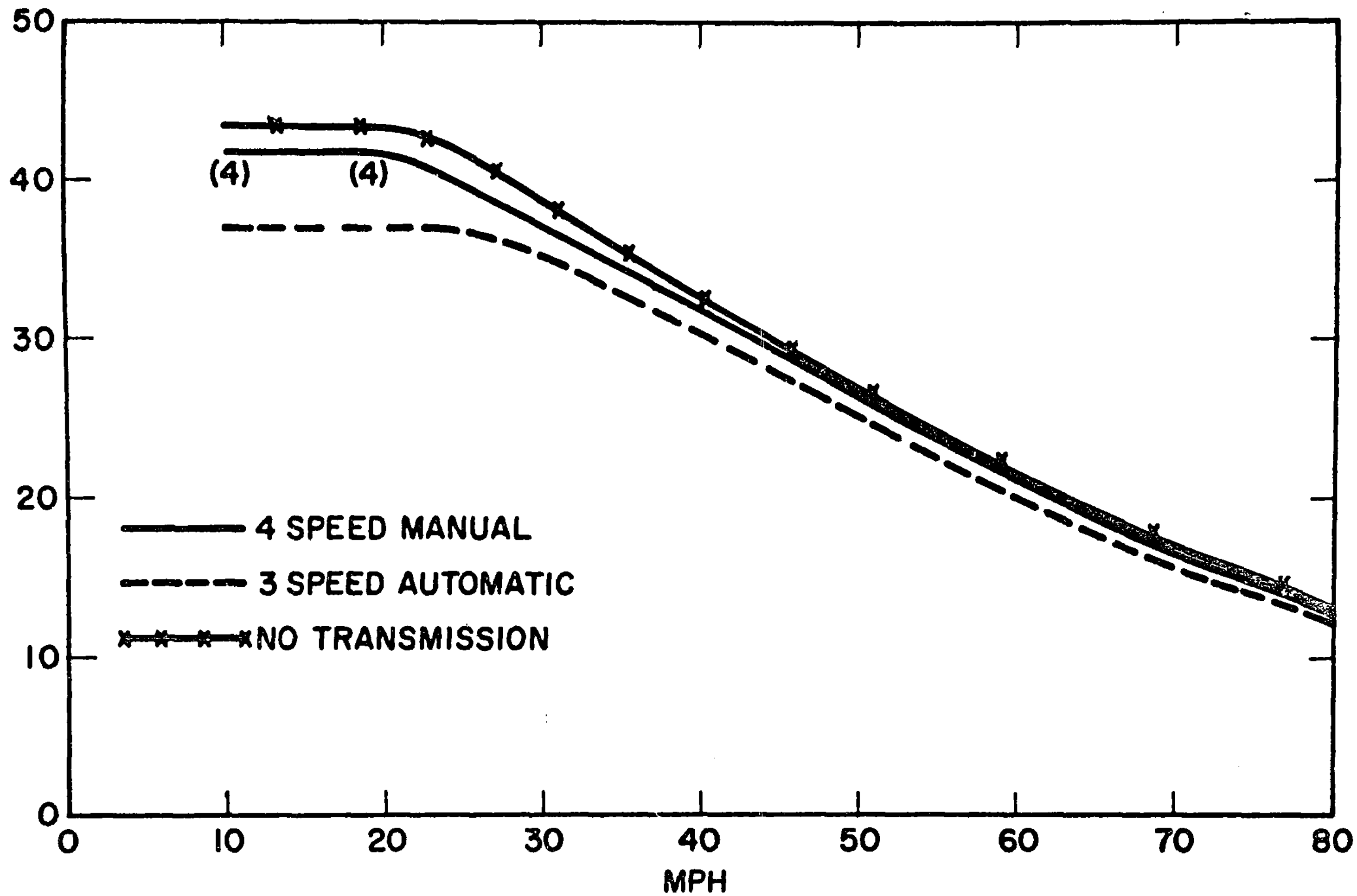


Fig. 129 Pinto - 60 HP — Calculated Fuel Economy

1. IMPROVED SFC WITH FLUORINOL-50.
2. REDUCED COMPONENT SIZE DUE TO REDUCED FLOW RATE.
3. REDUCED SYSTEM WEIGHT, ALUMINUM EXPANDER AND REGENERATOR.
4. REDUCED NUMBER OF PARTS, TWO-CYLINDER EXPANDER, THREE-CYLINDER PUMP, ONE FAN.
5. ONE SHAFT SEAL.
6. IMPROVED INTAKE VALVE DESIGN.
7. INTEGRATED EXPANDER, FEEDPUMP, INTAKE VALVE, AND HYDRAULIC PUMP.
8. INTEGRATED CUT-OFF AND FEEDPUMP CONTROLS.
9. REDUCED PARASITICS.
10. INTEGRATED REGENERATOR AND CONDENSER.
11. ELECTRICALLY DRIVEN CONDENSER FAN WITH ENERGY STORAGE FOR TRANSIENT.
12. ELIMINATED RELATIVE MOTION BETWEEN COMPONENTS, NO FLEX LINES.
13. IMPROVED PACKAGING AND FLEXIBLE CONFIGURATION.

Fig. 130 Improvements Relative to Preprototype System

Question (Lawrence Linden, MIT): The ambient design point temperature of 85°F was used for the condenser on both the S.E.S. and the Thermo Electron systems. What happens to performance at higher temperature? Is there a practical maximum?

Answer: Performance suffers at higher ambient temperatures, probably not much at 95°F, but at about 115°F the vehicle couldn't operate. On the other hand, performance improves at temperatures lower than 85°F.

Question (Y. Friedman, SES): Have you noticed any increase in condenser pressure or fan horsepower with extended running due to degradation of working fluid? How poisonous are decomposition products of the fluid? What is the solubility of oil in Fluorinal-85 and 50?

Answer: The working fluid has undergone over 2000 hours of continuous testing in the dynamic loop; several 3KW systems have been delivered to the Army, and these are operating. No problems with gradual degradation of the fluid at normal operating temperatures have been encountered. If exposed to temperatures above established stability limits it will decompose, but time of exposure is a factor. The fluid is classified as non-toxic. Oil is insoluble in the working fluid.

Question (R. Niggemann, Sundstrand Aviation): What physically happens to the system if you operate above the stability limits of the working fluid? Why was the piston expander selected over the turbine expander?

Answer: Although it is possible to operate for limited time above the stability limits of the working fluid, the performance degrades. Sludge, acids and non-condensible gases are formed. Although the peak turbine efficiency is high over a narrow speed range, the vehicle application requires operation over a wide range of speed and load. The piston expander has much better over-all efficiency under these load and operating conditions.

Question (T. Duffy, Solar): What is the means for closing the loop on the feedback combustor control?

Answer: The key measurement is the tube wall temperature on the superheater. This is monitored to avoid overheating and degradation of the working fluid.

Question (E. Heffner, GM Technical Center): Does EPA intend to test the steam and organic Rankine systems in the standard 4500 pound car?

Answer (Steve Luchter, EPA): The decision was made to use the steam engine for the prototype and to continue with the organic engine as a back-up system. Simultaneously it was decided to demonstrate the prototype steam system in a compact car. No fully drivable, 4500 pound car is planned. At present there is no plan to put the organic system in a compact car; however, the right is reserved by the Government to do this at a later date if the situation warrants it.

Question (Arthur Underwood, Consultant): What is EPA doing to alleviate the unnecessarily low NOx (0.4 grams/mile) requirement? It is understood some recommendations have been made.

Answer (Steve Luchter, EPA): Some internal work has been going on at Durham regarding the health effects of various NOx levels. Information about possible conclusions and/or recommendations has not been received. Appropriate contacts will be identified, so that inquiries can be made.

Question (J. Abbin, Sandia Laboratories): What expander and feedpump efficiencies have been demonstrated and what efficiencies are anticipated for the Prototype Engine?

Answer: Feedpump efficiencies vary between 70-85%. Expander efficiencies vary between 50 and 70%. At road load the expander efficiency is about 60%. These are measured values.

Question (L. Linder, MIT): Are there manufacturing problems associated with the Rankine engines analogous to those encountered by gas turbines with heat exchangers and turbine wheels?

Answer: One of the major advantages of the Rankine engine is its producibility. Operating temperatures and pressures are moderate; materials of construction are not unusual or scarce; methods of manufacturing and processing are used for or adaptable to automotive and Diesel engine practice. Thousands of hours of compatibility tests have been run on the lubricants, working fluids, and materials of construction. All of the materials currently involved are compatible and commonly available.

Question (Dr. Davoud, D-Cycle Power): On a previous program we had to pay $85 per gallon of Fluorinol-85. What are the prospects for reducing that price?

Answer: In production quantities projected prices for Fluorinol-85 range from 85 cents to $1.25 per pound.

D. California Clean Car Program, by M. Wenstrom, California Research, and R. Renner, Consultant (Guest Presentation)

The California Clean Car Project is being funded primarily by the State Assembly with the two prime contractors supplying supplementary funding. Two steam powered automobiles have been built, one by the Aerojet Liquid Rocket Company of Sacramento, and the other by Steam Power Systems, Inc. of San Diego.

Accomplishments to date are·

- Contract work began on development of two steam cars, November 15, 1972.
- Most major system components were fabricated and tested by November 15, 1973.
- Bench testing of complete systems was underway by February 1974.
- First operation of a test chassis on steam power (SPS) was on March 16, 1974.
- Both automobiles were completed and operational by May 1, 1974.
- Vehicles were ready for first public display and demonstration on May 15, 1974.

It is planned to make system improvements until July 15, 1974, and then to subject the vehicles to testing and evaluation by state agencies. A final report will be issued by the Assembly Office of Research in the fall of 1974.

It was recognized that in a project involving limitations in time and resources, equal attention could not be given to all aspects of development. Therefore, a conservative approach was needed. For example, given the choice between achieving low exhaust emissions or good fuel economy, it was decided to concentrate on the former, while leaving the latter for future work.

Aerojet's powerplant features a single-stage impulse steam turbine, driving through a hydrostatic transmission. The complete powerplant is located in the normal engine compartment and transmission tunnel. A steam generator built by Scientific Energy Systems and based on a design developed for the Environmental Protection Agency is used. Low emission characteristics have already been validated by test.

SPS has built a four-cylinder, double-acting compound-expansion steam engine. Power is delivered through a two-speed automatic mechanical transmission. The steam generator and condenser are located in the front of the car, with the engine, transaxle, and auxiliaries in the rear. The SPS car is also deriving benefit from EPA-funded combustion and steam generator research. Their steam generator has been supplied by the Solar Division of International Harvester Co.

Figures 131 and 132 show the two automobiles. The Aerojet car is a converted 1973 Chevrolet Vega coupe, while the body and chassis of the SPS car are of special construction and tailored to the powerplant configuration.

Figure 133 summarizes the characteristics of the vehicles and their propulsion systems. Figure 134 gives some of the test results to date, together with the expectations for this summer's testing. Figure 135 gives emissions standards and expected projected results.

Some of the development problems encountered include: fuel economy, system weight, noise, oxides of nitrogen, and controls.

During the last half of this summer, the cars will be evaluated with the assistance of state agencies. The technical evaluation will ascertain whether the state's goals have been met. It will also serve to provide much test data that have been lacking in regard to modern steam cars. Such data can provide a base of departure for future research and development.

Questions and Comments

Question (Dr. G. A. Brown, University of Rhode Island): How is it the term "adequate" is used for the performance of the steam bus when the

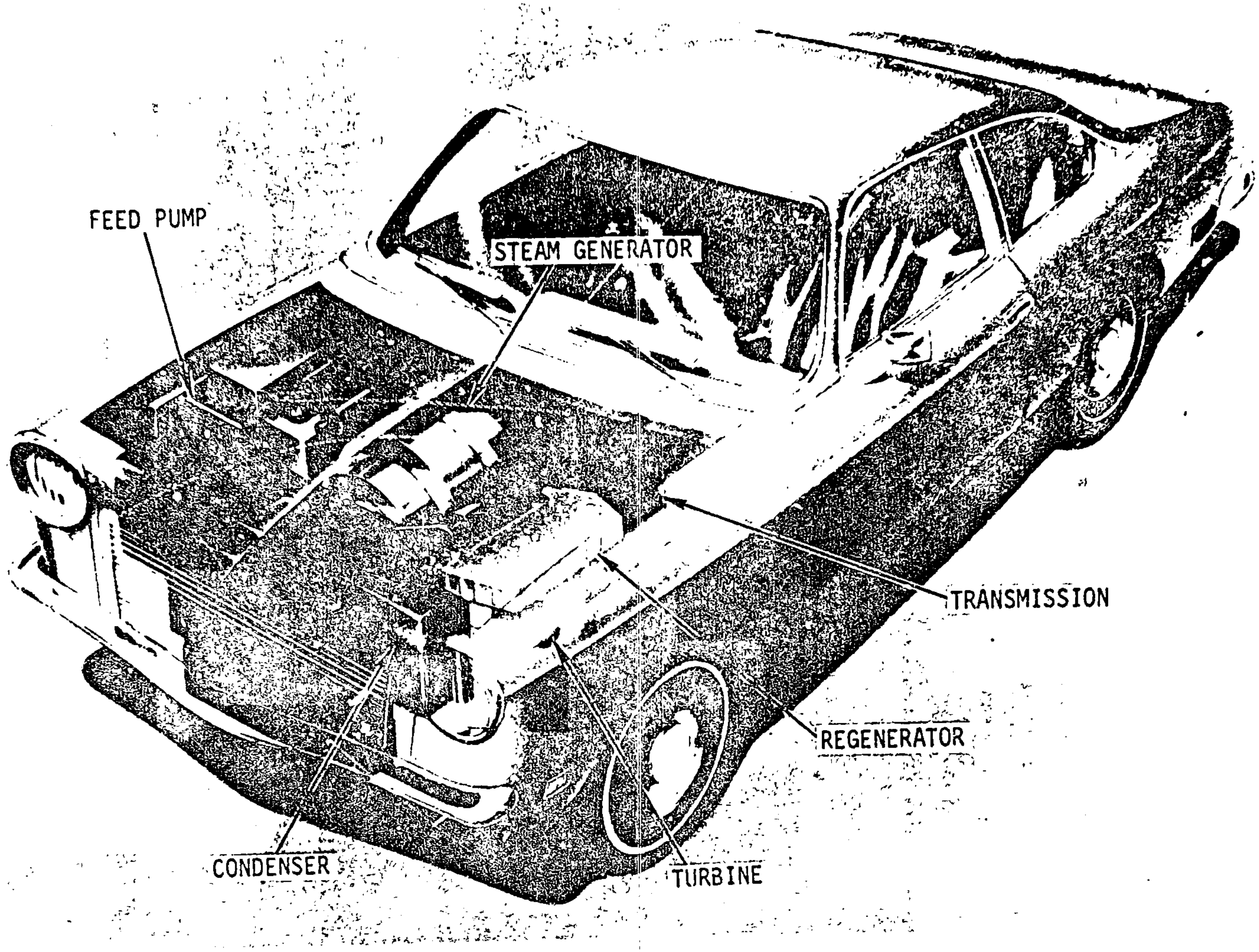


Fig. 131 Artist's Rendering of Aerojet Steam-Powered Vega

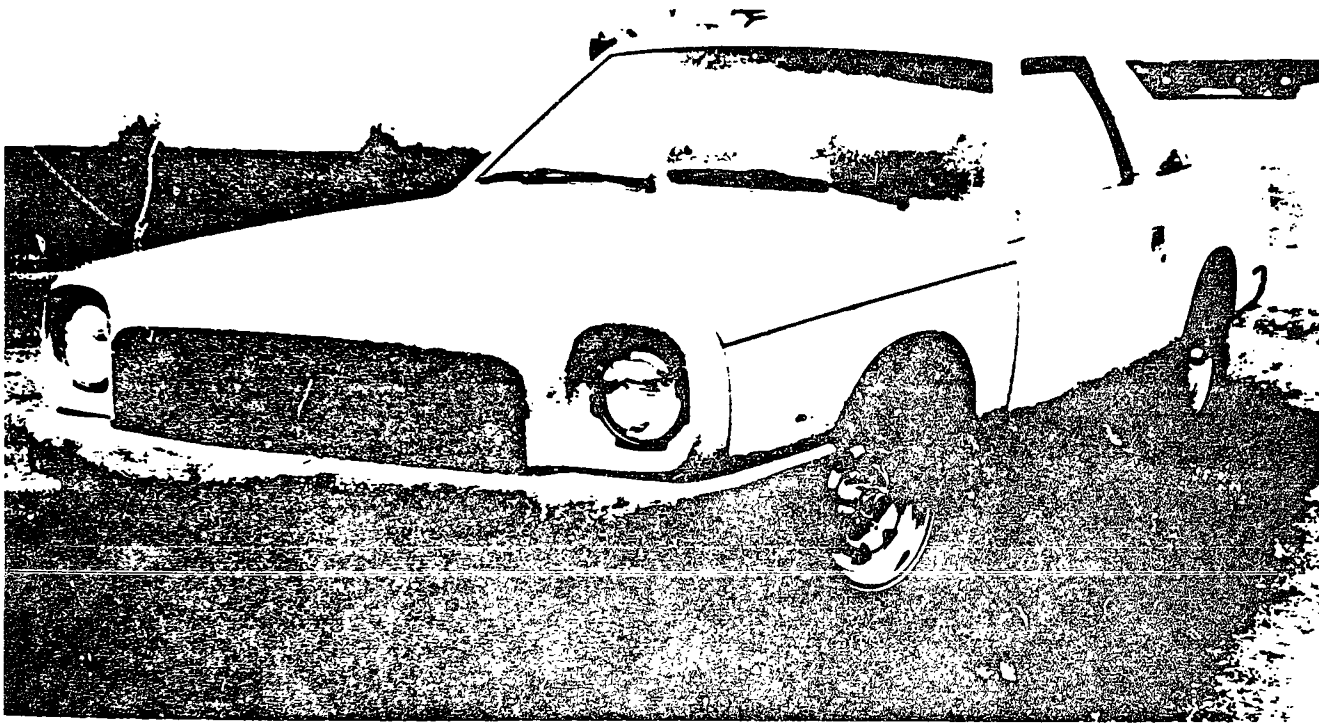


Fig. 132 Steam Power Systems Car Prior to Engine Installation

Vehicle

	Aerojet	SPS
Type	Chevrolet Vega	Special Construction
Vehicle construction	Unit body	Chassis w/separate body
Approx. curb weight, lb (wet)	2,905	3,030
Max. rated Payload, lb.	705	750
Gross Weight, fully loaded, lb.	3,655	3,780

Power System

Steam Generator Type	Monotube	Monotube
Burner Type	Air Atomizing	Spinning Cup
Rated max. Steam Flow, lb/hr	660	650
Rated max. fuel flow, lb/hr	50	48
Expander Type	Impulse turbine	4-cyl. recip. (double acting)
No. of expansion stages	1	2
Expander rated gross hp	6[illegible]	65
Expander rated rpm, max.	60,000	2,400
Expander inlet pressure, psia	500	1,000
Steam temperature, F	1,000	800
Condenser frontal area, ft	4.1	6.1
Condenser thickness, in.	4.5	3.6
Powerplant dry weight, lb*	970	940

* Powerplant dry weight includes transmission but not differential, and excludes batteries, fuel tank, and driver's controls.

Fig. 133 Vehicle and Powerplant Characteristics

	Aerojet	SPS
Tested Performance as of May 3, 1974 (mostly inferred from system bench tests)		
Power System Max. net bhp (a)	48	45
Specific fuel cons., lb/bhp-hr (a)	0.95	1.03
Idle Fuel cons., lb/hr	11.7	6.2
Cold starting time:		
- First movement of car, sec.	155	130
- To full power, sec.	315	270
Est. best fuel mileage, mpg	12	12
Max. Road Horsepower Developed (b)		36
Expected Performance - July 15, 1974		
Emissions, CO, g/mi (c)	0.5	1.2
Emissions, HC g/mi (c)	0.1	0.14
Emissions, NO_x g/mi (c)	0.17	0.22
Urban fuel mileage, mpg (c)	8-10	9-11
Best fuel mileage, mpg	16	17
Max. speed, 0% grade, mph	75	84
Max. speed, 5% grade, mph	50	57
Sound levels, exterior @ 50' SAE J968A, dBA	74	74
Sound levels, interior, dBA	72	72

Fig. 134 Powerplant and Vehicle: Test Data and Performance Expectations

(a) Best performance, based on net power into transmission after all powerplant auxiliaries are driven.

(b) Aerojet, by chassis dynomometer; SPS, by acceleration trails. Installed systems had not yet been tuned to optimum levels.

(c) Over Federal Driving Cycle.

EMISSIONS LEVELS (Grams/mile)			
	CO	HC	NO_x
1974 Standards	39.0	3.2	2.0
Original 1976 Federal Standards	3.4	0.41	0.4
California Clean Car Project Goals	1.7	0.2	0.2
Range of expected values, California Clean Car Project	0.2-0.8	0.05-0.1	0.14-0.2

Fig. 135 Comparison Emission Standards* and Projected Results

*The original standards of 0.41 g/mi HC, 3.4 g/mi CO and 0.4 g/mi NO_x have now been postponed - perhaps until the 1980's. Project goal for emissions is to demonstrate no more than one-half of the original 1976 Federal standards.

performance, according to the numbers, is only one-third to one-seventh that of a comparable Diesel bus? Why is effort being devoted to a closed cycle, turbine drive when it is generally known and accepted that the part load fuel economy is inherently very low?

Answer: Reports on the California Steam Bus Program present quantitative data in comparison with Diesel engine data; the lower fuel economy was not hidden; however, the buses did operate well enough to go from stop to stop, picking up and dropping off passengers in regular revenue service. These buses operated over regular routes including the hills in San Francisco.

Concerning the turbine efficiency, it is important to compare the drive system including the turbine gear box and transmission. The Aerojet combination acts to keep the turbine running over its optimum, high efficiency speed range. On this basis it compares favorably with other systems.

Question (Joseph Abbin, Sandia Labs): What fuel economies are projected for the California Steam Cars?

Answer: Concerning the SPS system, avenues of approach for improved fuel economy are:

- Reduction of heat transfer and steam leakage losses
- Improved valve timing
- Reduced water rates at light loads
- Reduced parasitic power losses; possibly exhaust steam driven condenser and boiler fans.

Aerojet expects to get about 14 mpg with a high speed transmission. There is an advanced compound type cycle which could possibly yield up to 20 mpg; however, it is beyond the scope of the present contract.

Question (E. Doyle, Thermo Electron): Why are the start-up times to first movement as long as they are?

Answer: These are not due to boiler limitations (Boiler is less than 30 seconds), but to other current system limitations. Since the cars have literally been running only a few days, the starts have purposely been conservative until more is learned about these systems in these vehicles. It is expected that these times will be substantially reduced as testing proceeds.

Question (Dr. Davoud, D-Cycle Power): What is the valve system in reciprocating expander?

Answer: Double acting piston valves are used with variable cut-off provided by a swing eccentric mechanism which changes the phase angle and stroke length of the valve simultaneously.

E. Advanced Boiler Studies, by Dr. Frank Paul, Carnegie Mellon University

The Mechanical Engineering Department of Carnegie Mellon University received a grant from EPA for research addressed to an improved vapor generator design for Rankine cycle automobile engines. Work was initiated in May 1973.

To date, this work has included a survey of commercial contractors, EPA contractors, and other manufacturers of vapor generators; an evaluation of new and existing heat transfer technology; and preliminary synthesis of a new design configuration based on transient response and compactness.

General constraints imposed for the survey were: volume less than 40 cubic feet and a firing rate of 3 million BTU per hour. From the 56 inquiries and 36 responses to the survey, the following commercial vapor generator manufacturers were able to come at least close to the imposed constraints, although all were low pressure, relatively large designs:

- Single or multiple monotube (oil or gas fired)
    - Clayton Manufacturing
    - Vapor Corporation
    - Kanzler Steam Transport, Div. of Autocoast

- Pot type with fire tubes (oil or gas fired)
  - Eclipse Lookout
  - James Leffel
- Pot type with electric heating
  - Chromalox Division of Emerson
  - P. M. Lattner

The industrial developers for small Rankine Cycle engines include:

- EPA contractors (All single and multiple monotube)
  - Aerojet Liquid Rocket
  - Lear Motors
  - Scientific Energy Systems
  - Thermo Electron
  - Solar
- Other Manufacturers
  - DuPont (Doerner rotational)
  - Inter Continental (Huttner rotational)
  - Saab-Scandia (Multiple tube capillary)

Conclusions from the survey were:

- No commercial manufacturers of vapor generators were identified as applicable to automotive Rankine Cycle engines.
- Recent technology development has concentrated on single or multiple monotube designs for compactness. Monotube designs are limited by slow process time constants on the order of 10 to 20 seconds.

As a result of the survey and analytical consideration of the fundamental factors and phenomenon controlling the response and size of the basic heat transfer equipment, a new conceptual design was synthesized. Generically, the design is a rotational preheater/boiler plus a monotube superheater as shown schematically in Fig. 136. This approach provides a "sharp" liquid-vapor interface, with "flash" boiling. It also provides a lumped rather than distributed configuration which reduces resident time theoretically improving response. Anticipated problem areas include:

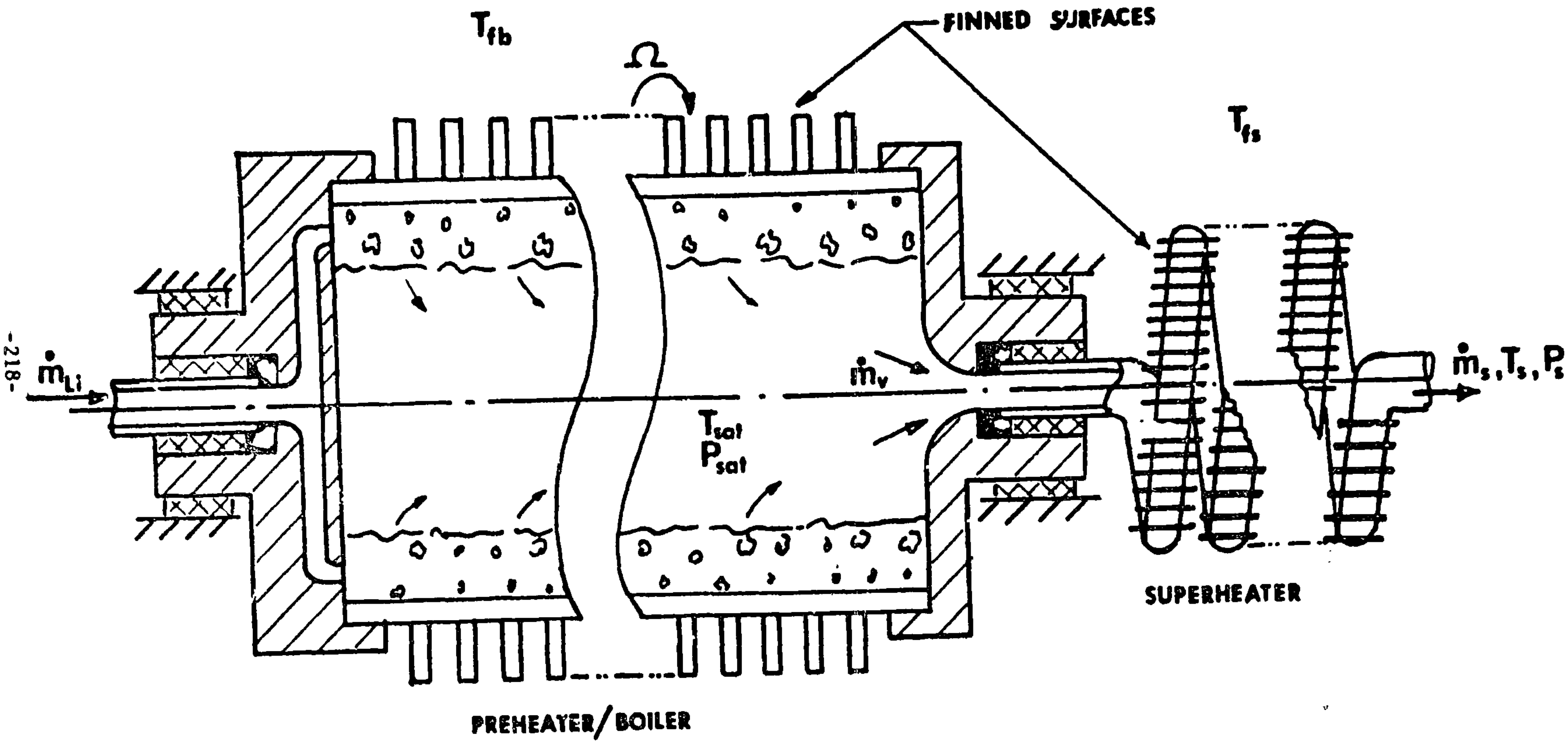


Fig. 136 Vapor Generator Schematic

- Internal heat transfer in the preheater/boiler

  Critical heat flux is important. Boiling heat transfer in high acceleration and pressure fields permit the preheater (economizer) and boiler to be designed as a single rotational unit. Boiling heat transfer is improved in centrifugal force fields. Effects of pressure are not well established when combined with centrifugal force fields.

- Preheater/boiler shell stresses

  Strength and materials selection pose design constraints. (The monotube superheater is not considered a problem.) Practical geometric limits are: maximum diameter - 12 inches; maximum wall thickness - 0.125 inches.

- External combustion gas heat transfer

- Transient behavior

The calculated dynamic response of a rotational preheater/boiler plus monotube superheater, designed to match SES mass flow and heat flux rates at full power is shown in Fig. 137. Key dimensions of such a system are:

- Preheater/Boiler:
  - Diameter = 12 inches
  - Wall Thickness = 0.125 inches
  - Length = 32.4 inches
  - Finned Surface (Double Effective Surface Area)

- Superheater:
  - External Tube Diameter = 0.5 inches
  - Internal Tube Diameter = 0.37 inches
  - Length = 26 feet
  - Finned Surface (Double Effective Surface Area)

The transient response of the present monotube is about 20 seconds as compared to about 2 seconds (calculated) for the rotational plus monotube superheater.

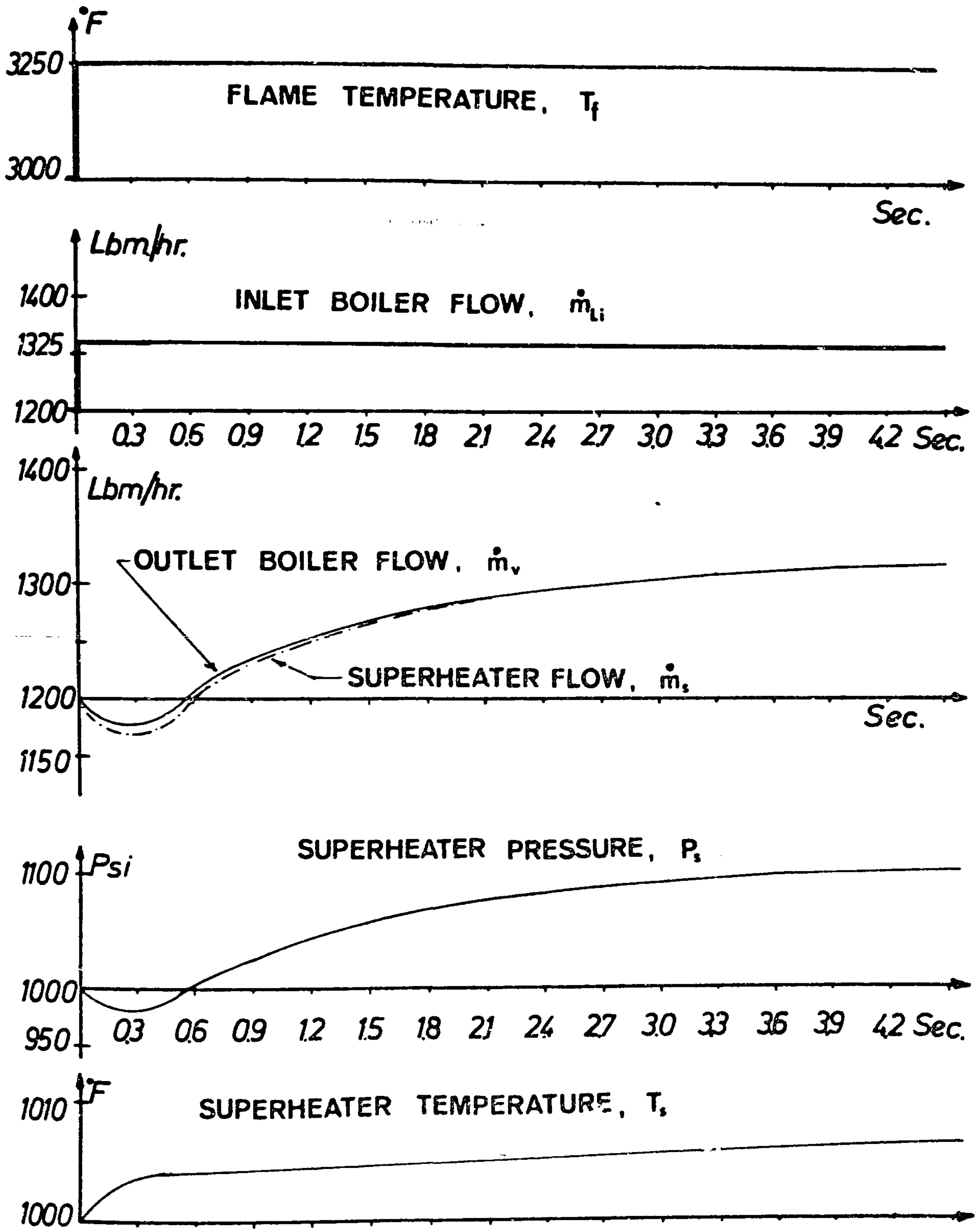


Fig. 137 Vapor Generator Response (Full Power Condition)

Compactness in terms of preliminary weight and volume estimates compare as follows:

Monotube:	3.2 cu. ft.; 125 lb. (est.)
Rotational plus monotube superheater:	5.3 cu. ft. (est.); 100 lb. (est.)

The next proposed steps are:

- Construction and laboratory evaluation of a scaled bench test design under
  - Steady-state conditions
  - Dynamic conditions
- Analysis of the design for
  - Heat transfer
  - Strength and geometry
  - Dynamic response

Questions and Comments

Question (C. Amann, GM Technical Center): The prime problem is the high pressure rotating seal. How do you plan to approach this problem?

Answer: The high pressure (1000 Psi), high temperature (600°F) is recognized as a major problem. Some information on this will be obtained during the bench tests. Some information may also be available from the work of Dornier and Huettner on their lower pressure seals.

Question (Y. Friedman, SES): Where is the economizer in the design? If no economizer is used, very fast response can be achieved, but efficiency is sacrificed. Is this factor taken into account?

Answer: Sub-cooled water (about 220°F) is taken into the boiler and, in essence, the preheater and boiler are integrated. It is planned to mix the feed water with the boiling water in a way which will not inhibit the boiling process. Efficiency characteristics have not yet been considered in detail.

Question (Dr. Davoud, D-Cycle Power): How much water will be in the boiler?

Answer: About 2 pounds of water are maintained in the boiler during the transients.

V. DIESEL ENGINES, ALTERNATIVE FUELS, ELECTRIC VEHICLES, AND NEW EPA FUEL ECONOMY TEST CYCLE

A. Diesel Engine Study, Ricardo, Ltd., England (Presented by J. J. McFadden, EPA)

The scope of the program encompasses four main tasks: (1) Comprehensive Literature Search, (2) Problem Area Trade-Off Methodology, (3) Engine Configuration Study, and (4) Recommendations for Further Research. Tasks 1 and 2 are complete; Tasks 3 and 4 are in progress and will be completed in about one month.

The performance aspects used and a comparison of the weighting factors determined by a committee and by 18 experienced members of the Ricardo staff are shown in Fig. 138. Some of the conclusions reached in Task 2 are as follows:

- Black Smoke
  - Not an aesthetic problem if engine complies with 1974 federal smoke regulation. (Attainable by attention to local mixing and overall air-fuel ratio at rated conditions.)
  - Project vehicle has such a high power to weight ratio that visible smoke conditions should only be attained for extremely short periods during hard accelerations.
  - Turbocharged engines may have a low speed transient problem. (The Comprex is one possible approach to a solution.)
- Blue Smoke
  - Can be unpleasant from sidewalk, particularly as it is most commonly formed under idle conditions. This problem can be minimized by careful attention to combustion chamber design and fuel injection equipment characteristics.
- Odor
  - Small high speed Diesel can have an odor problem, particularly at light load conditions if misfire conditions are approached. It can be minimized by addition of light load advance.

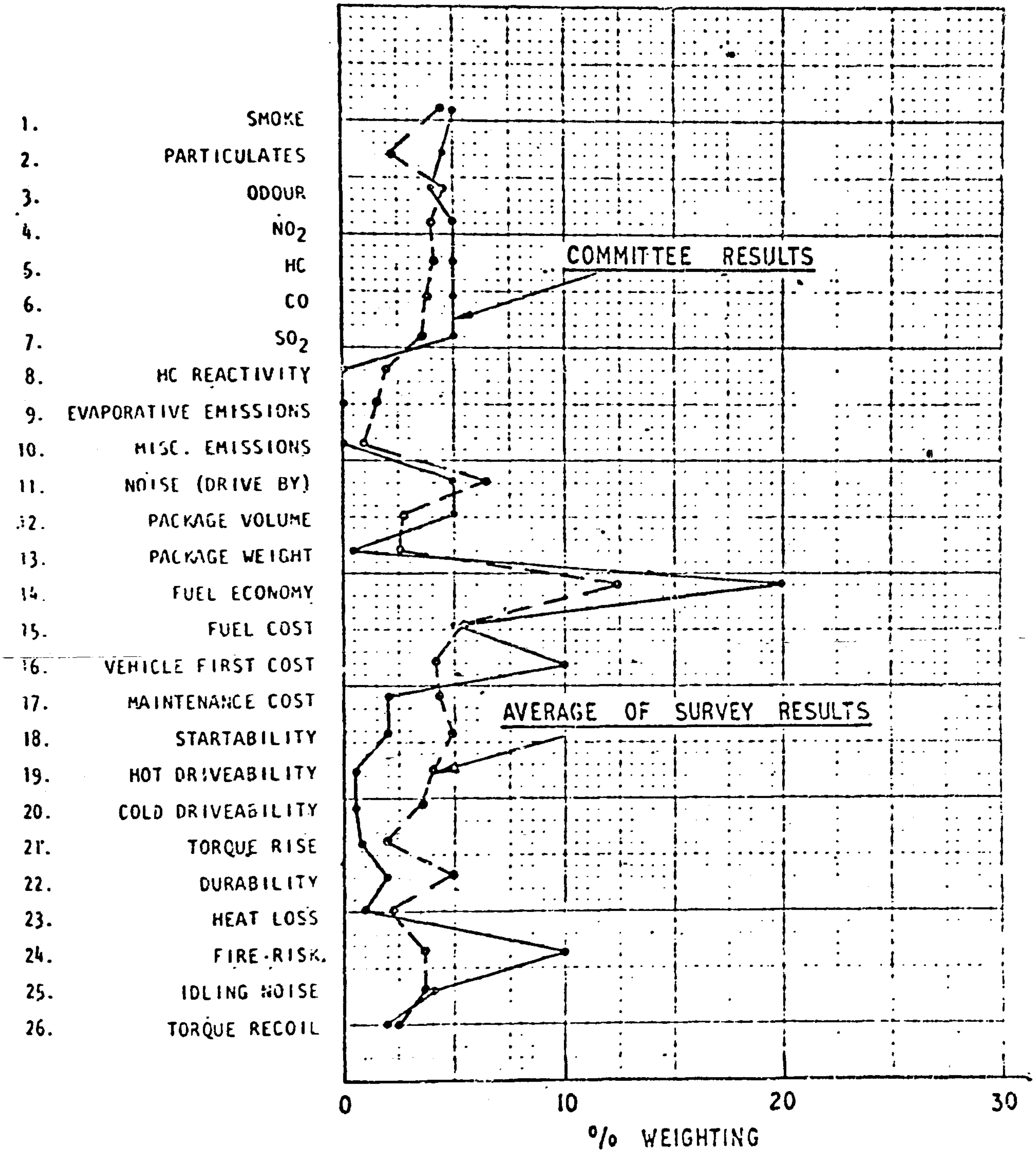


Fig. 138 Light Duty Vehicle Powerplant Survey Results

- Odor at full load is minimized by combustion chamber development and reduction of smoke levels.
- The identification of several odorous components has been achieved, but quantitative assessment has yet to be perfected. The Arthur D. Little Odormeter may advance technology in this area to a significant extent.

- Gaseous emissions
  - Turbocharging increases NOx levels by increasing charge temperature, but allows further retard for the same smoke limit.
  - Exhaust gas recirculation is effective in reducing NOx levels, particularly over CVS cycle where it reduces mass flow rates but durability has yet to be proved. It increases smoke levels.
  - Water injection is also effective in reducing NOx, but has the benefit of not significantly altering engine performance. Logistics/installation/engine durability problems make this approach unattractive.
  - Timing retard is the most effective single parameter for reducing emission levels. Smoke limited performance of indirect injection (I.D.I.) engines normally deteriorates less rapidly with retard than from direct injection (D.I.) engines.
  - From limited data available, emission levels from 2-stroke engines should be of same order as from 4-stroke engines of similar performance.
  - From heavy duty experience, it is predicted that application of a D.I. chamber will increase NOx and CO levels; also, HC levels may rise rapidly at retarded timings.
  - It is predicted that a high speed (1000 rev/min) conventional naturally aspirated D.I. engine could not achieve primary target levels due to low smoke limited performance at retarded timings.

- Gaseous Emissions, Naturally Aspirated 4-Stroke Indirect Injection
  - 3.4 G/mile CO can be achieved.
  - 0.4 G/mile HC may be attainable on prototype vehicles. The possibility of maintaining this level in production without the use of hang-on devices is open to doubt.
  - 1.5 G/mile NOx can just be achieved from a prototype current generation engine using timing retard alone. Exhaust gas recycle may be necessary to allow sufficient margin for production compliance.
  - 0.4 G/mile NOx has been achieved with a highly modified prototype engine in a European type vehicle. This target could not be achieved with a practical American vehicle.
  - From most conventional engines, mass emissions of all pollutants increase over CVS-2 with engine swept volume, NOx to a lesser extent than HC and CO.
  - A low powered vehicle would have less difficulty in attaining the target objectives with the additional benefit of improved fuel economy.

The Engine Configuration Study (Task 3) includes consideration of the engine schemes shown in Fig. 139. Probably the most viable candidate for short term, minimum lead time consideration is the naturally aspirated, indirect injection, V8 concept described in Figs. 140 and 141. As a retrofit concept, existing gasoline engine tooling could be effectively implemented and the light duty Diesel could be developed within a relatively short development cycle.

The Prototype Vehicle Specifications which the various engine schemes are supposed to fulfill are:

- 3500 lb. vehicle
- Acceleration: 0-60 mph in 13.5 seconds
  20-70 mph in 15 seconds
- High speed pass maneuver to 80 mph in 15 seconds

	V8 NA IDI	V6 TC IDI	Inline 6 TC IDI	V6 TC DI	Inline 6 TC DI	V6 2 Stroke Loop IDI	Inline 6 2 Stroke Thro DI	4 Cyl. Compound DI	2 Rotor 2 Stage Rotary
Bore in.	3.46	3.54	3.54	3.66	3.66	3.89	3.26	3.66	-
Stroke in.	3.86	3.94	3.94	3.7	3.7	4.48	4.48	3.66	-
HP	128	128	128	128	128	128	128	128	128
Piston area sq. in.	75.3	59.1	59.1	63.1	63.1	71.3	50.1	42.1	-
Swept Volume cu. in.	290	232.7	232.7	233.6	233.6	320	224.8	154.1	-
Weight	700	680	720	660	680	760	800	670	500
Box Volume	11.18	11.6	12.7	11.0	12.0	12.7	16.77	11.3	9.16
HP/cu. in. Swept Volume	0.44	0.55	0.55	0.55	0.55	0.4	0.57	0.83	-
HP/sq. in. Piston Area	1.7	2.16	2.16	2.0	2.0	1.8	2.55	3.04	-
HP/ft^3 Box Volume	11.45	11.03	10.08	11.63	10.66	10.08	7.63	11.33	13.98
lb/cu.in Swept Volume	2.41	2.92	3.09	2.83	2.91	2.37	3.56	4.35	-
lb/HP	5.47	6.1	6.4	5.16	5.31	5.9	6.25	5.23	3.9

Fig. 139 EPA Diesel Impact Study - Engines Under Consideration

3.46" (88 mm) x 3.86" (98 mm) x V8

292 CID (4.78 LIT)

128 BHP @ 4000 REV/MIN (88 LB/IN^2 BMEP)

210 LB. FT. TORQUE @ 2000 REV/MIN (109 LB/IN^2 BMEP)

PISTON SPEED = 2560 FT/MIN (13 m/s)

HP/IN^2 PISTON AREA = 1.71

Fig. 140 Engine Configuration Study - 4-Stroke Naturally Aspirated Comet Vb

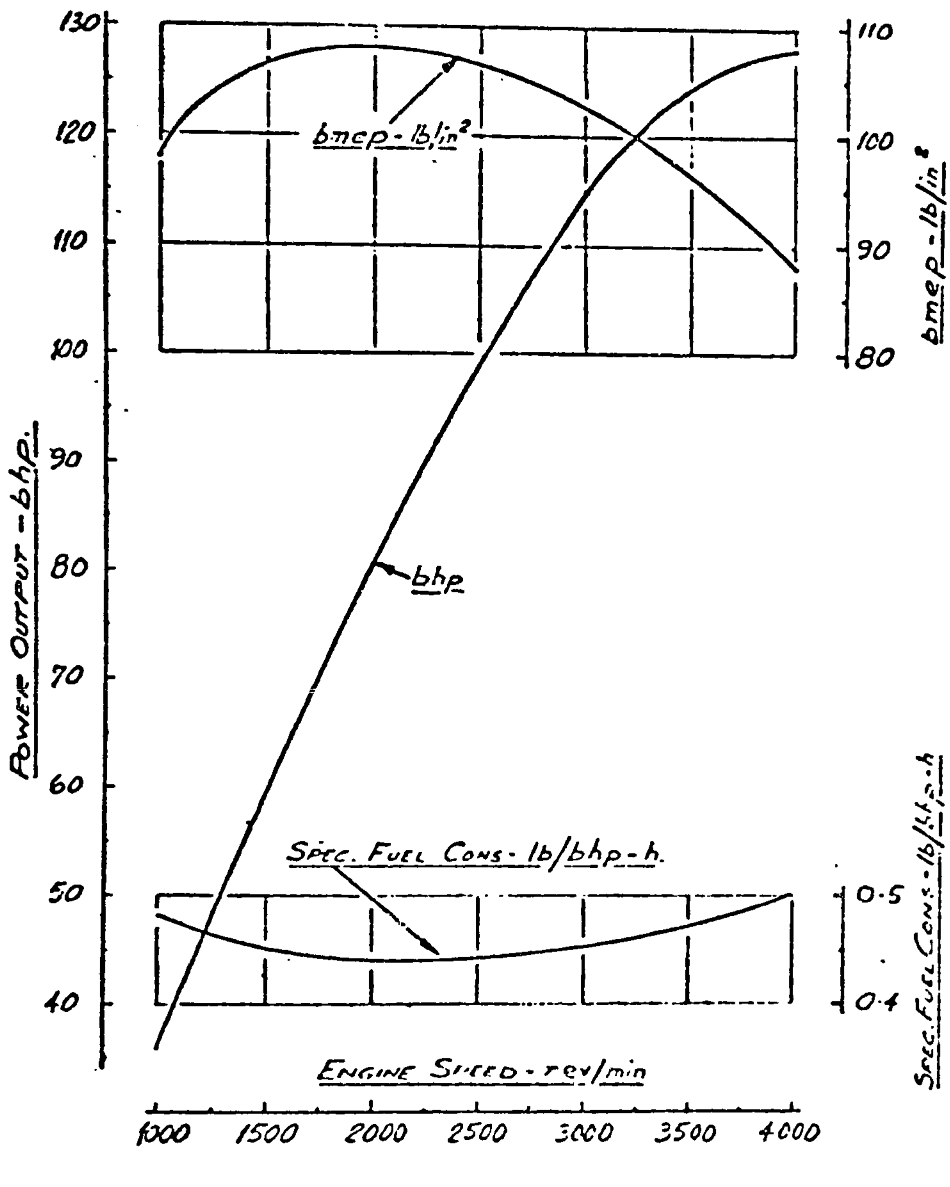


Fig. 141 EPA Diesel Impact Study – Estimated Performance Curve for Naturally Aspirated I.D.I. Engine

- Primary emissions goals: 0.41 gm/mi HC
  3.40 gm/mi CO
  1.50 gm/mi NOx
- Secondary Emissions Goals: Same except 0.4 gm/mi NOx.

For comparison, a standard European gasoline engine rated at 130 BHP at 5000 rpm is being used (see Figs. 142 and 143).

Questions and Comments

Question (Dr. J. E. Davoud, D-Cycle Power): Will these engines have better acceleration, fuel consumption, etc. than the Mercedes Diesel, which is perhaps the most widely marketed Diesel engine in the U.S.?

Answer: Subjectively, the driveability of the lower weight Diesel seems to be much more acceptable and lively than the heavier engines.

Comment (Mr. Reynolds, Jet Propulsion Laboratory): A Diesel vehicle is being run on the West Coast. (About 100 vehicles have been converted to Diesels to date.) It uses a Ricardo designed, 6-cylinder, indirect injection engine. The turbo-charged version produces 130 hp; it weighs 550 lbs. Over the EPA, Federal Driving Cycle, it gets 24.8 mpg with about 0.2 G/mi HC, 2.0 G/mi CO, and 1.0 G/mi NOx.

Question (T. Duffy, Solar): What is the part load BSFC of the Diesel concept, particularly at about 0.1 of rated power (average FDC power requirement is about 0.1 max power)?

Answer: Part load data are not readily available; this will be followed up.

Question (C. Amann, GM Technical Center): Although infrequent smoke is mentioned, is the ultimate objective to eliminate all smoke?

Answer: Yes

Comment (C. Amann, GM Technical Center): Add-on devices were mentioned as a means of achieving 0.4 gm/mi HC levels. However, thermal and catalytic reactors require elevated temperature to work. Because the Diesel has very good light load fuel economy, the exhaust temperatures are very low; hence, these add-on devices may not work.

183 CID (3 LITRE) 6 CYLINDER ENGINE

SPECIFICATIONS TO MEET PRIMARY EMISSIONS TARGETS

PETROL INJECTION; OXIDISING CATALYST, EGR + AIR INJECTION
OR
CLOSE TOLERANCE CARBURETTORS IN PLACE OF PETROL INJECTION

ENGINE WEIGHT - 400 LB
FUEL CONSUMPTION - 15 MPG (U.S.) ON LA-4
PREDICTED EMISSIONS - HC 0.1, CO 0.5, NOx 1.3

PROBLEM AREAS:

1. CATALYST DURABILITY (30 000 MILES)
2. USE OF NOBLE METALS (BEING REDUCED)
3. COST OF EMISSIONS CONTROL DEVICES (ABOUT $200 PRODUCTION COST)

Fig. 142 130 BHP Gasoline Engine

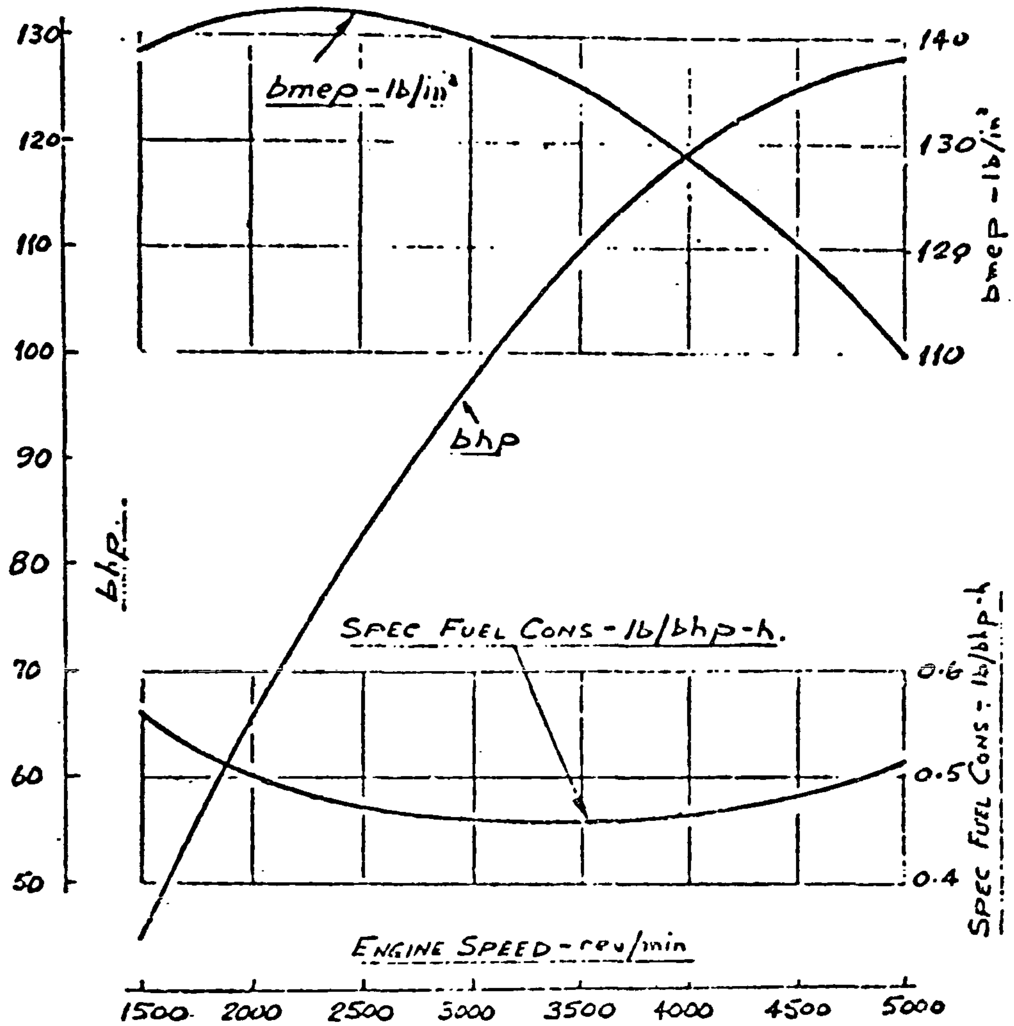


Fig. 143 EPA Diesel Impact Study — Estimated Performance Curve for Gasoline Engine

In comparing the Diesel engine with the European gasoline engine in a 3500 lb. vehicle, it is important to make sure the difference in weight of the gasoline and Diesel engines is properly accounted for. The heavier Diesel will in turn require a heavier vehicle structure to support the weight.

<u>Question</u> (Robert Miller, Eaton Corporation): What is meant by your term "retrofit"?

<u>Answer</u>: For the short term scheme, it appears that a conversion or retrofit from gasoline to Diesel is a possibility.

<u>Question</u>: If Mercedes' 4-cylinder, 240D engine were doubled to 8 cylinders, it would closely match the displacement and power of the 130 hp engine scheme suggested. How would it compare in performance? Have emissions data been taken on the 4-cylinder 240D?

<u>Answer</u>: It is expected that the performance would be quite similar. Emissions data have been taken on the Mercedes 240D.

<u>B. Alternate Fuels, by J. B. Pangborn, Institute of Gas Technology</u>

The objective of this study is to assess the technical and economic feasibility of alternative fuels for automotive transportation. Because of the unsatisfactory situation now developing in which the U.S. is becoming increasingly dependent on imported petroleum, the major emphasis in the selection of an alternative fuel is based on its long-term availability from domestic sources. In addition, economics, competition with other energy applications for limited energy resources, safety, handling, environmental impacts, and system compatibility are being taken into account. This study is limited to chemical fuels, and, except for fuel cell vehicles which use a chemical fuel, electric vehicles are excluded.

In recent years the United States has realized that its projected supply of crude oil will not be sufficient to meet the expected increased demands of the future. In fact, current projections of crude oil supply and prtroleum fuel utilization show that, beginning in the period 1975-1980, the domestic petroleum supply may not satisfy the U.S. transportation energy demand. Since ground transportation, chiefly automobiles, consumes a majority of the transportation energy, automobiles probably will have to find another energy source and possibly even a new fuel before the turn of the century.

The initial consideration list of domestic energy sources, four abundant auxiliary material sources, and potential alternative fuels that could be synthesized from these energy and material sources are given below. The conventional crude oil and natural gas resource base is excluded. Also excluded is any fuel that would produce significant amounts of combustion products which are not normally found in air.

Energy Sources	Auxiliary Material Sources	Potential Automotive Fuels
Coal	Air (O_2, CO_2, N_2)	Acetylene
Shale oil	Rock (limestone)	Ammonia
Tar sands	Water	Carbon monoxide
Uranium and thorium	Land	Coal
Nuclear fusion		Distillate oils
Solar radiation		Ethanol
Solid wastes (garbage)		Gasoline (C_5 - C_{10})
Animal wastes		Heavy oils
Wind power		Hydrazine
Tidal power		Hydrogen
Hydropower		LPG (synthetic)
Geothermal heat		Methanol
		Methyl amines
		Natural gas (C_1 - C_2)
		Napthas
		Vegetable oils

The criteria used for fuel selection are based on the following factors:

- Adequacy of energy and material availability and competing demands for fuel
- Safety (toxicity) and handling properties of fuels

- Relative compatibility with transport and utilization facilities
- Severity of environmental impacts and resource depletion
- Fuel system economics

Figure 144 shows schematically the fuel selection procedure and required information inputs.

To assemble, evaluate, and compare the pertinent fuel information, numerical values were assigned to the merits of the various fuels and were used to construct Fig. 145. This is a tabulation of the relative merits of the alternative fuels, and when quantitative data allow, the values have been normalized to that of standard gasoline (the reference base). This is an illustrative and overall time frame table. The study program actually deals with three separate treatments, one for each of the time frames, 1975-85, 1985-2000, and beyond the year 2000. The rating system for fuel selection is outlined below:

- Synthesis Technology:
  - 1 = Probable; commercial process, or demonstration plants coule be built
  - 2 = Possible; developmental, needs pilot plants
  - 3 = Speculative; conceptual or laboratory methods
  - 5 = Moderate technology gap
- Fuel Availability:
  - 1 = Probable; energy supply available and fuel not required elsewhere
  - 2 = Possible; energy potentially available and fuel not required elsewhere, but is desired as a chemical commodity
  - 3 = Speculative; energy supply doubtful and/or fuel is desired elsewhere
  - 5 = Eliminated; energy supply not adequate and/or the fuel is required for a deficit elsewhere
- Safety and Handling:
  - Toxicity ratio = $\left(\frac{\text{ppm fuel}}{\text{ppm gasoline}} \right)^{-1}$
  - Transportability (bulk):

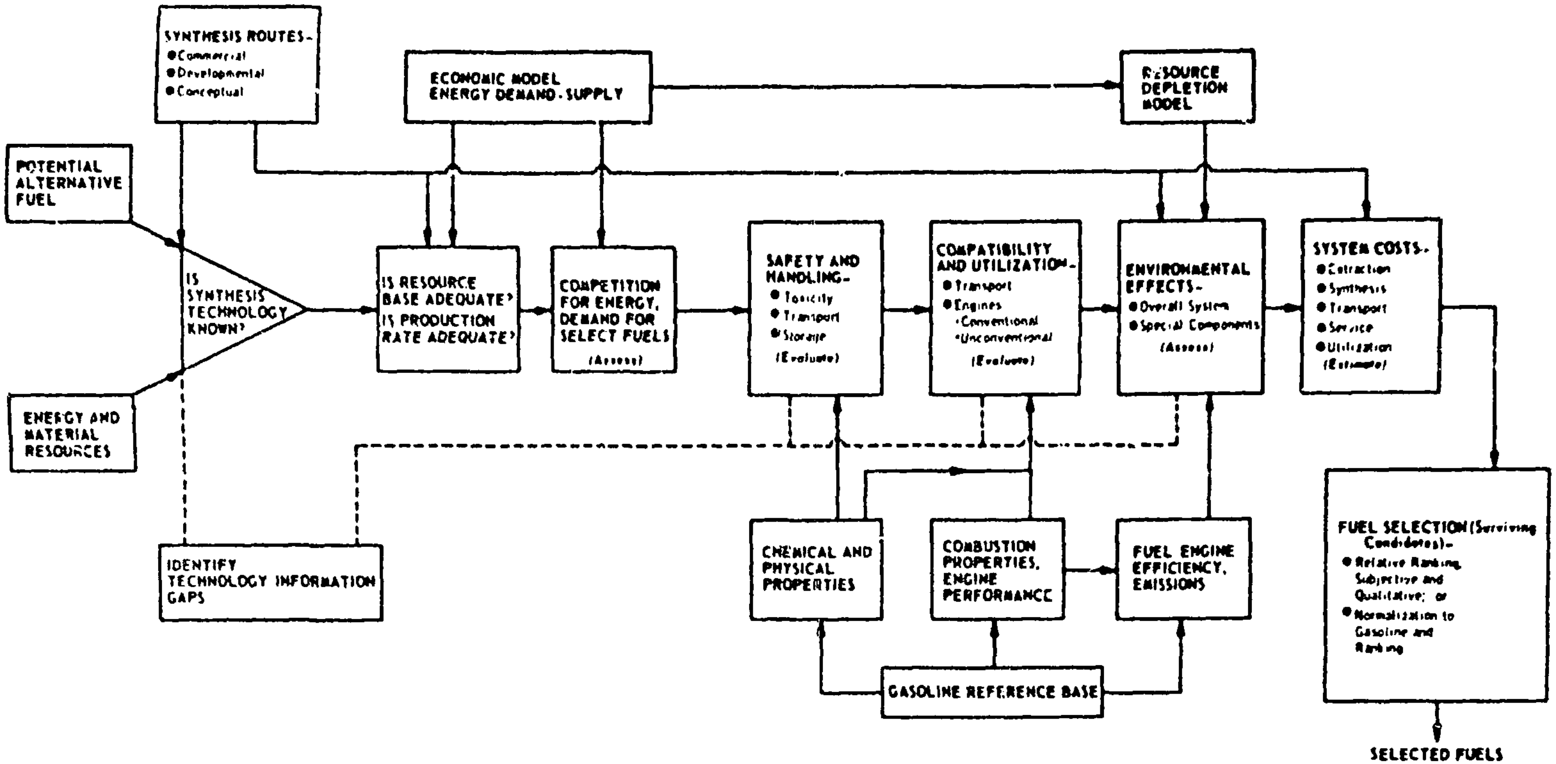


Fig. 144 Alternative Fuel Evaluation Chart

Fuel	Synthesis Technology	Fuel Availability Competition '75-'85	'85-2000	2000+	Safety and Handling: Toxicity	Transportability	Tankage	Compatibility: Transmission	Distillation	Conventional Engine	Unconventional Engine	Environmental Effects	Costs at Station	Score (Σ)	Final Rating
C_2H_2	1	2	2	2	0	1	23.2	5	3	4	3	2	[illegible]	56.2	12
NH_3		[illegible]	2	2	5	2	4.7	2	3	3	2	2	2	32.[illegible]	4
CO	1	2	[illegible]	2	5	2	41	2	4	3	3	2	1.5	[illegible]	12
Coal (SRC)	2	2	2	[illegible]	0	2	2.2	2	3	5	3	5	9.[illegible]	30.[illegible]	[illegible]
Distillates (Diesel Oils)	1	2	2	2	1		2.0	2	2	4	2	2	3.4	24.[illegible]	2
C_2H_5OH (Agricultural)	1	5	5	3	0.2	1	2.6	2	2	2	2	2	4	31.4	[illegible]
Reference	1	1	2	1	1	1	2	1	1	1	2	2	1	13	1
Syn. Gasoline	1	2	2	2	1	1	2	1	1	1	2	2	1.2	13.2	2
N_2H_4	2	2	[illegible]	[illegible]	500	3	7.6	5	5	4	2	2	4	44.[illegible]	14
H_2 (liquid) from	1	2	2	2	0	1	6.2	2	3	2	2	2	2.2	27.4	4
SLPG (propane)	5	5	5	1	0	1	2.4	2	3	2	2	2	1.4	33.5	4
CH_3OH	1	2	2	2	2.5	1	3.8	2	2	2	2	2 (5)	1.1	25.4	3
CH_3NH_2	2	2	2	2	50	1	3.4	3	5	5	3	2	3	53.4	13
SNG	1	5	5	3	0	1	3.1	2	3	2	2	2	1.4	30.5	5
Vegetable Oil	1	5	5	3	0	1	2.1	2	2	5	2	2	10	40.1	12

Fig. 145 Fuel Selection by Ranking Relative to Gasoline

1 = Excellent; liquid or gas transport, can be piped (like gasoline or natural gas) and can be carried (pure) in simple tanks

2 = Good; solids transport, or can be piped after special precautions or preparations

3 = Poor; cannot be piped or carried conveniently, must be added to a carrying agent for handling and safety

— Tankage = $\left(\frac{\text{fuel tankage weight}}{\text{gasoline tankage weight}} \right) + \left(\frac{\text{fuel tankage volume}}{\text{gasoline tankage volume}} \right)$

- Compatibility:
  - Transmission and distribution:

    1 = Probably compatible; can use the present system

    2 = Possibly compatible; has its own system or can use the present system with modifications, some new equipment is needed

    3 = Compatibility is speculative; essentially all new equipment is needed for a workable system

    5 = Eliminated; not only incompatible, but new, sophisticated equipment is needed that is beyond practicality

  - Engine Compatibility

    1 = Probably compatible

    2 = Possibly compatible

    3 = Compatibility is speculative

    5 = Eliminated, presumed incompatible

- Environmental Effects:

  Only solvent-refined coal (SRC) will produce emissions of the type that are beyond the capability of automotive emission controls that are now under development. Overall system effects are indeterminate at this time. All fuels are given a "2", except coal which is given a "5".

- Costs:

  Utilization costs, $/mile, are not included. The costs are for the fuels at the service station. The reference gasoline cost (extax) is $2.60 (1973).

$$\text{Cost} = \frac{\text{est fuel cost}}{\text{gasoline cost}}$$

Conclusions: According to the rankings and final rating of Fig. 145, the most promising alternative fuels are synthetic gasoline and hydrocarbon distillates. Methanol is the next most attractive liquid fuel. Thus, further, more detailed comparisons between methanol and synthetic gasolines are justified. Hydrogen is a speculative fuel, which will become more attractive as fossil carbon resources are depleted.

The final phase of this study is now in the process of completion. It involves the development of recommendations and scenarios for the introduction of the most promising alternative fuels in each of the three time periods.

Questions and Comments

Question (C. O. Thomas, Institute for Energy Analysis): In the presentation, assured coal resources were given as 1.6 trillion tons. This figure has been unchanged in the literature since 1942; it may be misleading. More recently, a distinction has been made between "resource base" and "recoverable reserves" by current technology and economics. Numbers as low as 200 million tons (lower by a factor of 8) are currently being used for recoverable reserves. (Ref: McElvy, Science, 1972, and Paul Averett, USGS Professional Paper No. 82.) The reason for bringing this up is that the oil and chemical industry in the past have been far more rigorous in treating proven reserves and recoverable reserves than the coal industry. If comparisons are to be made between coal and oil industries, they should use the same basis for comparison.

Answer: This is correct and allowance for this factor is taken into consideration in the analysis. The 1.6 trillion tons represents an upper bound; not all of it is economically recoverable.

Question (Dr. J. E. Davoud, D-Cycle Power): A 1% efficiency was mentioned for solar conversion and agricultural conversion of crops to fuel. This is generally accepted, but are there prospects for improving this, such as: selected breeding, fast growing crops, etc?

Answer: There are prospects for improvement to perhaps 2% (double), but beyond that it is doubtful.

C. Alternative Fuels, by Dr. R. M. Kant, Esso Reserach and Engineering

This program is being conducted toward the same objectives and with the same scope and work statement as the IGT program reviewed above.

An initial list of candidate fuels was narrowed down in the first phase of the study and the following fuels were identified for detailed analysis: gasoline and distillate from shale and coal, and methanol from coal (Fig. 146). The first part of the analysis focused on the economics of producing, manufacturing and marketing these fuels. The conversion technology in each case was chosen on the basis of a combination of factors: (1) a good probability that it will be commercialized, (2) capable of producing high yields of liquids and (3) availability of sufficient published information to allow an economic analysis (Fig. 147). It is likely that processes other than those indicated will also be commercialized and may eventually be favored. It is simply too early to make such a judgment.

Based on the choice of technology, it was possible to estimate the cost of the various alternate fuels at various stages between the recovery of the resource and the distribution of the final automotive fuel at the pump. It is estimated that none of these fuels will be produced in significant quantities before 1979 in the case of shale fuels and 1981-83 in the case of hydrocarbon liquids from coal. The technology for producing methanol from coal via coal gasification is further along than the other alternates, but, allowing for construction time, it is difficult to see how such a commercial plant could be on-stream before 1979 at the earliest. Projections were made for these fuel costs through the year 2000 (Fig. 148). These projections attempt to take account of potential improvements in technology as well as compensating features such as increasing cost of coal and the need to build new pipelines. The projections also show the effect of the so-called "learning curve" representing evolutionary improvements rather than more substantial breakthroughs in technology. The relative cost of the fuels is not changed over this time period.

FUEL	SOURCE	
GASOLINE	SHALE	CHOSEN FOR DETAILED STUDY
DISTILLATE	COAL	
METHANOL	COAL	
ETHANOL	CARBOHYDRATES	
METHANE	COAL	
HYDROGEN	COAL OR WATER	
AMMONIA	COAL OR WATER	
HYDRAZINE	AMMONIA	

Fig. 146 Candidate Fuels

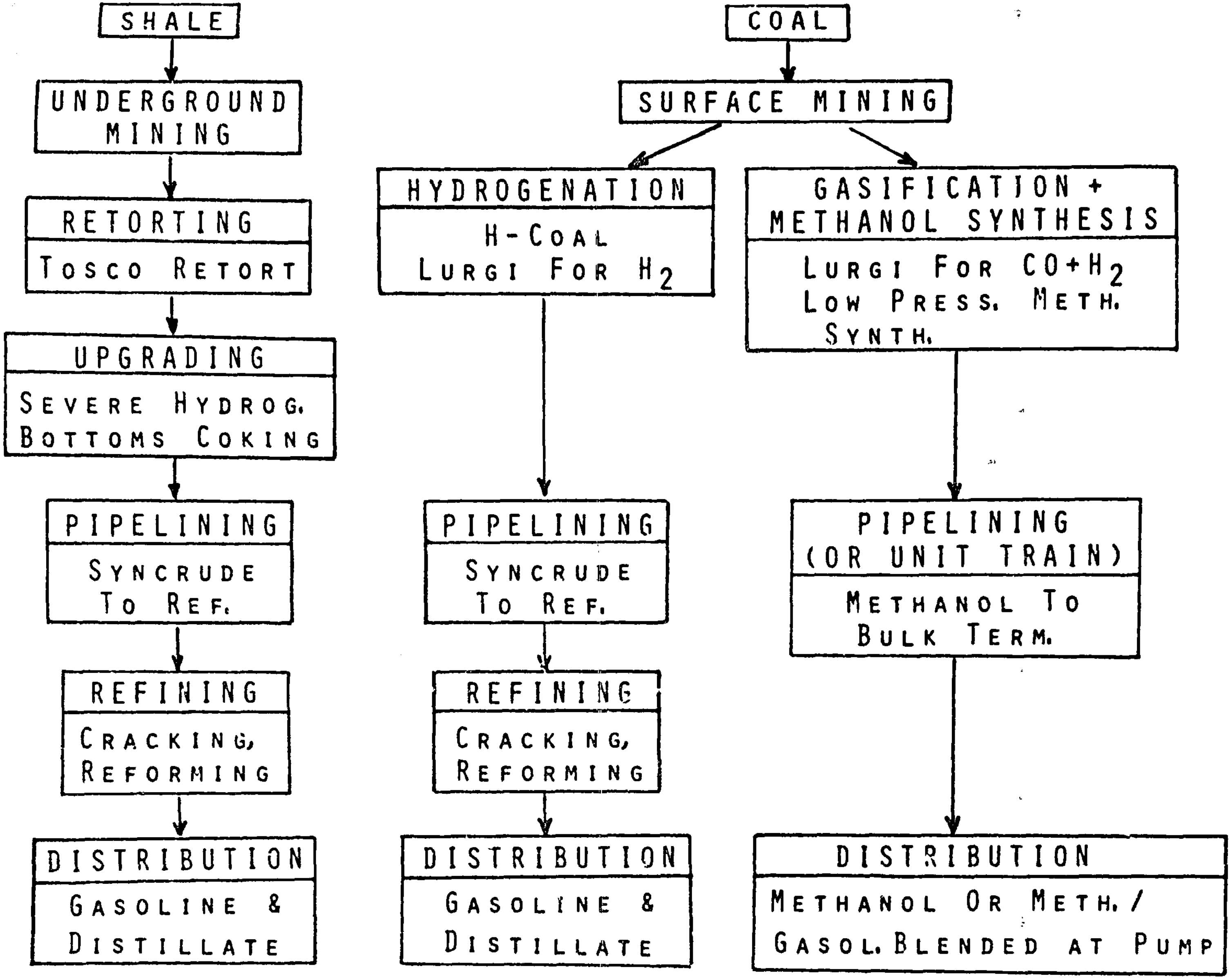


Fig. 147 Process Basis for Economic Evaluation

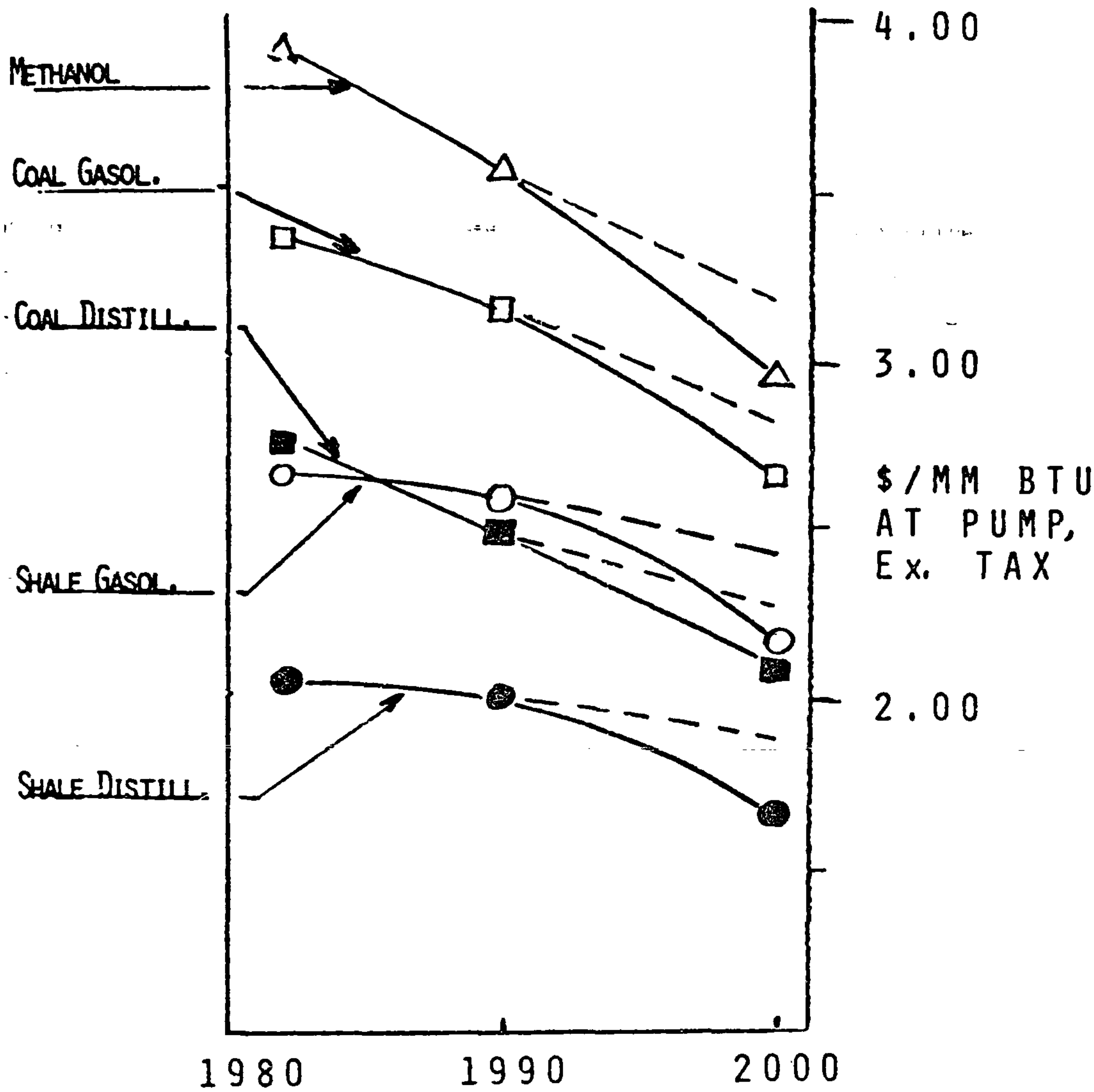


Fig. 148 Cost Projections for Alternative Fuels

The efficiencies of resource utilization are another parameter for assessing alternative fuels (Fig. 149). The overall efficiency for the production of shale fuels is lower than that for coal fuels, reflecting losses during underground mining and retorting. Improvements in these two areas might reasonably be expected as the industry grows, which would affect the overall efficiency of resource utilization. Alternatively, the efficiency of coal liquefaction could be improved if more selective catalysts and processes are developed. In the case of methanol from coal, the particular Lurgi gasification process benefits from the potential utilization of liquid by-products as process fuel. If this is not possible, the efficiency of the overall methanol production scheme would be significantly lower than that for coal liquefaction.

Another major part of the study considered the performance of these alternate fuels. Unfortunately, there are relatively few data on the product quality and the performance of shale and coal derived fuels. It was therefore necessary to infer potential problems and advantages on the basis of very limited information.

Gasolines from coal and shale are expected to have similar aromatics content to petroleum gasolines at high octane numbers (Fig. 150).

Shale distillates are expected to have acceptable cetane numbers for use as automotive Diesel fuels. However, these materials are rather paraffinic and could lead to excessive pour points in low temperature truck applications. De-waxing or pour depressant additives are potential solutions to this problem. Coal distillates probably will have cetane numbers too low for use as Diesel fuels. The solutions to this problem would include diversion of the distillate to other uses, blending with shale or petroleum fractions, or the use of cetane improvers. More data are required to evaluate the suitability of coal distillates as gas turbine fuels.

Turning to methanol, this alternative fuel could lead to increased thermal efficiencies in spark-ignition engines (Fig. 151), if proper modifications are made, taking account of high octane number, low volatility, high heat of

<table>
<tr><th></th><th colspan="2">FRACTION OF ENERGY IN CRUDE RECOVERED IN TOTAL PRODUCT</th></tr>
<tr><th></th><th>GASOLINE</th><th>GASOL. & DIST. CO-PRODUCTS</th></tr>
<tr><td>SHALE HYDROCARBONS</td><td></td><td></td></tr>
<tr><td>MINING</td><td colspan="2">0.60</td></tr>
<tr><td>RETORTING</td><td colspan="2">0.80</td></tr>
<tr><td>UPGRADING & REFINING</td><td>0.70</td><td>0.82</td></tr>
<tr><td>OVERALL</td><td>0.33</td><td>0.39</td></tr>
<tr><td>COAL HYDROCARBONS</td><td></td><td></td></tr>
<tr><td>MINING</td><td colspan="2">0.85</td></tr>
<tr><td>LIQUEFACTION</td><td colspan="2">0.75</td></tr>
<tr><td>REFINING</td><td>0.85</td><td>0.95</td></tr>
<tr><td>OVERALL</td><td>0.55</td><td>0.60</td></tr>
<tr><td>METHANOL FROM COAL</td><td></td><td></td></tr>
<tr><td>MINING</td><td colspan="2">0.85</td></tr>
<tr><td>SYNTHESIS</td><td colspan="2">0.65*</td></tr>
<tr><td>OVERALL</td><td colspan="2">0.55</td></tr>
</table>

* ASSUMES LIQUID BY-PRODUCTS FROM GASIFICATION CAN BE USED AS FUEL.

Fig. 149 Efficiencies of Resource Utilization

GASOLINES

- LIKE PETROLEUM AT HIGH OCTANES
  - -- CA. 60% AROMATICS AT 95 RES. O.N. (CLEAR)
  - -- DUE TO CATALYTIC REFORMING RESPONSE OF NAPHTHAS
- COAL NAPHTHAS MORE AROMATIC THAN SHALE NAPHTHAS
- NEED MOTOR AND ROAD OCTANE DATA
- NO SULFUR OR NITROGEN PROBLEMS FORESEEN

DISTILLATES

- SHALE DISTILLATES SHOULD HAVE ACCEPTABLE CETANE NUMBER (40-45), BUT MAY HAVE POUR POINT PROBLEMS FOR LOW-TEMP. TRUCK APPLICS.
- COAL DISTILLATES PROBABLY WILL HAVE CETANE NUMBERS TOO LOW FOR AUTO. DIESELS: CAN DIVERT TO OTHER USES, BLEND, USE CETANE IMPROVERS, ETC.
- NO SULFUR OR NITROGEN PROBLEMS FORESEEN
- NEED DIESEL AND GAS TURBINE PERFORMANCE DATA

Fig. 150 Performance of Coal and Shale Gasoline and Distillates

- POTENTIAL FOR EFFICIENCY INCREASE IN SPARK-IGNITION ENGINES -- IF MODIFICATIONS TAKE ACCOUNT OF:
  - -- HIGH OCTANE NUMBER, BY INCREASING COMP. RATIO.
  - -- LOW VOLATILITY, HIGH HEAT OF VAPORIZATION, AND LOW HEAT OF COMBUSTION.
- SUCH A MODIFIED ENGINE WOULD NOT BE SUITABLE FOR CONVENTIONAL FUELS.
- EXCELLENT POTENTIAL AS GAS TURBINE FUEL.
- PROMISING FUEL CELL FUEL -- EITHER DIRECTLY OR VIA REFORMING TO H_2.

Fig. 151 Performance of Methanol

vaporization and low heat of combustion. However, such a modified engine would not be suitable for conventional fuels. Methanol has excellent potential as a gas turbine fuel, particularly for stationary turbines where distribution costs are much lower than in the case of automotive fuels. Finally, methanol is an attractive fuel for fuel cells either for direct use or via reforming to hydrogen.

Recently, much publicity has been given to the proposal to use methanol/gasoline blends as an automotive fuel in the near-term future. It is important to assess the potential problems and advantages associated with such a strategy (Fig. 152). Methanol/gasoline blends are very water sensitive so that it is essential that a dry blend be supplied to the consumer and that it not pick up significant quantities of water during use. Conceivably, it may be possible to prevent or circumvent this water sensitivity problem, but information in this area is not yet available. Also, methanol and gasoline form extremely non-ideal solutions which leads to high vapor pressures. In the case of gasoline, the high vapor pressure would probably result in vapor lock, necessitating a reformulation of the gasoline by backing out butanes and possibly some pentanes. If this is necessary, the value of adding methanol, from the point of view of energy conservation, is questionable, unless alternate disposition is provided for the displaced hydrocarbons which is of higher value than their use in gasoline. It is important to demonstrate the effect of these potential problems on vehicle driveability -- e.g., acceleration, starting, stalling, etc.

On the other hand, the use of methanol/gasoline blends would have certain benefits including high blending octane and potentially some improvement in fuel economy measured in miles per BTU. Emissions with methanol/gasoline blends would be lower, in most modes of operation, but the improvement would not be sufficient to attain 1975+ standards without the use of catalytic converters.

In the course of the study, a number of information gaps were identified (Fig. 153). Most of these involve the need for developing new and improved technology as well as commercially demonstrating the effectiveness of existing technology.

- DEFINE POTENTIAL PROBLEMS AND ADVANTAGES FOR SPARK-IGNITION ENGINES.
- POTENTIAL PROBLEMS:
  - -- WATER SENSITIVITY: PHASE SEP'N. WITH <0.5% H_2O FOR 15% MeOH AT R. TEMP. -- ANY COST-EFFECTIVE FIXES?
  - -- VOLATILITY AND VAPOR LOCK: NON-IDEAL SOLUTIONS LEAD TO HIGH VAPOR PRESSURES -- TO AVOID VAPOR LOCK, MAY HAVE TO BACK OUT C_4 (+C_5).
  - -- DRIVEABILITY: DO ABOVE RESULT IN POOR PERFORMANCE -- IS LEANING OUT WITH METHANOL A PROBLEM?
- PROBABLE BENEFITS:
  - -- HIGH BLENDING OCTANE
  - -- LOWER EMISSIONS
  - -- IMPROVED FUEL ECONOMY (MILES/BTU)

Fig. 152 Performance of Methanol/Gasoline Blends

FUEL	AREA	NEEDED
HYDROCARBONS FROM SHALE	MINING + RETORTING	- LARGE DEMO. OF SPENT SHALE DISPOSAL *- IN SITU RETORTING
	UPGRADING + REFINING	- BETTER DENITROG. CATS - MILD VS. SEVERE UP-GRADING AT MINE
HYDROCARBONS FROM COAL	LIQUEFACTION	*- MORE EFFICIENT PROCESS FOR H_2 FROM COAL *- MORE SELECTIVE HYDROG. REACTION
	REFINING	- RESPONSE OF PROCESSES TO VARIOUS QUALITY COALS
METHANOL FROM COAL	MANUFACTURE	*- IMPROVED COAL GASIF. PROCESS - MORE EFFICIENT MeOH SYNTHESIS

FOR ALL FUELS NEED PRODUCT QUALITY AND PERFORMANCE DATA, ALONE AND IN BLENDS, IN VARIOUS AUTO. POWER PLANTS.

Fig. 153 Summary of Data Gaps

The overall conclusions of the study indicate that coal and oil shale are the best source for alternative automotive fuels. Although the resource is vast, environmental, social, legal, as well as technical constraints will limit the rate of production. As a result, complete replacement of petroleum with synthetic fuels is improbable and unnecessary until after the year 2000. Shale and coal hydrocarbons will be blended with petroleum as they become available. Their compatibility with petroleum is a major advantage. Capital commitments are now being made which tends to confirm this scenario.

Methanol could also be an alternative fuel for spark-ignition engines, but the modifications required would make the engine unsuitable for operating on conventional fuels. It seems more desirable to dedicate methanol for use in gas turbines, particularly of the stationary variety. This would release hydrocarbons, which are now being used in this application, for use as automotive fuel.

Questions and Comments

Question (P. Wilson, Chrysler Corporation): Please explain the 20% to 30% improvement in I.C. engine efficiency using methanol.

Answer: To take full advantage of the characteristics of the methanol, significant changes in engine design such as compression ratio, carburetion, manifold design, etc. can bring about such improvements in efficiency.

Question (R. Probst, Federal Mogul Corporation): Is work being done on methanol-based fuels mixed with materials other than gasoline?

Answer: Shale and coal derived materials should blend as well with methanol as gasoline. Work using other non-hydrocarbon materials has not been reported if it is going on. Higher molecular weight material just won't mix, so you are limited to gasoline types of material, ethers or higher boiling alcohols.

Question (Dr. L. Eltinge, Eaton Corporation): Where does the rising cost of petroleum cross the declining costs of alternative fuels shown in Fig. 148?

Answer: There is really no way of projecting what the price of petroleum will be due to numerous political as well as economic factors which will influence the price. Over the last year, the ex-tax price has gone from \$2.60 to \$3.50/MM BTU's at the pump. It might go as high as \$4.00 before reaching a plateau, or even declining.

Question (Dr. W. Hrynischak, Clarke Chapman): What effect can nuclear heat have on coal gasification and shale oil extraction?

Answer: It can have a very pronounced effect on cost. Gulf-Shell is considering various schemes for using the High Temperature Gas Cooled Reactor for coal conversion. But considering the time to design, build and test the system (5-7 years to prove system), it will be 10-15 years before significant production can be achieved. This factor was not considered in the study.

D. Combustion Studies, by Richard W. Hurn, U.S. Bureau of Mines (Guest Presentation)

In late March, the U.S. Bureau of Mines signed an inter-agency agreement with the EPA to do a jointly supported experimental investigation of the performance of:

- methanol and methyl fuel
- methanol-gasoline (derived from synthetics) blends (basically 91 and 96 octane levels; and aromatics in the range of 15 and 40%)
- coal and shale derived gasoline distillate fuels.

Tests will be run with engines on dynamometers and in vehicles on current production and on near term candidate low emission alternate automotive powerplants. Lean combustion limits, emissions and fuel economy maps, stoichiometry of mixtures, blend stability, water-alcohol miscibility, and motor-road octanes will be investigated. Prime attention will be focused on problems anticipated for the customer-user of the fuels.

Recent requests of the Government for industry to recommend realistic alternative fuels to give relief from dependence on foreign sources of crude oil in the 1980-1985 time frame resulted in only one clear answer: coal gaisfication and methanol. This explains the focus on methanol.

Fifty barrels of synthetic crude produced from Utah coal is being obtained. This will be further processed by pertinent current technology and processes to gasoline and distillates for test and evaluation at the Bureau of Mines. It is expected that these fuels will have hydrogen deficiency.

Questions and Comments

Comment (T. A. Guldman, Chevron Research): Since the Bureau of Mines asked the Industry to suggest alternate fuels, a large amount of capital (about $400,000,000) has been invested in shale; also, the suggestion has been made to substitute coal for liquid fuels (residual) which are being burned. This provides some alternatives other than just methanol. Methanol has enough disadvantages so that its introduction could be delayed. Corrosion and cost are examples. Materials compatibility is an important consideration.

Answer: Corrosion and materials compatibility problems are recognized and are being considered in the program. Large production of shale oil is of definite interest, but economic and environmental problems are very difficult in the near term time frame.

E. Fundamental Combustion Research - National Science Foundation (Guest Presentation)

As part of an expanded effort by EPA and others to coordinate the various activities in alternate automotive fuels research and development, EPA is working with NSF to conduct fundamental engine combustion research.

About $700,000 will be spent in FY '74 and about $1,000,000 in FY '75 for research grants at a number of universities on fundamental research as related to conventional engines and near term future alternate engines, such as the stratified charge engine. They will be looking at microscopic or fundamental combustion of current and alternate fuels to expand our knowledge and technology in this area.

F. Storage of Hydrogen by Hydrides, by J. J. Reilly, Brookhaven National Laboratory

Hydrogen would make an ideal fuel for almost all types of energy converters including the internal combustion engine. It is essentially non-polluting and it can be made from readily available, abundant raw materials and primary energy sources. However, a major problem involved in using hydrogen as a common fuel is the difficulty encountered in its storage and bulk (non-pipeline) transport.

Storage as a compressed gas seems impractical and hopelessly non-competitive because of the weight, expense and bulk of the storage vessels. Liquid hydrogen may be useful in certain circumstances, but the energy required for liquefaction is a large fraction of that which is later generated by its combustion. An even more important consideration is that liquid hydrogen would present a serious and, probably, insoluble safety problem if it were to be considered as a common fuel for individual use (e.g., automobile). However, there is an alternative to the conventional storage methods which at this date appears quite attractive, i.e., storage of hydrogen as a metal hydride. It is well known that some hydrides contain far more hydrogen per unit volume than does liquid hydrogen. It has been the goal of the Brookhaven research program to develop hydrides - or, rather, hydrogen-metal systems - which will have a high hydrogen content and which will meet certain requirements imposed by their use in conjunction with devices that use hydrogen for the production of energy.

Some of the pertinent properties of metal-hydrogen systems in general are summarized. Those of interest for our purpose are exothermic; i.e., heat is evolved when hydrogen is absorbed. They are almost always reversible, and the hydrogen can be recovered by lowering the pressure below, or raising the temperature above, the pressure and temperature required for the absorption process. At a given temperature, each hydride is in equilibrium with a definite pressure of hydrogen, its "decomposition pressure". If hydrogen is withdrawn and the pressure drops, decomposition occurs until the evolved hydrogen has built up to the decomposition pressure again.

This pressure is a function not only of the temperature but also of the amount of hydrogen in the solid phase. This quantity is not usually constant, as in stoichiometric compounds such as chlorides, but can often vary within rather wide limits. The way in which the dissociation pressure changes with the composition of the solid is shown in Fig. 154 for a typical, if slightly idealized, system. As hydrogen is taken up by the metal and the ratio H/M increases, the equilibrium pressure increases rather steeply until the point A is reached. Up to this point the solid consists of a solution of hydrogen in metal rather than a compound. At higher concentrations, however, a second phase appears, having the composition B; and the addition of hydrogen will not result in an increase of the equilibrium pressure until all of the solid phase has attained this composition. Above this "plateau" region, further enrichment of the solid in hydrogen requires a steep increase in pressure. The curves labeled T_2 and T_3 in the same figure show the effect on the pressure-composition relation of raising the temperature. At temperatures above $400^{\circ}C$, hysteresis is usually absent and the equilibrium pressure is the same whether hydrogen has been added to or removed from the system.

Hydride heats of formation, ΔH^f, can be determined either by calorimetry or by determining the temperature-dependence of decomposition pressure. Hydrides which have a high decomposition pressure at low temperatures generally have a relatively small value of ΔH^f.

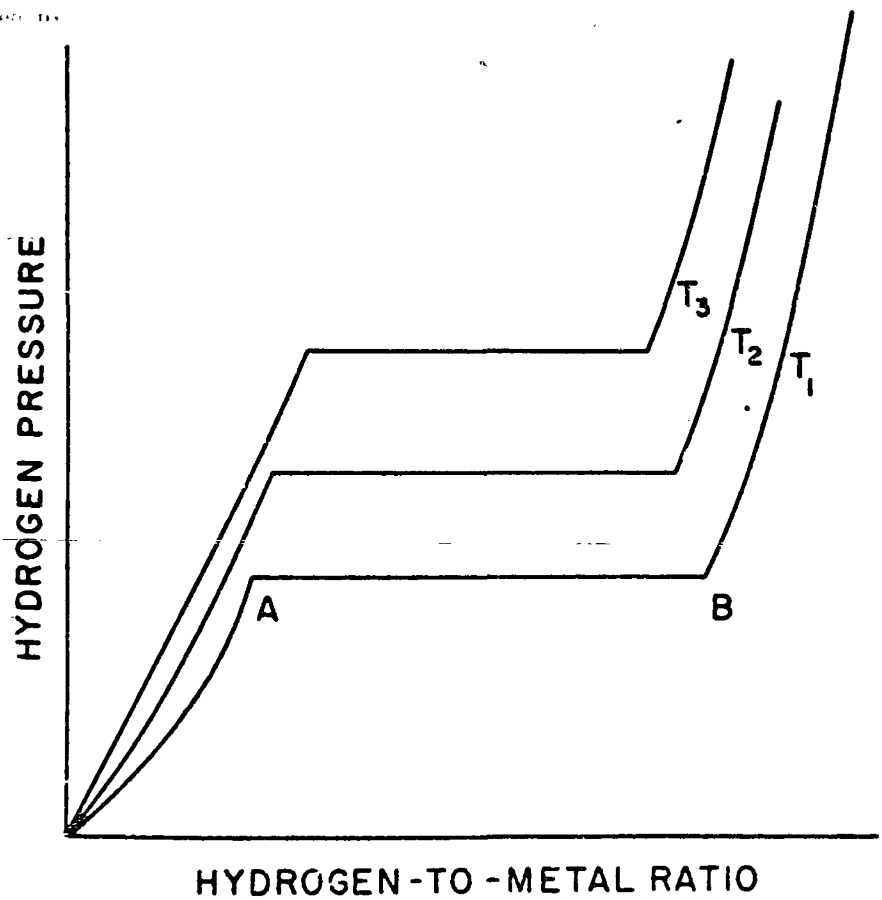


Fig. 154 Pressure vs. Composition Isotherms in a Typical Hydrogen-Metal System

Rates of hydrogen-metal reactions vary widely, and depend on several factors. One is the intrinsic nature of the system. Thus, certain titanium-cobalt alloys react, even when in large chunks, almost as fast as hydrogen can be supplied, while pure magnesium powder reacts very slowly. Another factor is cleanliness of metal surface; an oxide film will often result in a long induction period before a good rate is attained. Still another factor is the state of subdivision of the metal. This can usually be greatly increased by subjecting a sample to a series of hydriding-dehydriding cycles. Absolute surface areas as high as 2 square meters per gram have been obtained in this way, and the product was highly active toward hydrogen. Finally, it is possible to increase the rate of the combination reaction by the addition of small quantities of solid catalysts. Thus, the formation of MgH_2 is accelerated by the presence of nickel (or more accurately Mg_2Ni).

There are a number of criteria by which one may judge the suitability of a metal-hydrogen system for energy storage. For example, it was mentioned above that the hydrides are exothermic and that energy must be supplied for their decomposition. This need not, however, be a source of inefficiency. All energy producing devices, whether fuel cells or combustion engines, produce waste heat and it should be possible to utilize this heat for the decomposition of the dydride. We therefore require a balance between the heat produced and that required, both as to quantity and quality (temperature). In other words, the hydride should have an appreciable decomposition pressure (at least one atmosphere) at the temperature of operation of the energy-producing device. The application of hydride storage to hydrogen fueled vehicles is shown in Fig. 155. There are, of course, additional criteria by which one can judge the worth of a material according to one's particular needs. For example, a unique set of criteria has been developed by which any candidate metal-hydrogen system can be measured against the EPA program goals. These criteria are listed as Fig. 156. We have also experimentally screened a large number of alloys. All of these materials, when judged by this particular set of criteria, score lower than catalyzed magnesium hydride and can be eliminated as hydrogen storage media. It should be noted that the criteria, as presently constituted, include reversibility. This specification, when

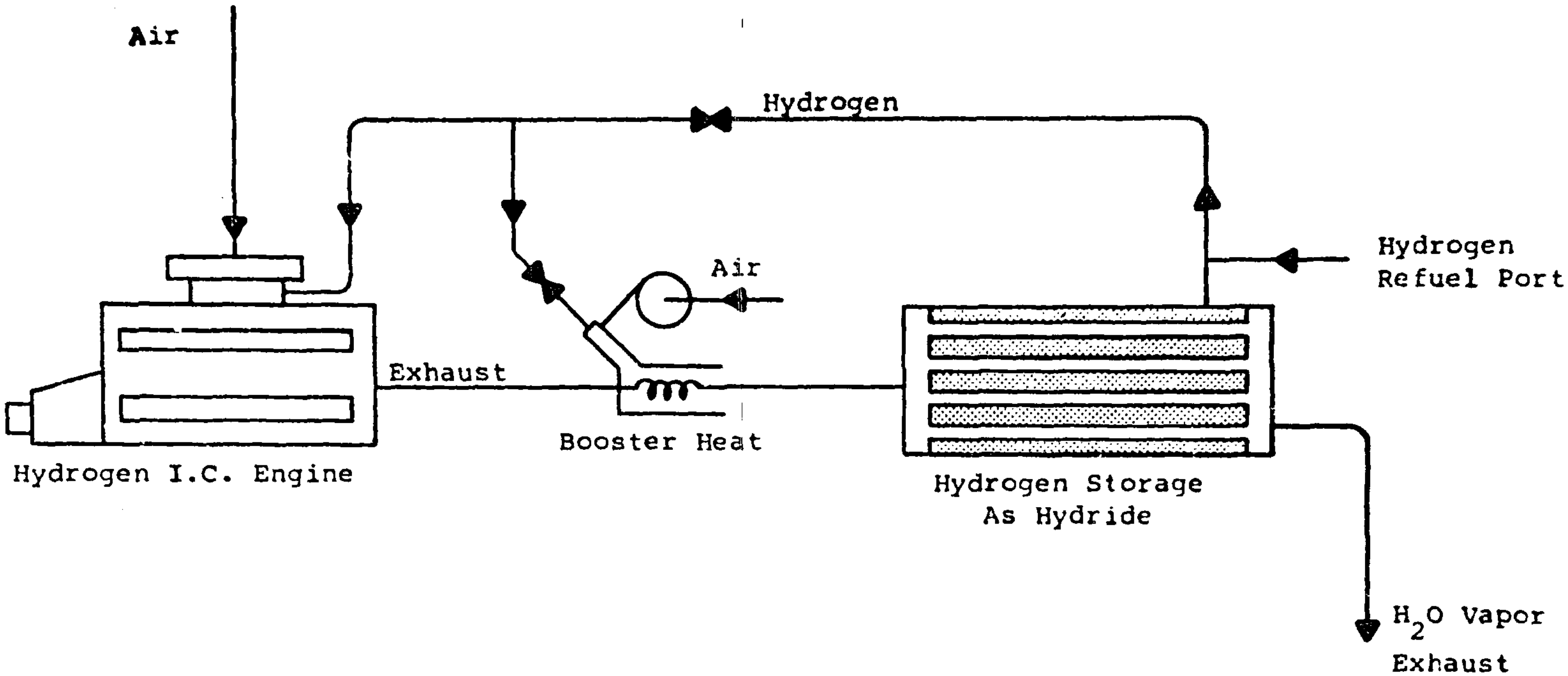


Fig. 155 Application of Hydride Storage to Hydrogen Fueled Vehicles

x - Series reactions required to constitute hydride and process is not simple or cheap.

1 - Special apparatus and extreme conditions are necessary

5 - Reaction takes place in situ with heating, cooling or pressurization

Hydrogen Content (by weight)

x - Contains less than 5% hydrogen

1 - Contains 5 - 10%

3 - Contains 10 - 20%

5 - Contains more than 20%

Hydrogen Content (by volume)

x - Contains less than 4 x 10^{22} atoms H/ml of hydride

1 - Contains 4 to 6 x 10^{22} atoms H/ml of hydride

2 - Contains 6 to 8 x 10^{22} atoms H/ml of hydride

3 - Contains 8 to 10 x 10^{22} atoms H/ml of hydride

5 - Contains more than 10 x 10^{22} atoms H/ml of hydride

Pressure/Temperature Relation

x - P > 2000 psia @ 150°F
T > 570°F @ 15 psia
1 - P = 1 to 2000 psia @ 150° F
T = 390 to 570°F @ 15 psia
2 - P = 500 to 1000 psia @ 150°F
T = 300 to 390°F @ 15 psia

3 - P = 200 to 500 psia @ 150°F
T = 5 to 300°F @ 15 psia

5 - P < 200 psia @ 150°F
P > 15 psia @ 5°F

Heat of Dissociation

x - Heat Dissoc (H_D) > 0.4 Ht. of Combustion (H_C) of hydrogen

1 - 0.2 < HD/Hc < 0.4

3 - 0.1 < H_D/ Hc < 0.2

5 - HD/Hc < 0.1

Safety (Hydrided and Dehydrided)

x - More hazardous than gasoline

1 - Same overall degree of hazard as gasoline

3 - Somewhat less hazardous than gasoline

5 - Significantly less hazardous than gasoline

x - More than $1000 (20 gal. gasoline equivalent) near or long term
Long range availability unlikely

1 - $500 to $1000 near and long term
Long range availability in doubt

3 - $200 to $500 near and long term
Availability reasonably certain

5 - <$200 near and long term
Availability certain

Physical Properties

x - Low melting point. Volatile in operating range. Corrosive, etc.

1 - Properties marginally acceptable

5 - Acceptable

Reaction Kinetics

x - Rate inadequate regardless of equipment design

1 - Rate adequate but equipment complex

5 - Rate adequate in simple equipment

Thermal Conductivity

x - Limits hydrogen availability regardless of equipment

1 - Acceptable for use but with complex heat exchange equipment

5 - Rate adequate in simple equipment

Cyclic Stability - physical

x - Effective for < 100 cycles

1 - Effective for 100 to 300 cycles

3 - Effective for 300 to 500 cycles

5 - Effective for more than 500 cycles

Cyclic Stability - contamination

x - Less than 300 cycles with high purity gas (HPG)
Less than 100 cycles with normal purity gas (NPG)

1 - 300 to 500 cycles (HPG)
100 to 300 cycles (NPG)
< 100 cycles with impure gas (IG)

3 - > 500 cycles with HPG
> 300 cycles with NPG
100-300 cycles with IG

5 - > 500 cycles with NPG
> 300 cycles with IG

Key:
x - Rejects candidate
0 - Unknown
1 to 5 - Rating scale

Fig. 156 Criteria for Evaluation of a Candidate Metal Hydride applied in the usual sense, eliminates certain complex hydrides (e.g., $Mg(AlH_4)_2$), which otherwise may be very attractive as hydrogen storage media. At present such compounds can only be made indirectly using wet chemical techniques.

Future work will examine the possibility of simplifying the synthesis of such compounds through the use of catalysts and/or alternate wet chemical reactions. Thus, if simple novel syntheses are possible, such systems, even if not directly reversible, could then be considered as practical hydrogen storage media.

Questions and Comments

Question: How do you store hydrogen in the hydride; do you have to refrigerate the system?

Answer: While charging the system, heat of formation is removed by water or coolant. While storing, the pressure is raised to the equilibrium pressure; this may be 300-400 Psi.

G. Gasoline-Hydrogen Fuel Blends, by R. Breshears, Jet Propulsion Laboratory

A high-efficiency, low-emission engine development project is currently underway, sponsored by NASA and EPA. The feasibility demonstration phase has been completed and the validation phase is now in progress.

The system has the potential of meeting the EPA 1977 standards while significantly improving fuel economy. It will use current fuels and engines, will have similar response characteristics to current engines, and will be low in cost considering both initial cost and fuel savings.

The concept (See. Fig. 157) is to use small amounts of hydrogen to allow the burning of gasoline at ultra-lean conditions. The hydrogen is generated aboard the vehicle by feeding gasoline and air to a hydrogen generator which produces hydrogen and carbon monoxide. The generated gas is mixed with gasoline and fed to a conventional engine. The required hydrogen is produced in

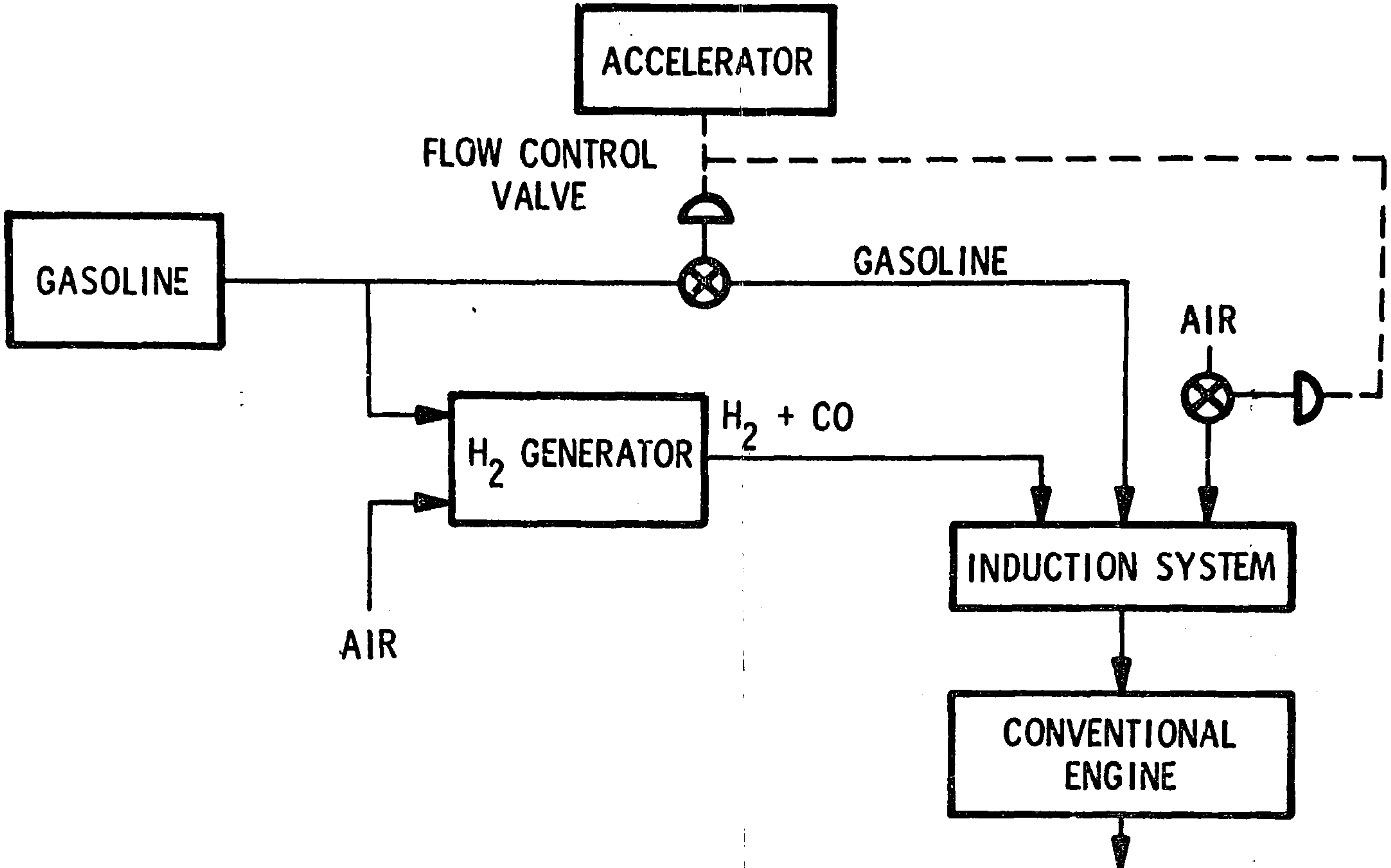


Fig. 157 JPL System for Low Emission Combustion in a Conventional SI Engine

the generator, and no hydrogen is stored aboard the vehicle. Previously, water was also fed to the hydrogen generator, but recent generator developments allow elimination of water feed.

In the initial single cylinder, CFR-engine work emissions from various fuels were compared in terms of grams of emission per horsepower-hour produced and combustion conditions expressed in terms of equivalence ratio. In CFR engine experiments it was shown that NOx emissions from gasoline could be reduced slightly by lean operation. With gasoline fuel levels equivalent to the EPA 1977 standard could not be achieved because misfire limits the minimum equivalence ratio to about 0.63. With hydrogen, however, the engine was operated down to equivalence ratios of 0.1 where the NOx emissions are less than 1/100 of the EPA standard and in fact down to the EPA ambient air standard (0.25 ppm). Since the extremely low NOx emissions achievable by lean combustion with pure hydrogen are not required, it is more practical to use small amounts of hydrogen to extend the operating range for gasoline down into the ultra-lean region. It is desirable to limit the amount of hydrogen needed to minimize the generator size and reduce the effect of generator inefficiency on overall fuel economy. Mixtures of hydrogen and gasoline in both the CFR and V-8 engines showed very low NOx emissions in the ultra-lean region (Fig. 158). Carbon monoxide emissions were measured and found also to be below the EPA 1977 standards, as long as adequate quantities of hydrogen were used to avoid misfire (Fig. 159). Hydrocarbon emissions have been measured and found to be above the EPA 1977 standard (Fig. 160). Further work will be needed to reduce hydrocarbon emissions.

The engine thermal efficiency was measured and found to be substantially increased by operation in the ultra-lean region (Fig. 161). Engine thermal efficiency data were taken across the rpm range at level road load conditions with gasoline only at maximum efficiency spark advance and equivalence ratio. The data for the same engine and induction system, but using hydrogen and gasoline, showed a substantial increase of thermal efficiency. A further increase in efficiency was shown by increasing turbulence in the combustion chamber. This was done by using shrouded valves (Fig. 162); other techniques should also be effective.

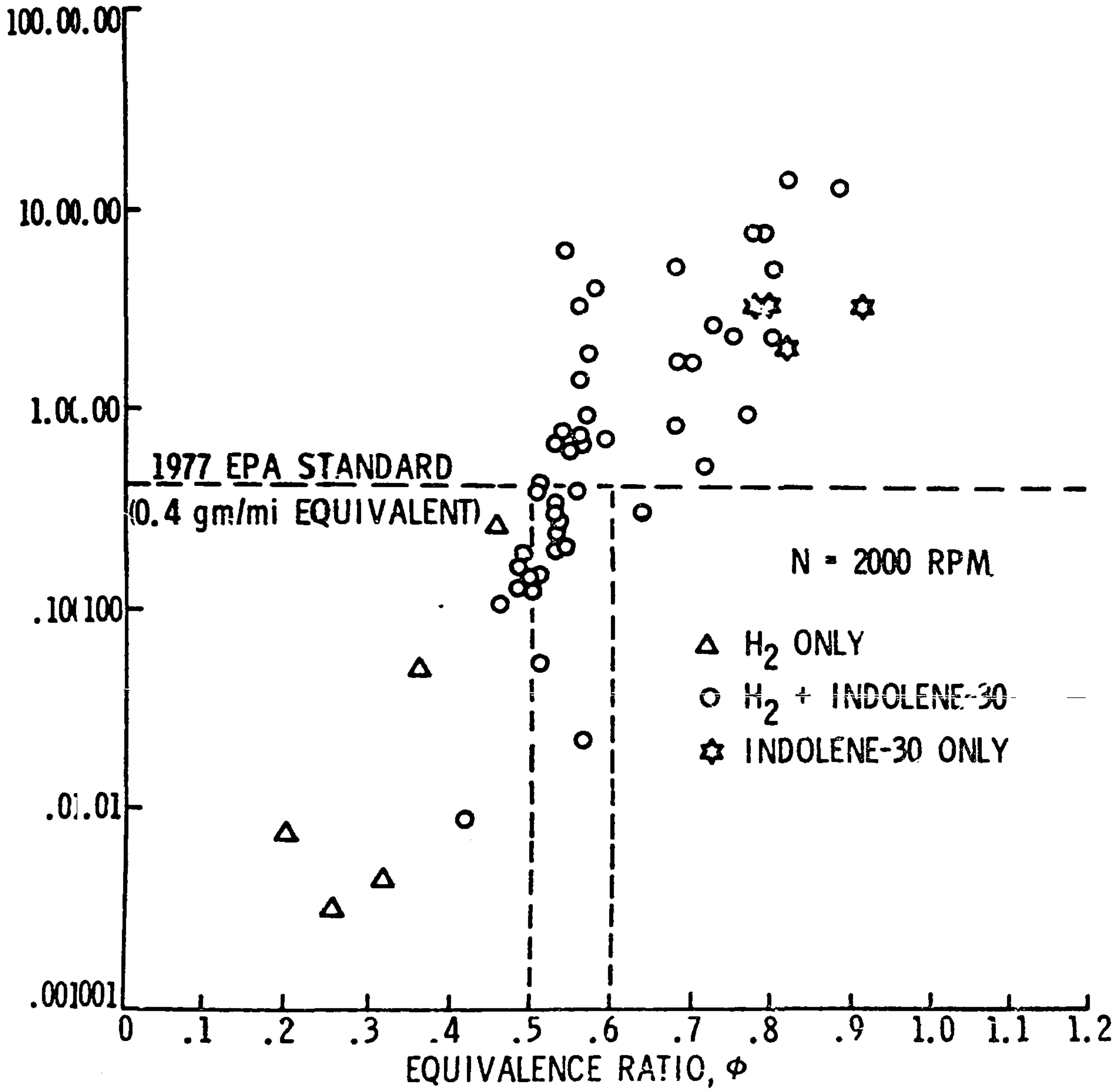


Fig. 158 NO_x Emissions V-8 Engine

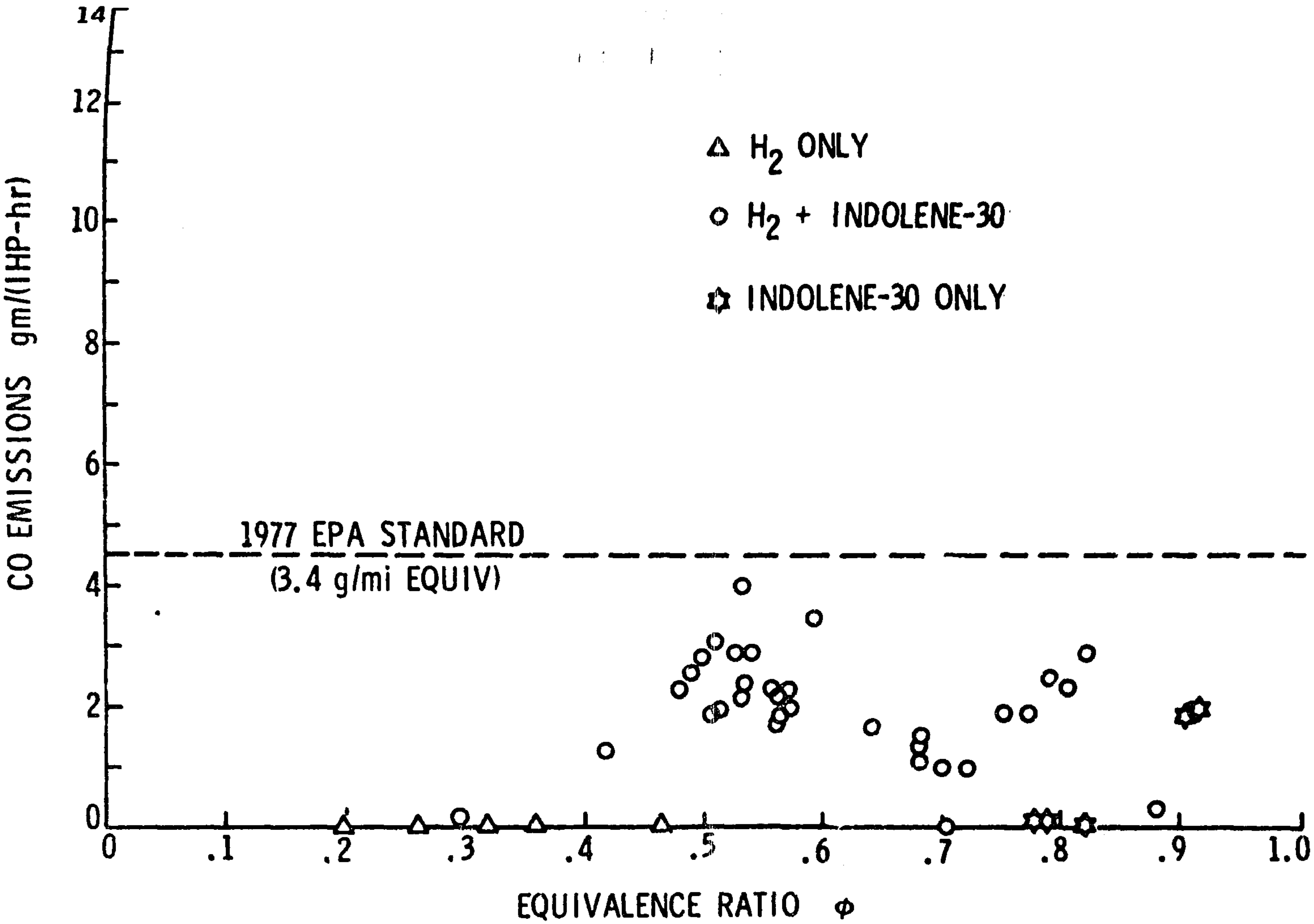


Fig. 159 CO Emissions V-8 Engine

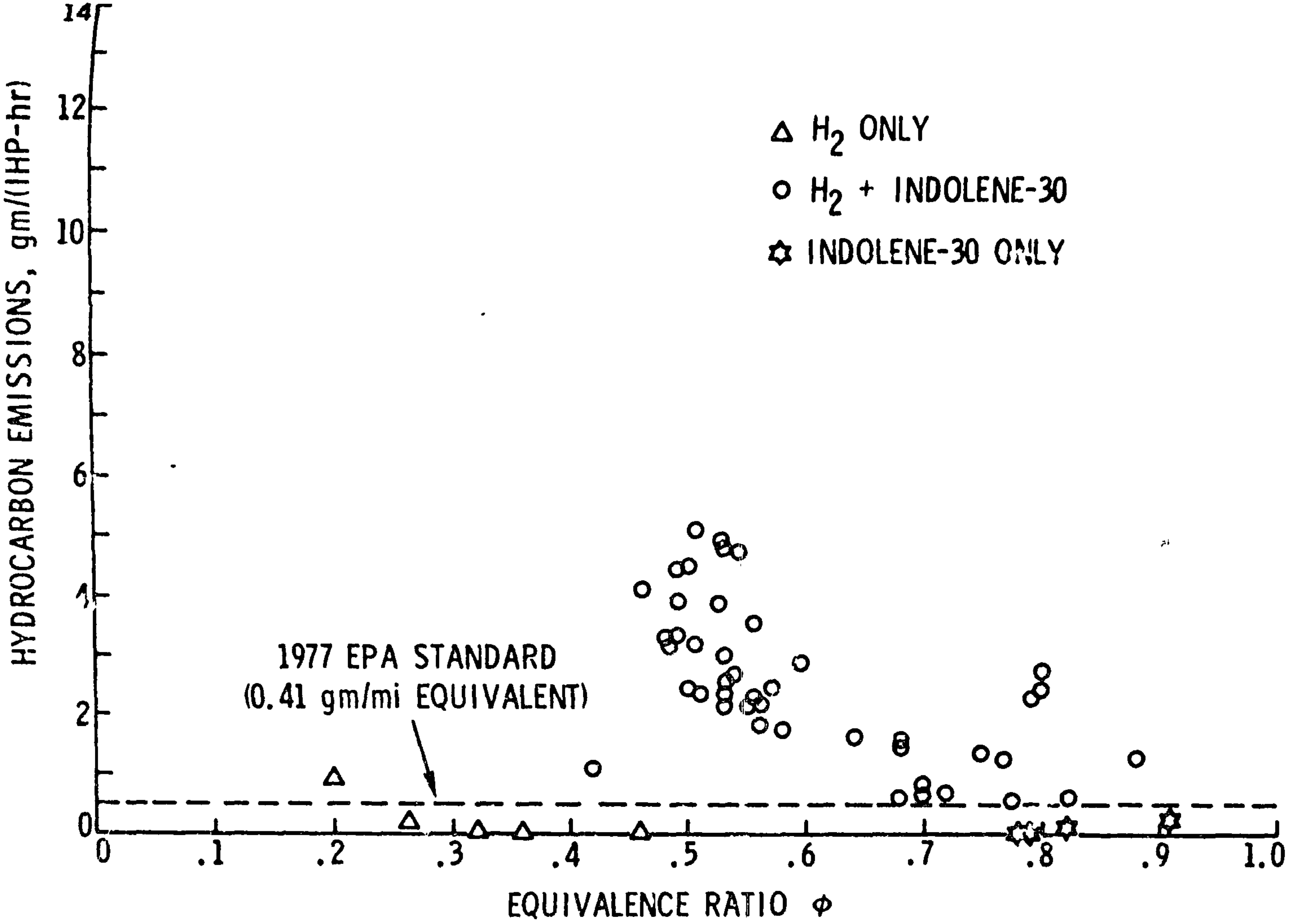


Fig. 160 Hydrocarbon Emissions V-8 Engine

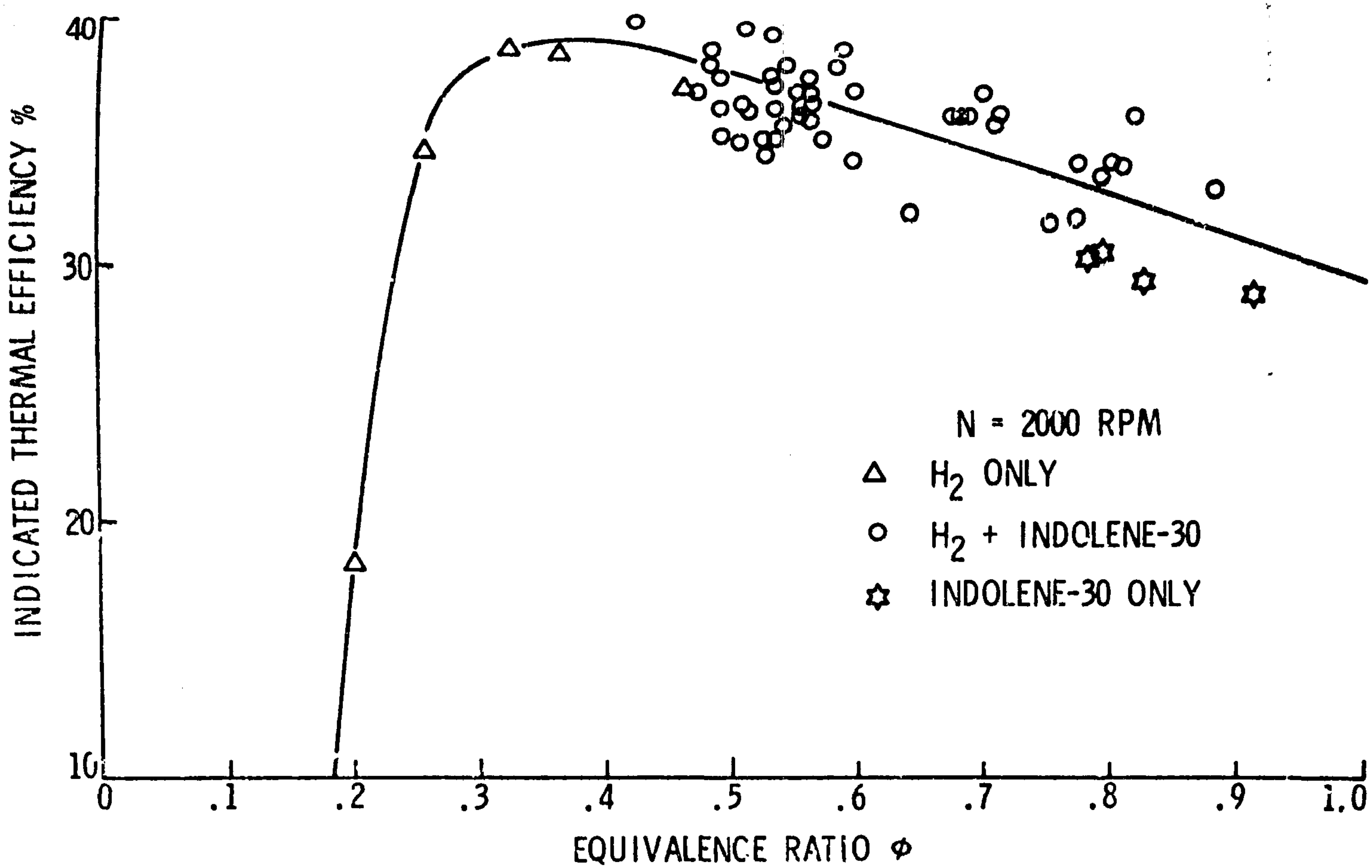


Fig. 161 Thermal Efficiency V-8 Engine

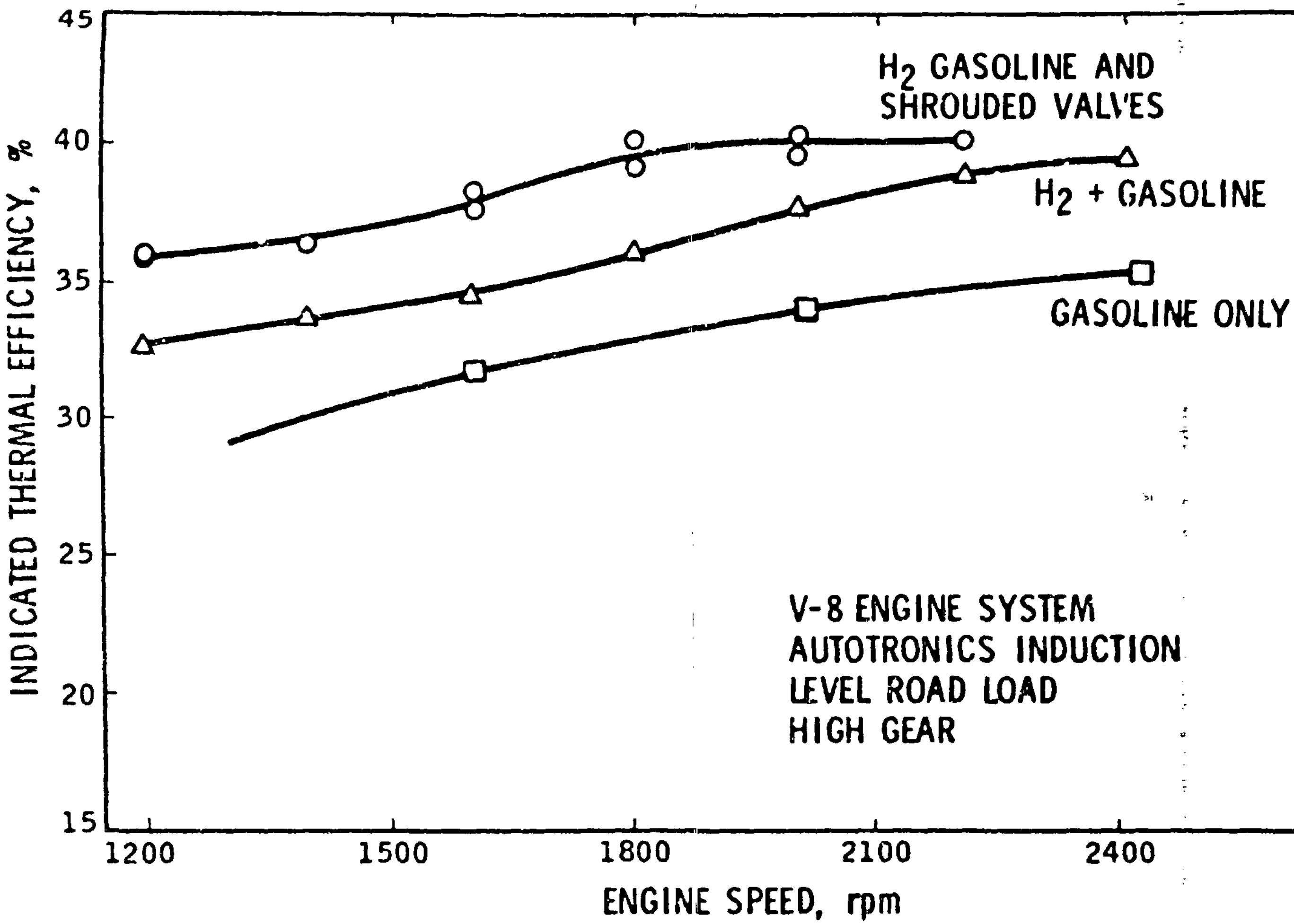


Fig. 162 Turbulence Effects on Engine Efficiency

The current V-8 engine hydrogen requirements to avoid misfire are about 6% hydrogen by weight in fuel at an equivalence ratio of 0.55. This should be compared with the lean flammibility limit of 1.5% by weight of hydrogen. The CFR-engine requires about 2% hydrogen to avoid misfire (Fig. 163). This indicates that substantial reduction in the V-8 engine hydrogen requirements should be possible. Testing has been initiated to evaluate the effects of engine modifications, such as improved fuel atomization and distribution, improved ignition system, and increased combustion chamber turbulence on the lean limit hydrogen requirements and hydrocarbon emissions.

The most critical development of this system is the hydrogen generator. The design chosen is similar to that used for commercial production of hydrogen from hydrocarbons. (The process is called partial oxidation hydrogen generation. See Fig. 164.) In this process, gasoline and air are reacted at 1500 to 2000°F, forming hydrogen, carbon monoxide, plus various hydrocarbons and diluents. Heat is supplied by pumping air into the generator and burning a portion of the gasoline. The reaction takes place in a reactor with or without the use of catalysts. The maximum theoretical hydrogen yield for a hydrogen generator with water, gasoline and air feed in 29% by volume. When no water feed is used, the generator air/fuel mass ratio must be greater than 5 to avoid soot formation. Under these conditions the maximum theoretical hydrogen yield is 24% by volume. The current catalytic generator will yield 22% by volume hydrogen without producing soot. This operation is achieved only with gasoline and air feed, and no water is used. The catalytic generator has an efficiency of 80%. These data show a major improvement over the much larger and earlier thermal generator which produced 14.5% by volume hydrogen with an efficiency of 67% and required water feed (Fig. 165).

Engine and hydrogen generator integration tests were made with the V-8 engine and the early thermal generator and also with a catalytic generator. The early thermal generator/engine combination showed about the same thermal efficiency as the unmodified engine. The higher performance catalytic hydrogen generator engine combination showed a substantial efficiency increase as compared with the unmodified engine. This improvement is in terms of the

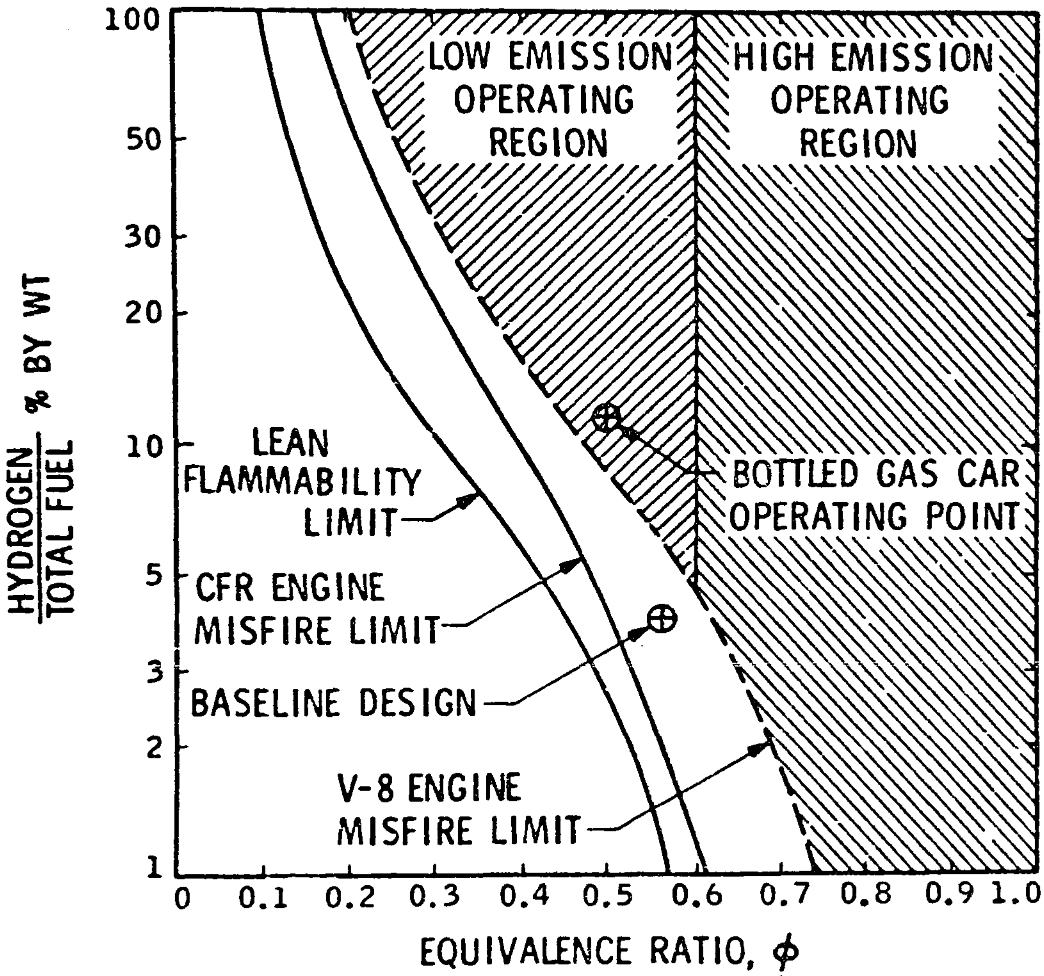


Fig. 163 Engine Hydrogen Requirements

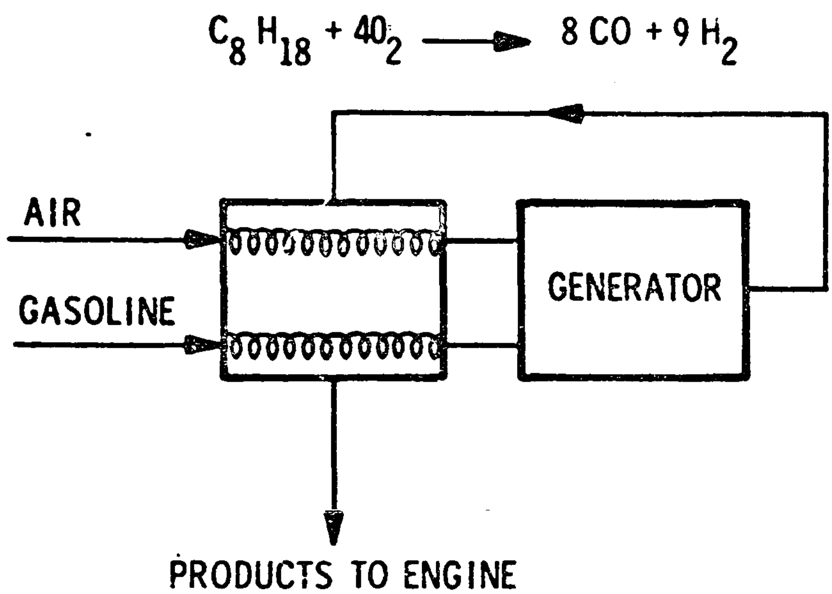


Fig. 164 Partial Oxidation Hydrogen Generator

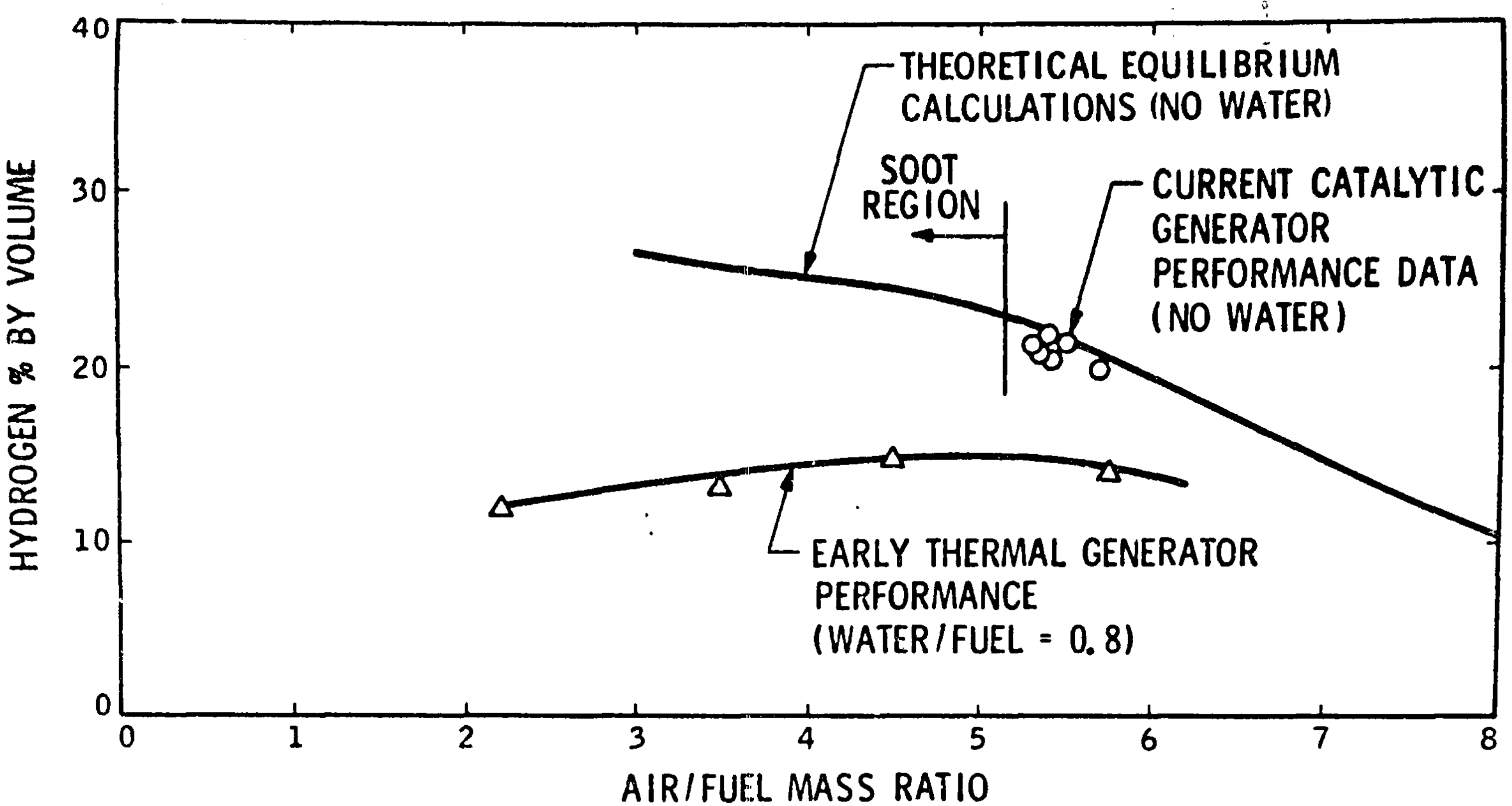


Fig. 165 Hydrogen Generator Performance

combined indicated thermal efficiency of the engine/generator combination (Fig. 166). The baseline design point represents an improved engine with reduced hydrogen requirements. This represents a 25% increase in efficiency over the unmodified engine.

A bottled-gas car has been built (Fig. 167) which used the experimental induction system and uses hydrogen from high-pressure cylinders mounted in the trunk. This car was tested using the EPA CVS cycle. The results to date show a dramatic reduction of NOx and CO emissions and a reduction of 34% in total fuel BTU's (Fig. 168). In a hydrogen-generator-equipped car, approximately 25% improvement in fuel economy is expected.

The overall status of the JPL system is:

- A compact high-performance hydrogen generator has been demonstrated.
- A V-8 engine has been operated with a hydrogen generator.
- The bottled-gas car shows high efficiency, low NOx, and CO emissions.

Future plans include:

- Fully characterize the engine/generator combination.
- Investigate the generator start-up and control problems.
- Test the engine modifications to reduce engine hydrogen requirements.

Current plans call for completion of the characterization by September 1, 1974.

Questions and Comments: None

H. Electric Vehicle Impact Study for Los Angeles, by William Hamilton, General Research Corporation

This study, although it focuses on the Los Angeles region, includes national implications of regional electric car use. Its ultimate concern is the comprehensive impacts of battery-electric car introduction in a conventional-automobile situation; it does not address hybrid-electric, steam, or other automotive alternatives. Impacts are sought on: environment, resources, economy, and society in 1980, 1990 and 2000.

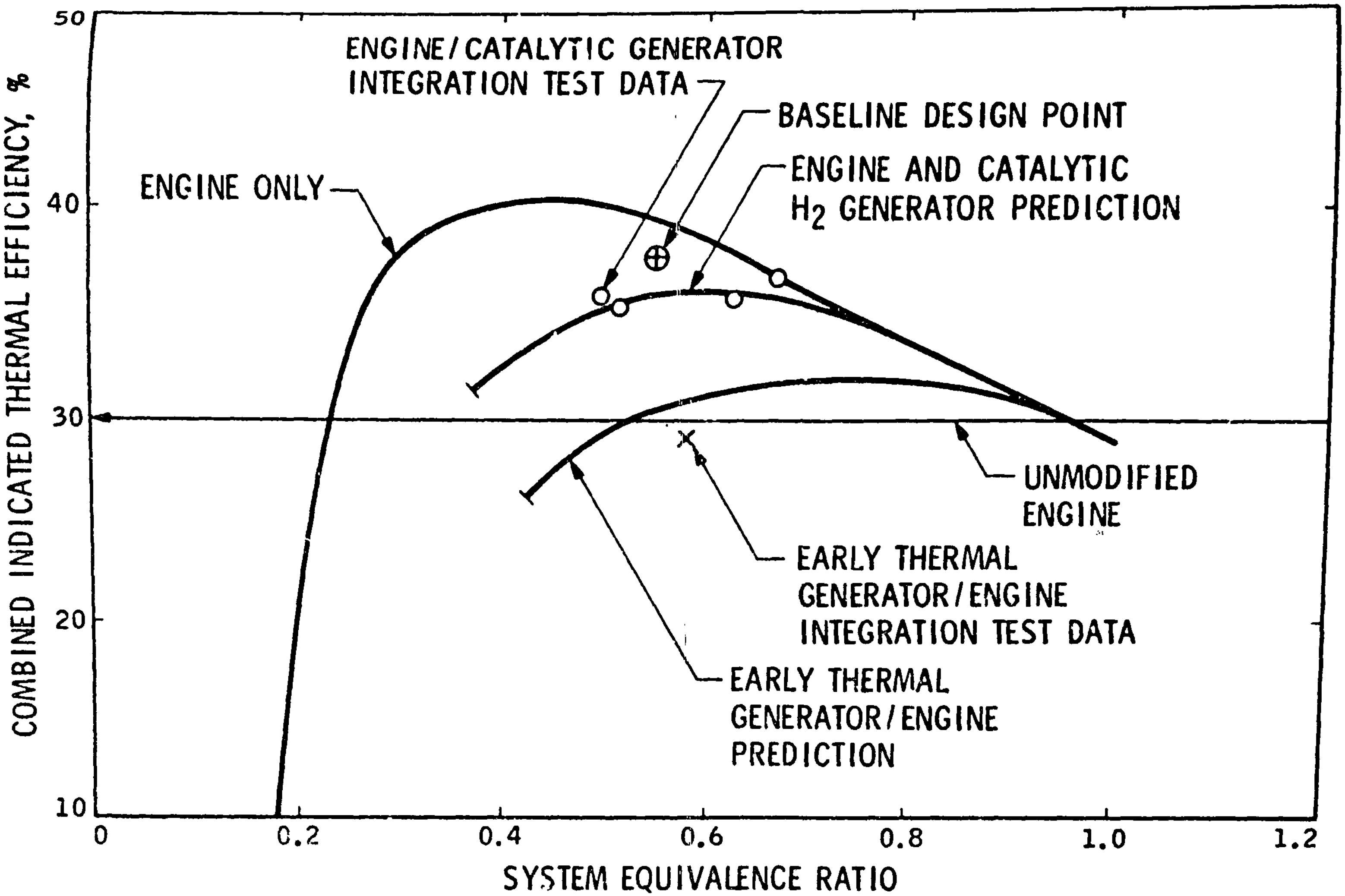


Fig. 166 Engine/Hydrogen Generator Thermal Efficiency

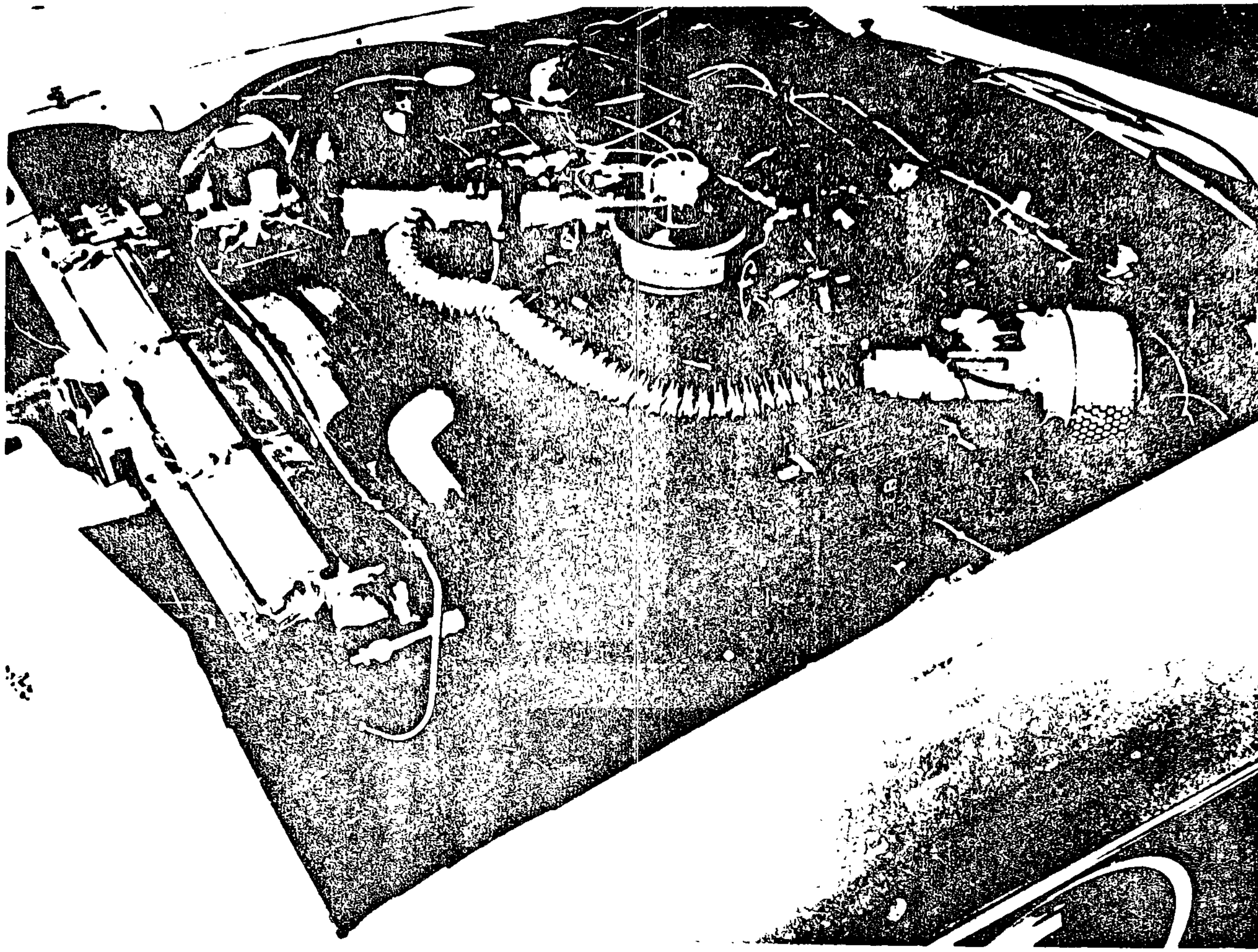


Fig. 167 Bottled Gas Car Installation

	UNMODIFIED VEHICLE	BOTTLED GAS CAR	EPA 1977 STANDARD
HYDROCARBONS (GM/MI)	2.29	2.6	0.41
CARBON MONOXIDE (GM/MI)	43.91	1.6	3.4
NITROGEN OXIDES (GM/MI)	1.75	0.52	0.4
FUEL BTU/MILE*	12,700	8400	

STATUS

TUNING OF CONTROL SYSTEM CONTINUING FUTURE TESTS EXPECTED TO SHOW NO_X BELOW STANDARD

* TOTAL GASOLINE AND HYDROGEN BTU's

Fig. 168 Bottled Gas Car Test Results

The basis for impact calculation is a characterization of electric cars performed under subcontract by Minicars, Inc., of Santa Barbara, California. Figure 169 shows parametric vehicle gross weights for a small shopping car and for a larger car with freeway commuting capability, together with specific range--weight combinations selected for subsequent use in the study. Ranges shown were evaluated on the SAE Residential and Metropolitan Area Driving Cycles, respectively. Maximum ranges at constant speed are over twice the figures shown. Figure 170 shows the performance of the batteries assumed for these 1980 calculations, together with performance of several advanced lead-acid traction batteries which have already been operated in experimental electric cars. Also shown is the performance of a lithium-sulfur battery which current development programs are expected to make available by 1990; its superior performance essentially removes electric car range restrictions forecast for 1980. As Fig. 171 suggests, even the 4-passenger vehicle is quite small, in the subcompact class; but adequate weight and space allowances are provided for compliance with future safety standards.

The impact of electric cars is measured relative to a future without electric cars. This future has been defined through the series of baseline projections: population, transportation, energy, economy and air quality. The ground rule in all these baseline projections has been "no surprises", that is, no drastic rationing of gasoline or electricity, nor other major dislocation of existing economic, social, and technological patterns. The baseline projections collectively envision much-reduced rates of population growth in Los Angeles, a very moderate expansion of transportation demand and the freeway system, a reduced but still substantial growth in the supply and demand for electric power, and a major improvement in air quality due to enforcement of existing automobile emission regulations.

Figure 172 shows an important product of the baseline energy projection: future fuel economy of the average automobile. The chart includes both the actual fuel economy over the past 40 years for all cars on the road and the measured economy for average new cars since 1957. Circles for future years are legislative and research goals and standards advanced during the past year.

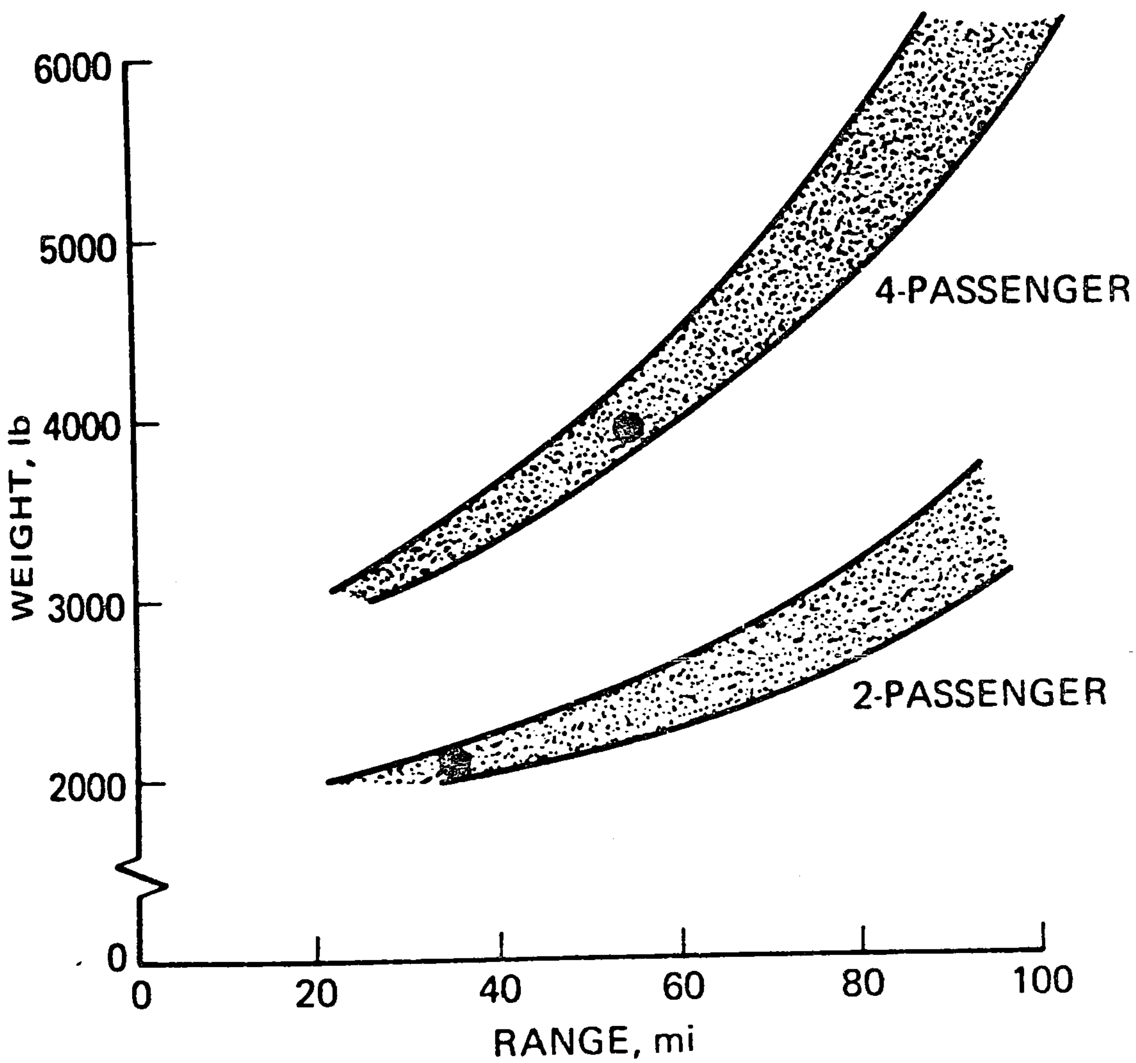


Fig. 169 Electric Car Weight Versus Range 1980

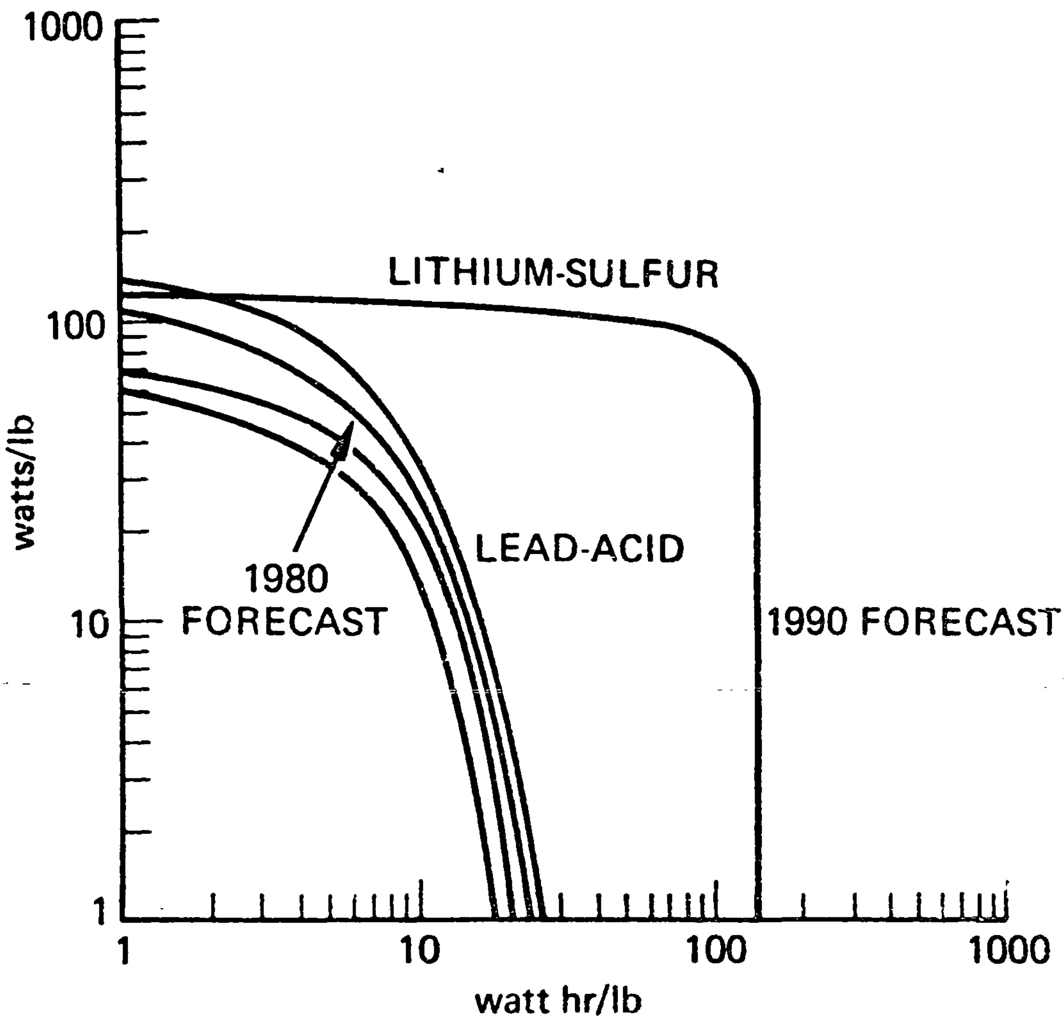


Fig. 170 Battery Characteristics

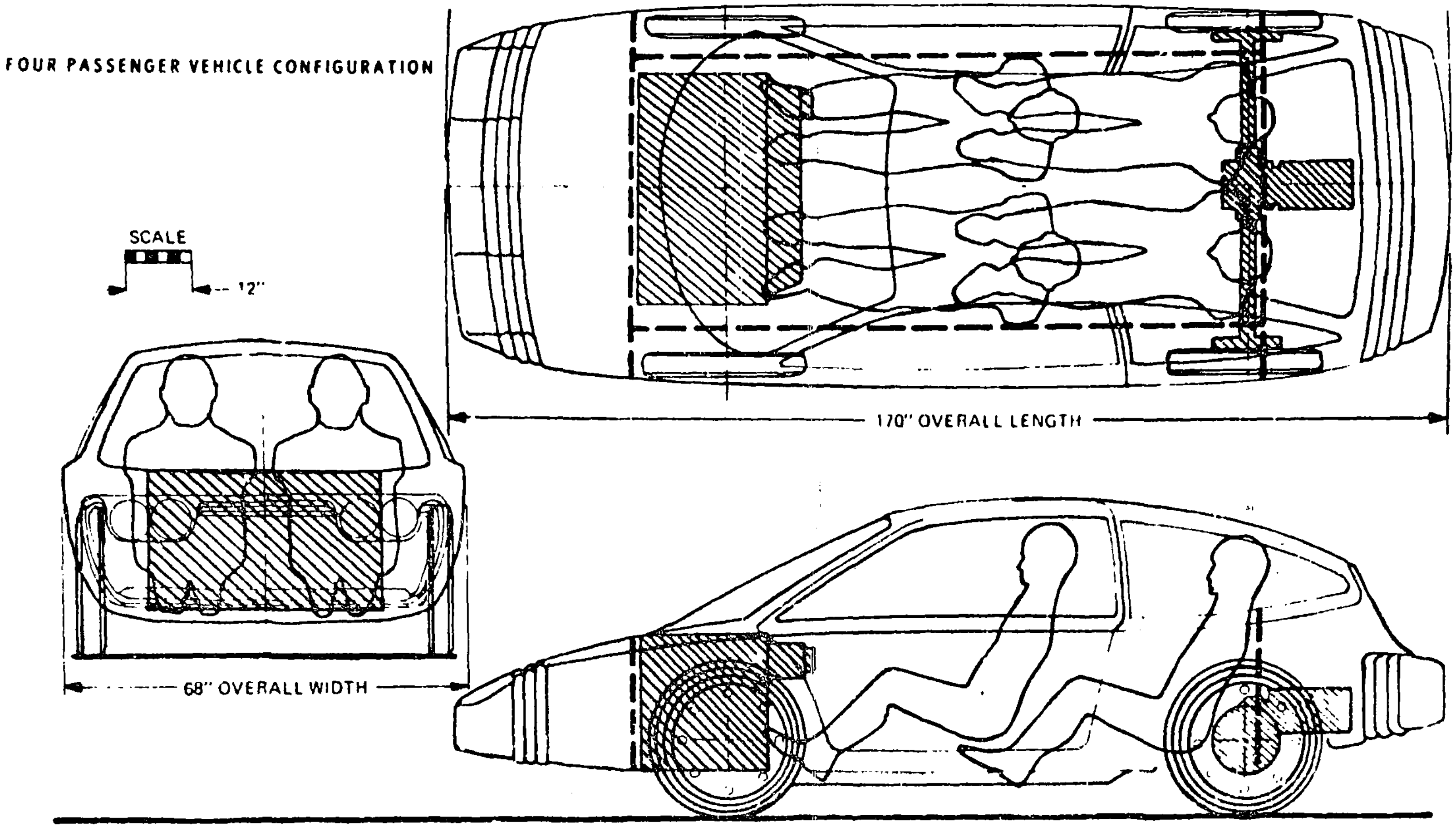


Fig. 171 Four Passenger Vehicle Configuration

Fig. 172 Projected Auto Fuel Economy

The baseline projection, which calls for a doubling of gasoline mileage by the end of the century, is based primarily on a near-term target cited by the EPA and a 1984 goal stated in legislation passed by the Senate six months ago.

Figure 173 compares the baseline fuel economy projection with prospects for electric cars. Here energy consumption has been transformed into fuel BTU consumed, either in the ICE automobile or in the power plant supplying recharge electricity. Points are shown in Fig. 173 for both 2- and 4-passenger electric cars; even the 4-passenger cars promise to remain as economical as the rapidly-improving baseline ICE car. In fairness, however, it must be noted that the baseline ICE car will provide more performance and accomodations than the 4-passenger electrics. In these respects the electrics are comparable to such subcompacts as today's Pinto--which is already more energy efficient than the 1980 electric counterpart is likely to be.

The energy baseline projection also investigated prospective availability of recharge power. Supply and demand were forecasted for peak days of future years, as illustrated for 1990 in Fig. 174. The shaded area of this chart shows capacity available, after reasonable allowances for maintenance, for overnight recharge of electric cars. By the year 2000, this available capacity will be adequate for electrification of all Los Angeles automobiles. It will generally be obtainable by activating oil-fired plants in the Los Angeles Air Basin, which will then be relegated to peaking service so that base loads may be met by cleaner, cheaper energy sources.

Baseline forecasts of NOx emissions in the Los Angeles region are shown in Fig. 175. Given emission controls now in prospect, they will drop significantly by 1990, while the automotive share drops even more dramatically. As Fig. 176 shows, automotive hydrocarbon emissions will similarly be reduced in future years to a very low relative and absolute level, as will CO emissions shown in Fig. 177. Even without electric cars, then, Los Angeles air quality is headed for a major improvement. Equally important, it will become relatively independent of future vehicular emissions. In this sort of future, electric cars can only produce relatively modest further improvement. A

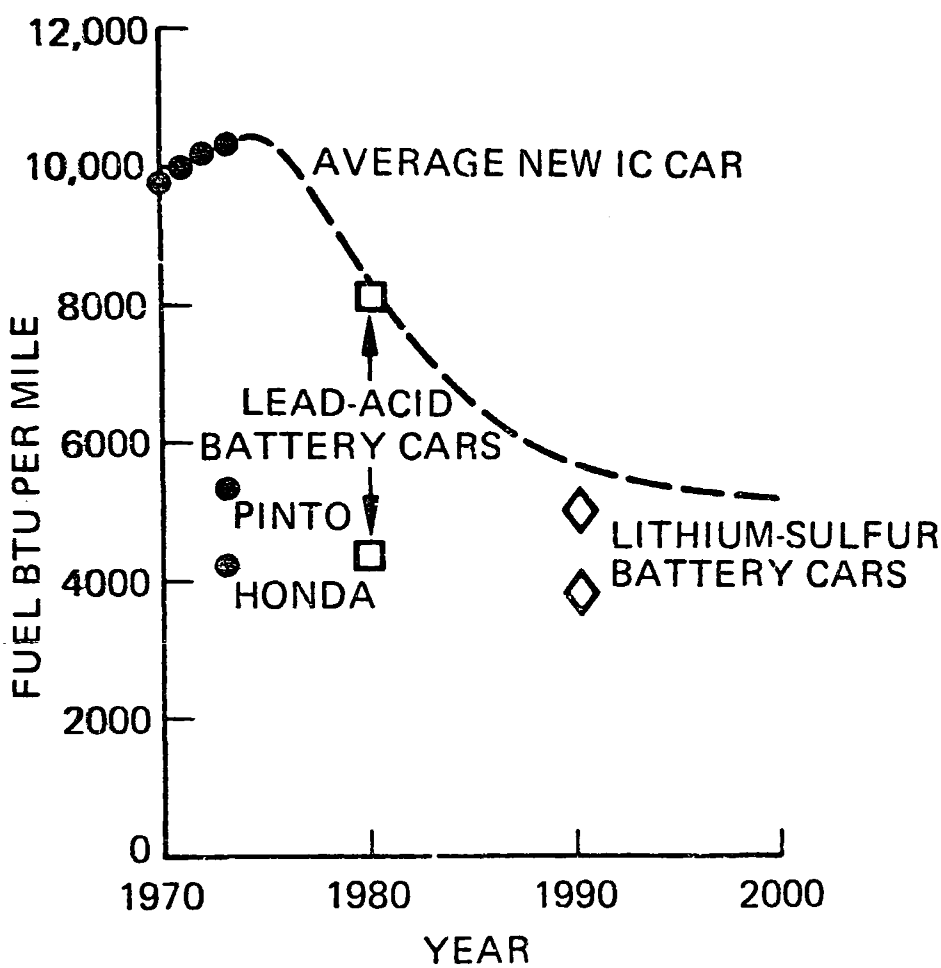


Fig. 173 Comparative Energy Consumption

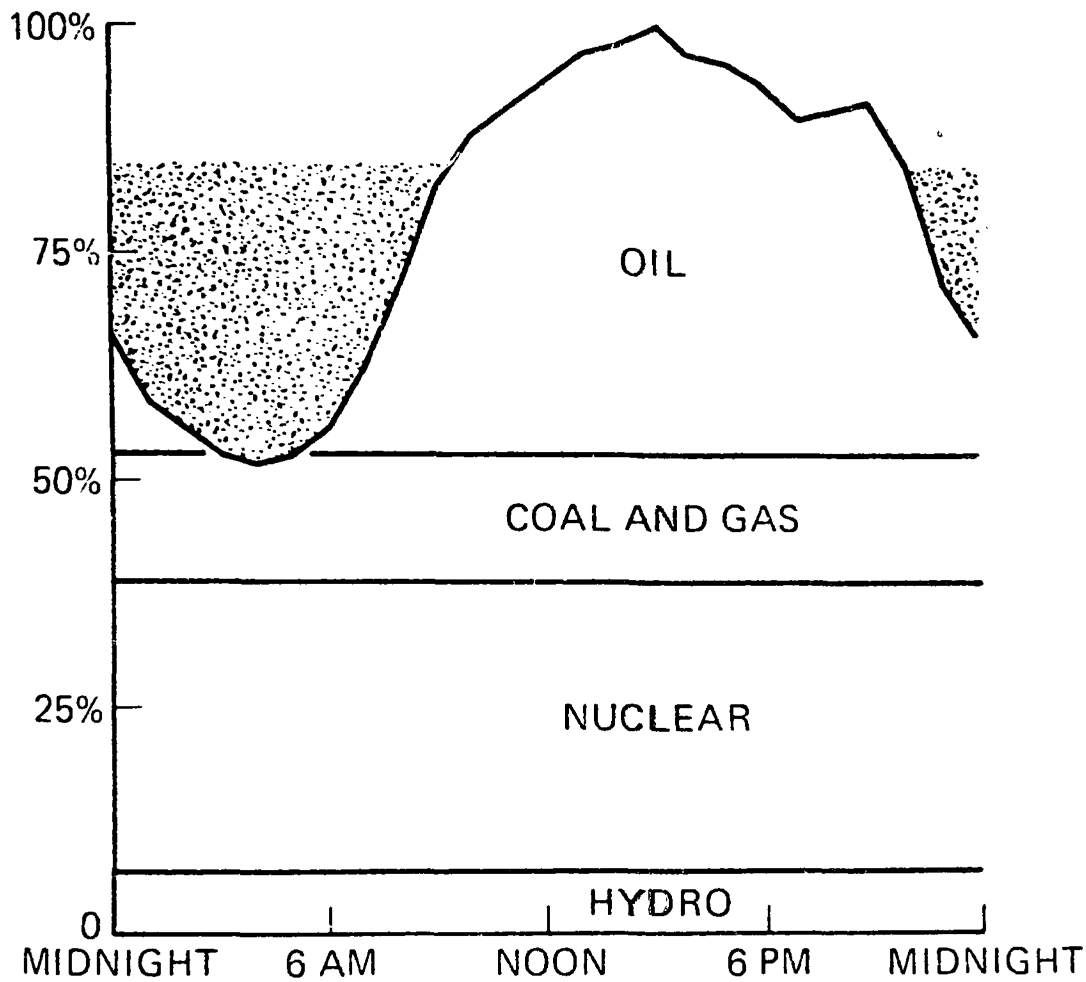


Fig. 174 Hourly Electricity Demand and Supply - Aug 1990

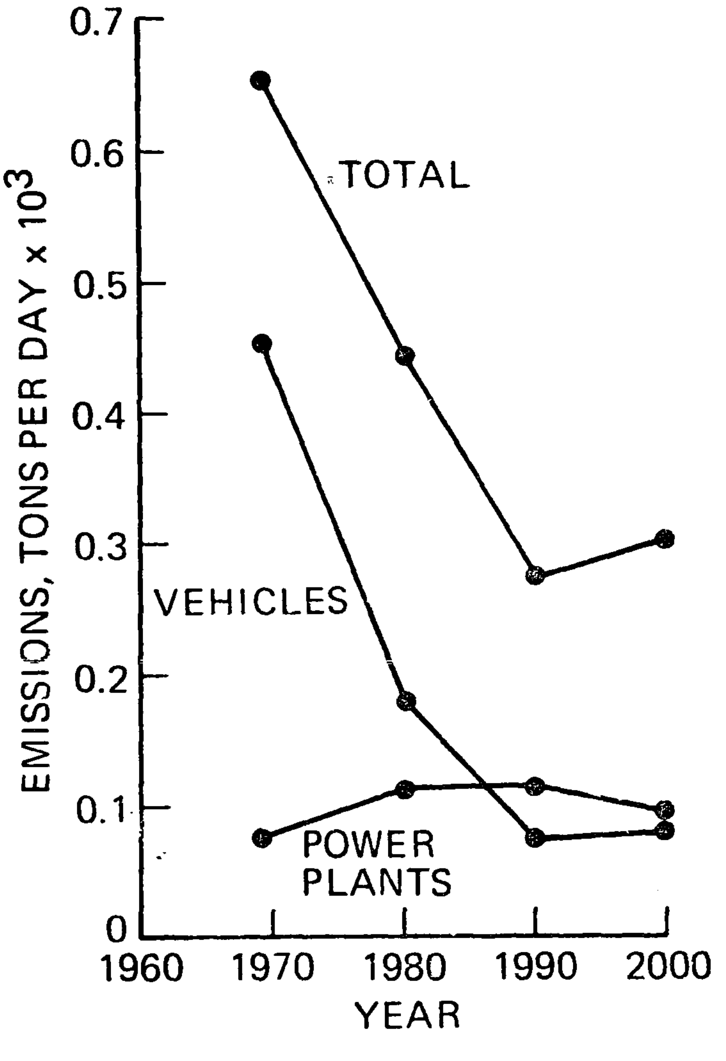


Fig. 175 Baseline Emissions: NO_x

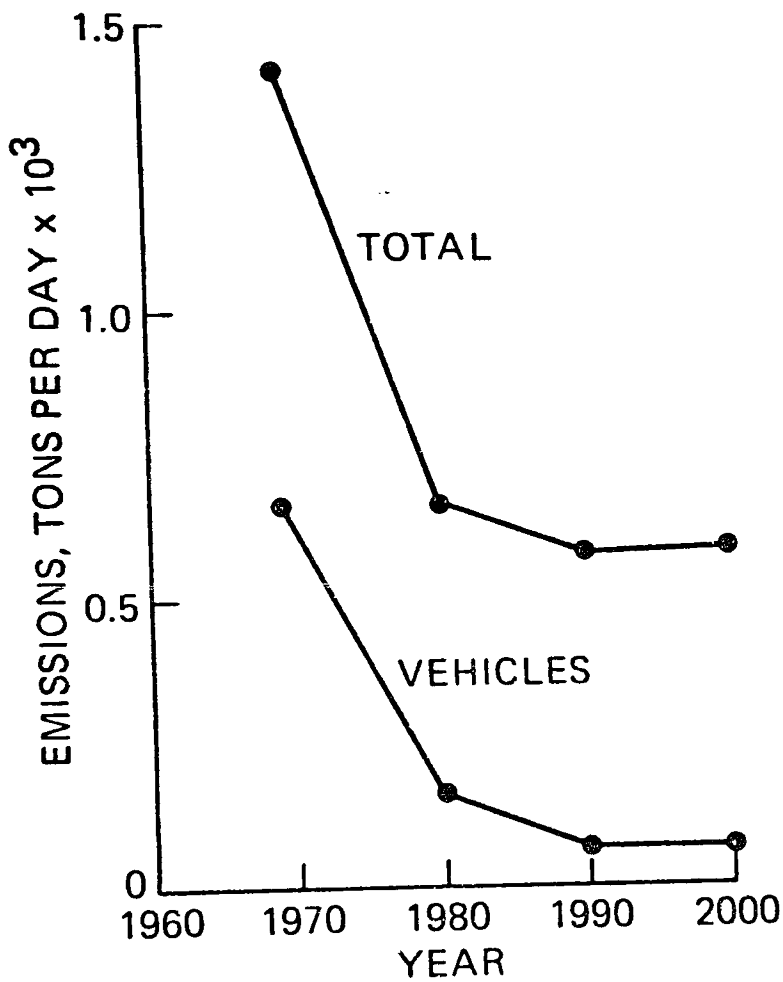


Fig. 176 Baseline Emissions: HC

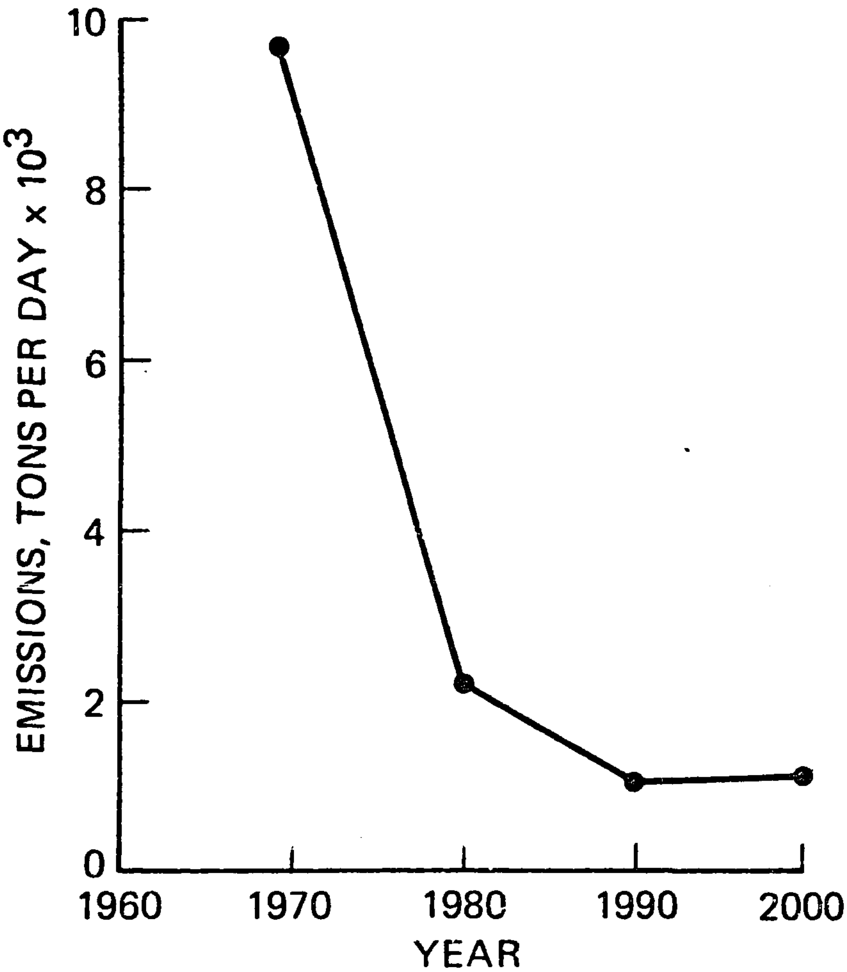


Fig. 177 Baseline Emissions: CO

detailed series of air pollution model runs has been completed for electric cars; its results, now being documented, are not easily summarized because they vary from one locale to another, depending on powerplant emission plumes.

Direct cost impacts of electric car use are illustrated in Fig. 178. Electric cars will be initially more expensive than their gasoline-fueled counterparts, but will last longer and will require less maintenance. Battery depreciation, however, leads to significantly higher total cost, at least until new battery technology appears. Figure 178 shows ranges of costs for 1990 ICE automobiles in 1973 dollars, with gasoline price ranging from 50-80¢ per gallon, and for expected average annual usage of 10,000 miles. Because their limited range qualifies them primarily for use as second cars, the lead-acid electric cars are likely to be driven only 6300 miles per year, at per-mile costs considerably higher than gasoline-fueled cars. The range of costs shown results from the range of uncertainty in cycle life of future batteries.

Until advanced batteries arrive, the extra cost of electric car operation will be among the more important economic impacts. There will also be a significant shift in regional economic activity. Substantial economic activity in the South Coast Air Basin will be affected by a shift from gasoline to electric automobiles. Where activity expands, or simply shifts to another kind of merchandizing, the impact is beneficial or moderate; but in gasoline sales, which electric cars will simply eliminate, significant adverse impacts arise. Jobs thus eliminated are particularly sensitive because they require few skills and are thus among the already limited prospects for disadvantaged groups.

Even when restricted to second-car use, and to single-family dwellings with off-street parking so that overnight recharge is easily arranged, a million Los Angeles automobiles could be electric in 1980, with much larger numbers in 1990 and 2000 when high-performance batteries make daily range adequate for first-car use in most households.

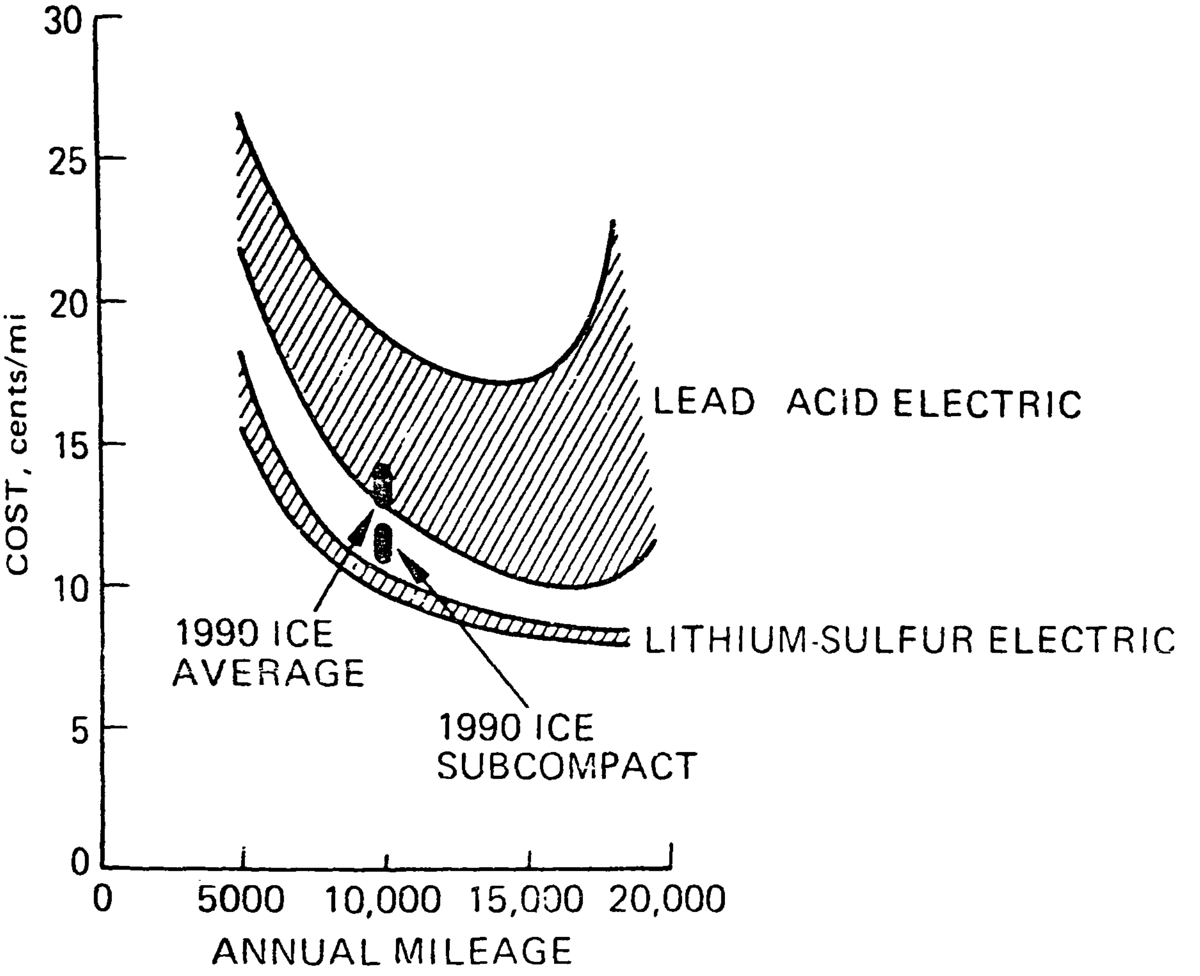


Fig. 178 Comparative Car Costs

The estimated number of electric cars likely to be saleable in Los Angeles under current market conditions is shown as the lower curve in Fig. 179. "High" or "medium" use curves in this chart presume public policies and actions encouraging electric car use and/or discouraging gasoline-fueled car use. Gasoline, for example, might be taxed sufficiently to eliminate the cost disadvantages of the electric cars, or a purchase tax on ICE cars might be imposed to achieve the same overall result. Elimination of the cost disadvantage for the lead-acid battery cars would require a gasoline tax of at least $1.70 per gallon or a purchase tax of $2400, even given the lower cost associated with the most optimistic battery cycle life. The impact of any such taxes obviously becomes a major consideration in the overall cost and benefit assessment for electric cars.

The impact study has recently been expanded to include several intermediate performance batteries. Once parametric impacts have been developed for cars using these batteries, overall cost-benefit ledgers and assessments of the most desirable level of electric car use will be completed. The project is now to be concluded in October.

Questions and Comments

Question: Referring to Fig. 174, the oil fired peaking power is usually the most expensive and least efficient power generated. Is this the electricity which is contemplated for recharging the electric car batteries?

Answer: It is assumed that ways will be found to get new, more efficient power plants on-line. But there are major conflicts in the Los Angeles area between power companies and the environmentalists. Agencies require 10 and 20 year forecasts from the utilities; if new plants are not permitted, then shortages and compromises can be expected.

Question (J. Appeldoorn, Esso Research): In Fig. 173, is this on-board BTU/mi? If not, the battery powered car consumption should be multiplied by 2½ to take into account the efficiency of the power plant and if peaking power is used, the factor should be 5.

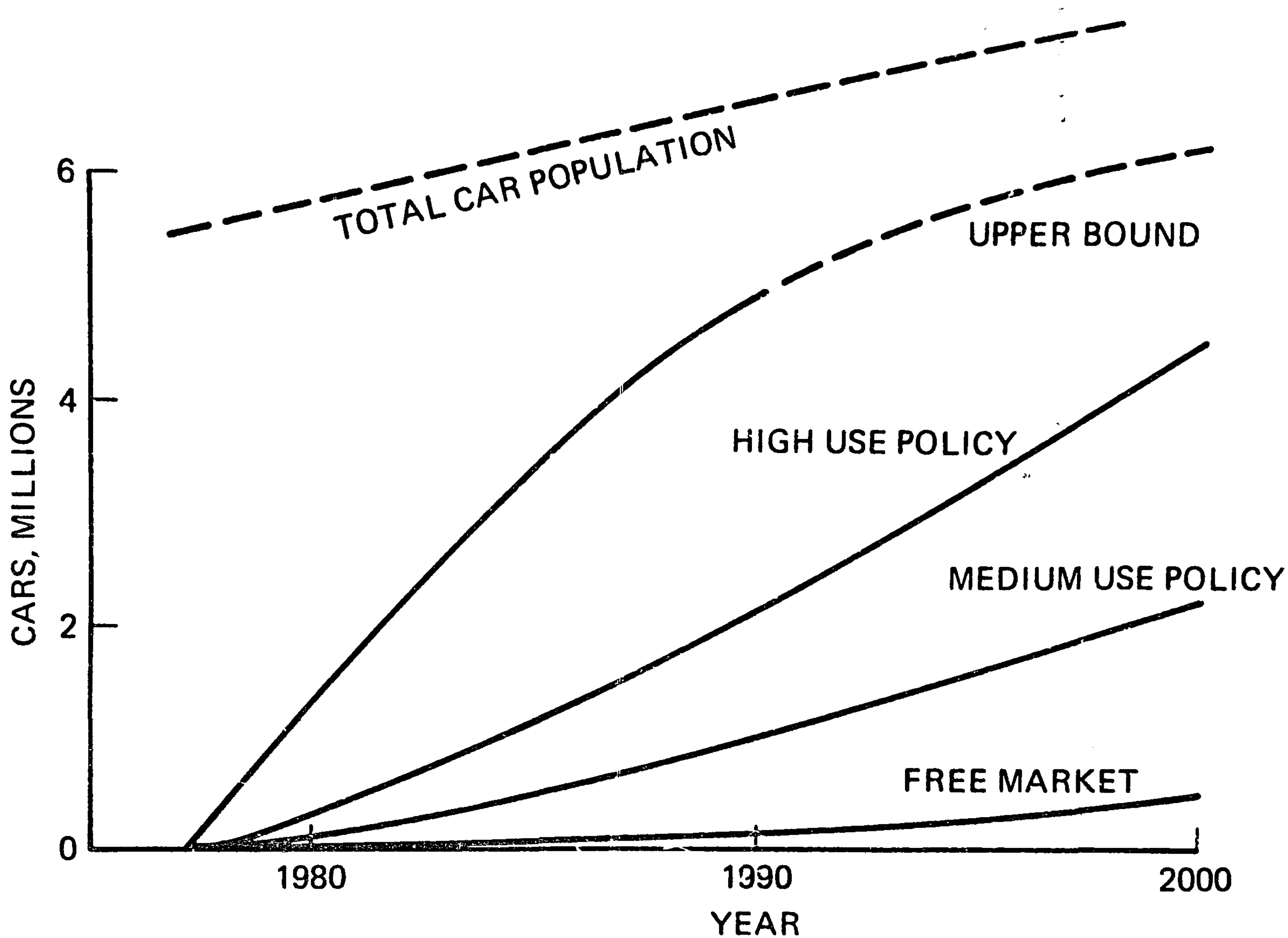


Fig. 179 Electric Car Population Projections

Answer: The BTU's plotted are the BTU's in the fuel burned at the power plant. Power plant and electric power distribution efficiencies are taken into consideration. Projections are for more efficient plants and not the jet engine-type peaking plants which are less efficient.

Comment (Dr. A. R. Landgrebe, AEC): It was pointed out that the August load curve (Ref. Fig. 173) is the worst month of the year for Los Angeles; more base load power would be available at other times of the year. It is believed that the advanced batteries will be available by the early 1980's; not 1990's. An AEC study shows that an electric car with energy from a reactor would be twice as efficient as a car driven with synthetic fuels.

Comment (Art Underwood, Consultant): Personal experience with golf carts has shown that practical maintenance on current electric vehicles is about three times that of a Cadillac from the consumer's viewpoint. The nuisance of inspecting and watering numerous cells and failure of relays were mentioned.

Answer: More advanced electric vehicles will avoid relay reliability problems with solid state control elements. A number of new developments like sealed lead-acid batteries should avoid or minimize watering inconvenience.

Comment (Dr. J. Salihi, Otis Elevator Company): The market for golf carts is continuiug to grow.

Question (S. Snyder, Ford Motor Company): The study is evolving to the practical and economic factors necessary to reach conclusions. One of the key questions is what is the cost of ownership of an electric vehicle on a fully comparable basis? If an electric vehicle is slightly more expensive, what is the packageability and performance? The American customer is extremely sensitive to these two factors. The electric car is heavy and less roomy due to space used by batteries.

Answer: Although difficult to predict, it is expected that the electric vehicle will indeed be significantly more expensive to operate (more than 10%). With the VW equaling sales of the Pinto at half the horsepower per ton and performance about equal to that of the electric, it is hard to say performance rules out the electric. Also recent surveys of customers are showing increasing concern for fuel economy and reliability and other factors. These are easier for the electric to achieve.

Question (Carl Thomas, Institute for Energy Analysis): Are you or any group you are aware of looking at a hybrid-flywheel battery system with regenerative braking capability?

Answer: This is not being actively considered by EPA at this time, but there is the possibility of re-considering such systems in FY 1975.

Question (Cmdr. E. Tyrrel, Dept of Trade and Industry, England): What about the availability and price of such materials as lead, lithium, and sulfur? Has this been taken into consideration?

Answer: These and other materials have been investigated on the economic-availability basis. Because this study only concerns Los Angeles at present, the quantities for that area are not significant on a national basis. However, the national implications will be covered in more depth in the final report.

Question: There is considerable question about the applicability of the car usage survey data from the Los Angeles transportation survey. Selected sampling of a few individuals indicates that quite often the second car in a family is used for long trips as well as the first car. Also, it is often used simultaneously for long trips by other members of the family.

Answer: All of the potentially useful data from the Los Angeles transportation survey was not dug out. The time and money for further effort on this data were not available. Its shortcomings and limitations are recognized.

Question (M. Laurente, Department of Transportation): What is the cause for increasing cost of the lead-acid batteries (Fig. 178)?

Answer: Life estimates for lead-acid batteries vary by a factor of 3:1. Annual replacement of the battery was assumed. A replacement might cost as much as $1000. More reliable data on life cycle costs are needed for this application. Even less is known about lithium-sulfur batteries.

Question (Petro-Electric): Can you say anything about Petro-Electric hybrid engine now on test?

Answer: Petro-Electric has a vehicle under test at EPA. It is a hybrid heat engine (Wankel) - lead-acid battery, d c motor driven vehicle. No other information is presently available.

I. New EPA Highway Fuel Economy Test Cycle, by C. D. Paulsell, EPA, Emission Control Technology Division, Procedures Development Branch

The EPA has for several years recognized that the light duty vehicle emission certification procedure provides reliable, reproducible information which can be utilized for calculation of vehicle fuel economy*. The certification test procedure incorporates a chassis dynamometer that exercises the test vehicle to simulate the power required of the vehicle during an urban drive in a major metropolitan area**. The carbon mass emissions from these tests can be used to calculate the average urban fuel economy; this calculation equally applies to all the vehicle types tested during the certification process and permits the effect of vehicle design parameters on urban fuel economy to be assessed. Publication of these urban fuel economy data for all classes of vehicles provides the consumer with one piece of information he can include as a criterion for determining the suitability of any given vehicle for filling his needs. The fact that more than half of the total vehicle miles accumulated are traveled in urban areas reflects the importance of knowing urban fuel economy.

The average vehicle owner tends to ignore urban ("aroung town") fuel economy because it is usually less than highway fuel economy and because highway fuel economy is more conveniently measured. Thus, the typical vehicle owner has conditioned himself to expect fuel economy data to refer to highway type

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* A Report on Automotive Fuel Economy, U.S. Environmental Protection Agency, Office of Air and Water Programs, Mobile Source Air Pollution Control, October 1973.

** Development of the Federal Urban Driving Schedule, Society of Automotive Engineers, Paper No. 730553.

operations and the publication of urban fuel economy data does not provide the information relative to his personal experience. Highway travel accounts for more than 40% of the total vehicle miles traveled making highway fuel economy a useful and valid criterion for judging vehicle performance. An appropriate dynamometer vehicle exercise which simulates typical highway operation could also be employed to measure highway fuel economy data. Publication of both equally valid fuel economy rates would be useful information for many individuals.

Thus, the purpose of this program was to measure road speed versus time profiles of vehicle operation on all types of highways and non-urban roads and to reduce these profiles to characteristic parameters which could be used to develop a composite driving cycle. This driving cycle could then be used to measure vehicle fuel economy under typical highway operation as simulated on a chassis dynamometer.

Through a very careful procedure of taking and analyzing road test data with several vehicles (described in detail in Appendix C) a composite Highway Driving Cycle was developed as shown both graphically in Fig. 180 and in tabular form in Fig. 181.

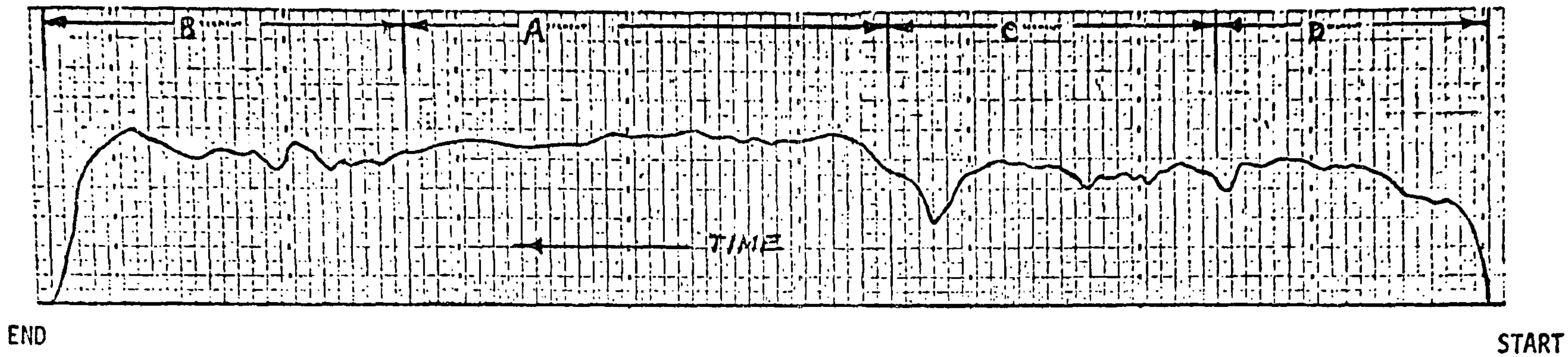

Fig. 180 Composite Highway Driving Trace

Segment Lenght (IN)		Segment	Average Speed (MPH)		Distance Traveled (Miles)		Elapsed Time (MIN)	Elapsed Time (SEC)	% Total Miles	
	(0.13)	(Idle)		(0.0)		(0.0)		2		(0.0)
9.5	(9.60)	D	41.157	(40.736)	1.629	(1.629)	2.375	144	15.93	(15.91)
11.5	(11.53)	C	43.841	(43.835)	2.101	(2.107)	2.875	173	20.55	(20.57)
17.0	(17.00)	A	56.096	(56.110)	3.973	(3.974)	4.250	255	38.85	(38.80)
12.5	(12.60)	B	48.421	(48.230)	2.522	(2.532)	3.125	189	24.67	(24.72)
	(0.13)	(Idle)		(0.0)		(0.0)		2		(0.0)
50.5	(51.0)	Overall	48.595	(48.200)	10.225	(10.242)	12.625	765	100.0%	(100.0%)
Inches		Total	MPH		Miles		Minutes	Seconds (12.750)		

NOTE: Previous overall average speed did not include 4 second idle period.

Fig. 181 Characteristics of Composite Highway Driving Cycle*

* Values applicable to the amended version (Mon. April 22, 1974) are shown in parentheses.

APPENDIX A

ORIENTATION OF ALTERNATIVE AUTOMOTIVE POWER SYSTEMS DIVISION IN EPA ORGANIZATION

APPENDIX A

ORIENTATION OF ALTERNATIVE AUTOMOTIVE POWER SYSTEMS DIVISION IN EPA ORGANIZATION

The EPA organization has five Assistant Administrators reporting to the Administrator, Russell Train: (1) Planning and Management, (2) Enforcement, (3) Water and Hazardous Materials, (4) Research and Development, and (5) Air and Waste Management. AAPS reports through Roger Strelow, Assistant Administrator for Air and Waste Management. Air and Waste Management, in turn, is comprised of five (5) offices as shown in Fig. A-1.

AAPS Division is part of the Office of Mobile Source Air Pollution Control under Deputy Assistant Administrator, Eric Stork, in Washington, D.C. Mr. Stork has four major functions, all located in Ann Arbor, Michigan. As shown in Fig. A-2 the AAPS Division is one of these functions.

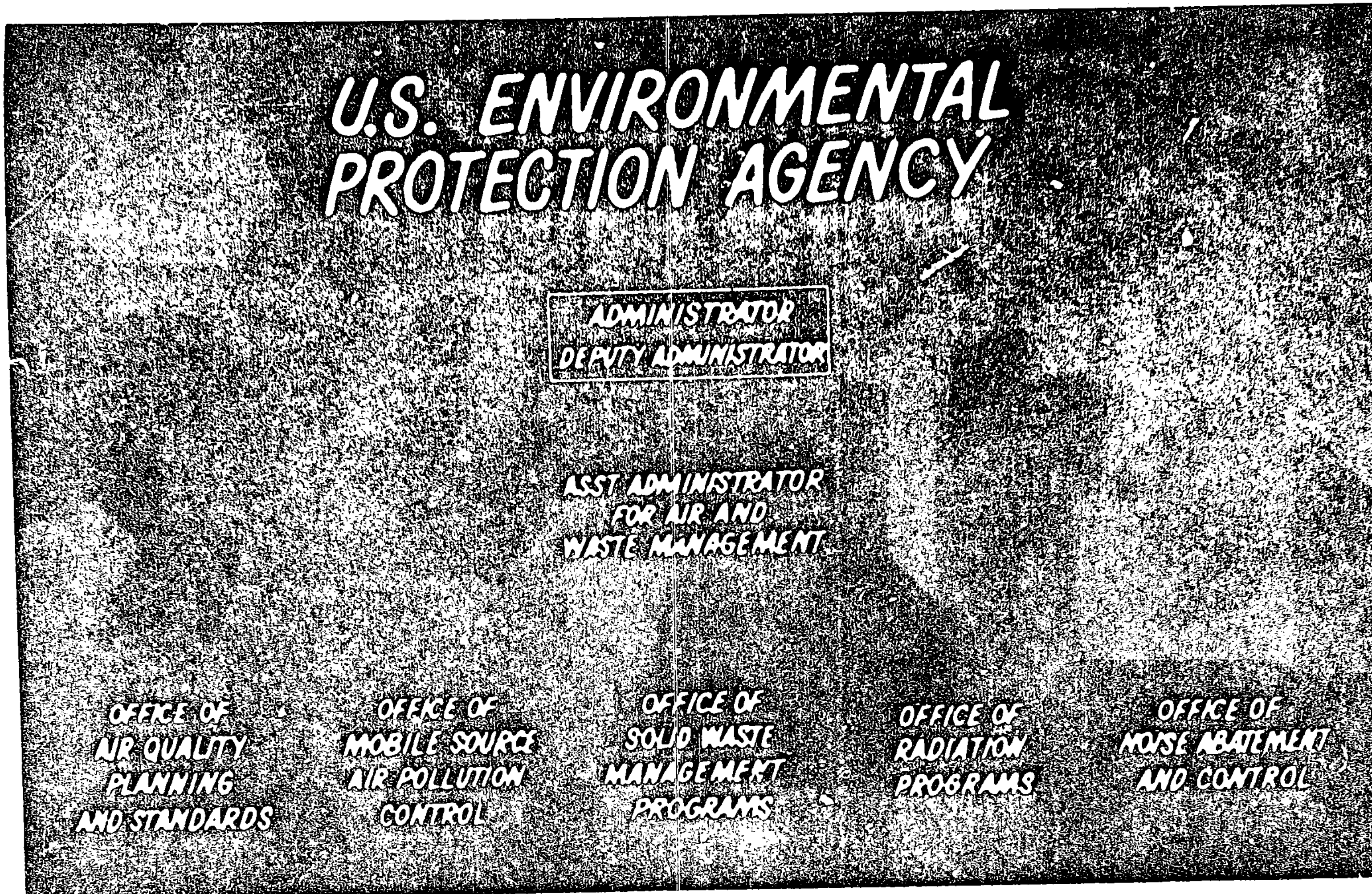
U.S. ENVIRONMENTAL PROTECTION AGENCY
ADMINISTRATOR
DEPUTY ADMINISTRATOR
ASST ADMINISTRATOR FOR AIR AND WASTE MANAGEMENT
OFFICE OF AIR QUALITY PLANNING AND STANDARDS
OFFICE OF MOBILE SOURCE AIR POLLUTION CONTROL
OFFICE OF SOLID WASTE MANAGEMENT PROGRAMS
OFFICE OF RADIATION PROGRAMS
OFFICE OF NOISE ABATEMENT AND CONTROL

Figure A-1

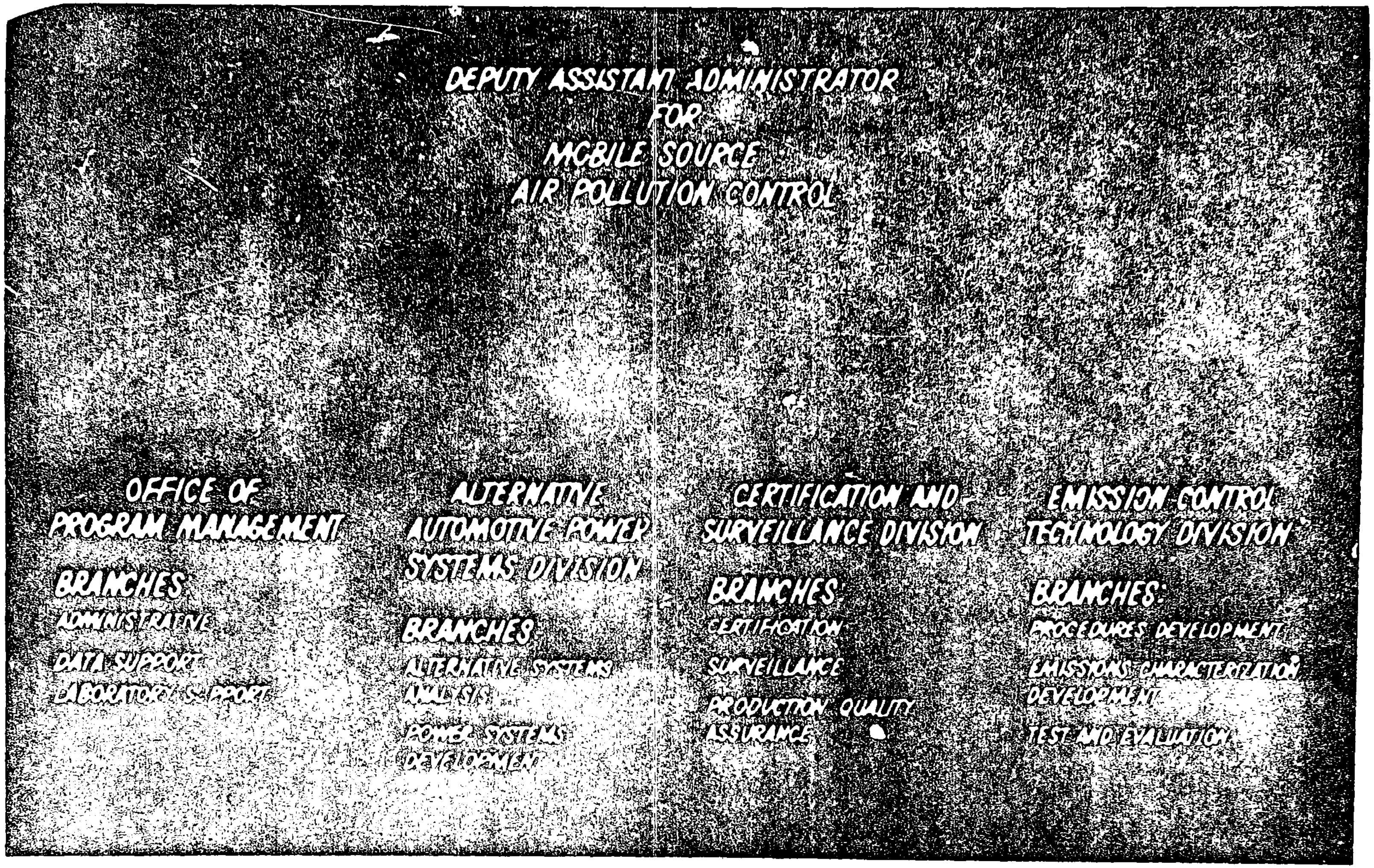
DEPUTY ASSISTANT ADMINISTRATOR
FOR
MOBILE SOURCE
AIR POLLUTION CONTROL
OFFICE OF
PROGRAM MANAGEMENT
BRANCHES:
ADMINISTRATIVE
DATA SUPPORT
ALTERNATIVE
AUTOMOTIVE POWER
SYSTEMS DIVISION
BRANCHES:
ALTERNATIVE SYSTEMS
ANALYSIS
POWER SYSTEMS
DEVELOPMENT
CERTIFICATION AND
SURVEILLANCE DIVISION
BRANCHES:
CERTIFICATION
SURVEILLANCE
PRODUCTION QUALITY
ASSURANCE
EMISSION CONTROL
TECHNOLOGY DIVISION
BRANCHES:
PROCEDURES DEVELOPMENT
EMISSIONS CHARACTERIZATION
DEVELOPMENT
TEST AND EVALUATION

Figure A-2

APPENDIX B

LIST OF ATTENDEES AND REPRESENTATIVES

APPENDIX B

LIST OF ATTENDEES AND REPRESENTATIVES

Consultants

Altman, Peter	Mills, Ken D.
Bachle, Carl	Percival, Worth
Dickerson, Dorman	Roensch, Max M.
Gay, Errol J.	Siegan, Bruce
Harmon, Robert	Underwood, Art
Huber, Paul	Way, Gilbert

U. S. Government Agencies

ARMY MATERIALS & MECHANICS RESEARCH CENTER	Lenoe, E. M. Messier, Donald
ARMY MOBILITY EQUIPMENT R&D CENTER	Belt, Richard
ARMY TANK AUTOMOTIVE COMMAND	Checklich, George Engle, Gene Jessel, Alfred Machala, Paul Petrick, Dr. Ernest Raggio, David G. Rambie, Edward Santo, H. Scully, Andrew Tripp, David Whitcomb, William Woodward, Robert
ATOMIC ENERGY COMMISSION	Landgrebe, Dr. Albert R. Stewart, Walter
BROOKHAVEN NATIONAL LAB	Hoffman, Ken Reilly, J. J. Waide, Charles
BUREAU OF MINES	Hurn, R. W.
DEPARTMENT OF THE ENVIRONMENT - CANADA	Reid, R.
DEPARTMENT OF TRADE & INDUSTRY - ENGLAND	Tyrrel, Commander E.

DEPARTMENT OF TRANSPORTATION - WASHINGTON, D.C.	Compton, Roger Fay, David Hirsh, Dan Husted, Robert Laurente, Michael Miller, Harold Raithel, Wilhelm
ENVIRONMENTAL PROTECTION AGENCY	Johnson, James Kittredge, George McSarley, J. A. Tate, Bill
ENVIRONMENTAL PROTECTION AGENCY - ANN ARBOR	Barber, Kenneth Brogan, John Cain, William Ecklund, Gene Hagey, Graham Hopkins, Howard Hutchins, Peter Kaykaty, Gabriel Kenney, Dyer Kramer, Saunders B. Luchter, Stephen Mirsky, William Murrell, Dill Naser, Howard Paulsell, Don Schulz, Robert Sebestyen, Tom Sutton, Pat Szczepaniack, Ed Thur, George
FEDERAL ENERGY OFFICE - WASHINGTON, D.C.	Thomson, Dr. Robb
GENERAL SERVICES ADMINISTRATION	Ullrich, Robert
INSTITUE DE RECHERCHE DES TRANSPORTS, FRANCE	Pierre, Dreyer
INSTITUTE FOR DEFENSE ANALYSIS	Hamilton, Robert C. Riddiel, F. R.
JET PROPULSION LAB	Barber, Thomas Breshears, R. Laumann, G. Meisenholder, G. W. Moore, Nick Phen, Robert Raymond, R. Riebling, Robert Spiegel, Joe Stephenson, R. Rhoads

LOS ALAMOS SCIENTIFIC LABORATORY	Stewart, Walter
NAVAL ENGINEERING CENTER	Byrnes, William F.
NASA, HEADQUARTERS	Johnson, Paul Van Landingham, Earl E.
NASA, LEWIS RESEARCH CENTER	Butze, Fritz Heller, Jack Packe, Dan Stone, Phil Wong, Robert Wood, James
SANDIA LABORATORIES	Blackwell, Arlyn, N. Hartley, Danny Jones, M. O.
UNITED STATES POSTAL SERVICE	Gerlach, Lewis

Press

AUTOMOTIVE NEWS	Rowland, Roger
CHILTON BUSINESS PUBLICATIONS	Eshelman, Ralph
GAS TURBINE PUBLICATIONS	Farmer, Robert
MC GRAW-HILL PUBLISHERS	Hampton, William
PRODUCTION MAGAZINE	Hopkins, Charles
STEAM AUTOMOBILE CLUB	Lyon, Robert
UNITED PRESS INTERNATIONAL	Lechtzin, Edward
WALL STREET JOURNAL	Condacci, Greg

Industrial, Educational and Research Organizations

ADVANCED MATERIALS ENGINEERING LTD., ENGLAND	Egenolf, J. Hryniszak, Dr. W.
ADVANCED POWER SYSTEMS	Carpenter, Scott Wyle, Steve
AEROJET LIQUID ROCKET CO.	Jones, Roy Rudnicki, Mark
AEROSPACE CORPORATION	Lapedes, Don Meltzer, Dr. Joe
AIRESEARCH MFG. CO.	Castor, Jere Lewis, Leon
ALLIED CHEMICAL	Allen, Robert
AMERICAN AIRLINES	Porter, G. R.
AMERICAN HONDA	Amito, Eiji
AMERICAN MOTORS	Burke, Carl Green, Raymond Jones, W. Porter, G. R.
ARTHUR D. LITTLE INC.	Hurter, Donald
ATLANTIC RICHFIELD	Lease, C. A. Mrstik, A. V.
AUTOMOTIVE RESEARCH ASSOCIATES	Bungh, Howard M.
AVCO	Paulov[illegible], R.
BATTELLE MEMORIAL INSTITUTE	Hazard, Herb
BATTELLE PACIFIC NORTHWEST	Loscutoff, Walter
BENDIX CORPORATION	Datwyler, Walter Mayer, Endre McGlinn, E. J.
BORG WARNER CORPORATION	Hallberg, Irving Mercure, Robert
ROBERT BOSCH CORP.	Denneler, Kurt
WM. BROBECK AND ASSOC.	Brobeck, W. M. Younger, Francis

CALSPAN CORPORATION	Davis, James
CARNEGIE MELLON UNIVERSITY	Macken, Dr. Nelson Negeanu, M. Paul, Dr. Frank
JAY CARTER ENTERPRISES	Carter, Jay Jr. Kuykendall, Hugh
CATERPILLAR TRACTOR CO.	Billington, L. J. Kline, Jan C.
CELANESE CHEMICAL CO.	Baker, Norman
CHAMPION SPARK PLUG	Lentz, L. R.
CHANDLER EVANS	Riordan, Mike
CHEVRON RESEARCH	Guldrman, R. A.
CHRYSLER CORPORATION	Alexander, Bert Angell, Peter Ball, G. A. Callison, James C. Cogswell, Dewane Collister, Howard Dudash, Jim Franceschina, J. Golec, Thomas Gross, Jerome Hagen, F. A. Huebner, George Koontz, H. E. LeFevre, H. P. Lewakowski, J. J. Mann, L. B. Martin, F. McGuire, Larry McNulty, William Miklos, A. A. Nogle, Tom Otto, A. K. Pamperin, R. C. Power, W. Roy, A. Samples, Doran K. Schmidt Fred Scobel, Ken Sparks, N. W. Stecher, George Stempien, Bill Stoyack, Joseph Sumner, J. I. Valeri, Russ Wagner, Chuck Willson, P. J.

CLIMAX MOLYBDENEUM	Morrow, Hugh Spenseller, D. L.
CORNING GLASS WORKS	Lanning, John McBeath, C. Wardale, David
CUMMINS ENGINE CO.	Mather, K. J.
D CYCLE POWER SYSTEMS	Davoud, Dr. J. E.
DANA CORPORATION	Charlesworth, W.
JOHN DEERE	Stewart, Tom H.
DUPONT	Green, Karl F. Van Burskirk, O. R.
EATON CORP.	Chute, Richard Confair, Les Danis, L. J. Eltinge, Dr. L. Mueller, Bob Richardson, Robert Saeters, R. A.
ESCHER TECHNOLOGY	Escher, William Tison, Roy
ESSO RESEARCH	Appledoorn, John Furlong, L. E. Kant, F. Salvesfen, R. H.
ETHYL CORPORATION	Clark, Gill Sneed, Richard B. Zeitz, A. H. Jr.
EXCELLO	Weldy, R. K.
EXXON CHEMICAL	Pennekamp, E. F. H.
FEDERAL MOGUL	Castledine, W. Probst, Robert
FORD MOTOR COMPANY	Auiler, J. E. Bates, Bradford Blumberg, Paul Chapman, W. I. Daby, Eric Davis, D. A. Fisher, E. A. Fuciniari, C. A.

FORD MOTOR COMPANY (cont.)	Gratch, Serge Havsted, P. H. Howes, B. Laurance, Neal Macauley, William Marshall, A. E. Mason, F. J. McLean, A. Mumford, Jack Paluszny, A. Peitsch, G. Peters, Norman Philips, C. W. Rahnke, C. Rossi, L. R. Secord, John Snyder, S. F. Stadler, H. Stockton, Thomas R. Swatman, Ivan Wade, W.
FOSECO INC.	Hawthorne, P. Rice, Ron
FRANKLIN INSTITUTE	Rauch, Burton
GARRETT CORPORATION	Bartlett, Parker Flinn, Donald E. Miliacca, Lee
GENERAL ELECTRIC	Bond, Jim Dutram, Leonard Frank, R. G. Keister, J. E.
GENERAL MOTORS CORPORATION	Bly, K. B. Casey, Gary L. Colucci, Joseph M. Fleming, J. D. Stebar, R. F.
GENERAL MOTORS DETROIT DIESEL	Baugh, E. Mayo, George Sullivan, Robert
GENERAL MOTORS TECHNICAL CENTER	Agnew, W. G. Amann, Charles Bell, Albert H. Chana, Howard Collman, John Cornelius, Walter Dimick, David Feiten, James B.

GENERAL MOTORS TECHNICAL CENTER (cont.)	Frederickson, Hans Hammond, D. C. Hanley, George Hartman, Dr. J. L. Heffner, Earl Hietbrink, Earl Huellmantel, L. W. Kutchey, J. A. Malik, M. J. Mathews, Charles Mitchell, Harry Niepoth, George Nordenson, G. E. Skellenger, G. Stettler, R. Vickers, Paul Whorf, R. P.
GENERAL OPTIONICS	Blythe, Richard
GENERAL RESEARCH	Hamilton, William
GTE-SYLVANIA	Corcoran, Richard Kleiner, R.
HOLLY CARBURETOR	Brantman, Leon McCabe, Pat
HORST POWER SYSTEMS	Horst, Tom E. Kelly, George
HOWMET	Boyle, Jim Higgins, Mike
INSTITUTE FOR ENERGY ANALYSIS	Thomas, Carl O.
INSTITUTE OF GAS TECHNOLOGY	Fore, James G. Gillis, Jay Pangborn, Dr. John
INTERNATIONAL HARVESTER	Bech, N. G.
INTERNATIONAL NICKEL COMPANY	Billin, R. M. Tuffnell, Glenn W.
INTERNATIONAL RESEARCH & TECHNOLOGY	Jones, T.
ISUZU MOTORS	Tsukagawa, Satoru
KELSEY-HAYES	Adler, Irving Havel, C. J. Miles, Thomas E.

ROBERT KEYES & ASSOC.	Schweppe, Howard
KLOECKNER-HUMBOLDT-DEUTZ/GERMANY	Killmann, I. G.
LEYLAND MOTORS	Barnard, Mark
LOCKHEED	Lawson, Jim
LUBRIZOL CORPORATION	Fuchs, E. J. Scher, R. W. Sieloff, Frank
MASSACHUSETTS INSTITUTE OF TECHNOLOGY	Linden, Lawrence
MECHANICAL TECHNOLOGY INCORPORATED	Decker, Otto Raber, R. A. Sternlicht, Dr. Beno
MERCEDES BENZ	Diefenbacher, Eberhard
MINER MACHINE DEVELOPMENT CO.	Miner, S. S.
MITRE CORPORATION	Stone, John
MITSUBISHI MOTOR CO., JAPAN	Ishimaru, Y. Okazaki, Y. Saito, Y. Takaishi, Takeo Takebe, T.
MOBIL RESEARCH & DEVELOPMENT	Crosthwait, Richard E. Perry, R. H.
MONSANTO CORP.	Miller, Dr. David Winslow, Frank
MOTOROLA	Copeland, John Lace, Mel Mathey, Charles Ronci, Bill
R. D. MUELLER & ASSOC.	Parker, Andrew Shadis, William
NISSAN MOTOR CO.	Saito, T.
JOSEPH LUCAS NORTH AMERICA, INC.	Burgess, Anthony Mandell, John
NORTH AMERICAN PHILLIPS	Loeffler, Larry Lynch, Brian
NORTH AMERICAN ROCKWELL-ROCKETDYNE	Bremer, George Combs, Paul

NORTON COMPANY	Houck, E. W.
OAKLAND UNIVERSITY	Blythe, James
ONAN CORPORATION	Drury, E. A. Lehmann, W. J.
ORSHANSKY TRANSMISSION	Huntley, P.
OTIS ELEVATOR	Salihi, Dr. Jalel
OWENS-ILLINOIS	Brock, T. W. Gray, Marion Kormanyos, Ken R. Pei, Y. K. Woulbroun, J. M.
NOEL PENNY TURBINES	Noble, Dr. David Silverstone, Dr. C. E.
PHILIPS PETROLEUM CO.	Schirmer, Robert M.
RAY POTTER & ASSOCIATES	Potter, Ray
POWER DYNETICS	Wood, Homer
PRATT WHITNEY AIRCRAFT	Allen, Marvin Billman, Lou Wagner, W. Barry
QUEST D CYCLE POWER	Wildman, William
RICARDO CONSULTING ENGINEERS, ENGLAND	Palmer, Mike
ROHR CORP.	Edwards, Jack
ROLLS ROYCE MOTOR LTD.	Williams, T.
C. G. A. ROSEN	Harshum, James A.
SAAB SCANIA	Koch, Berhl Palm, Bengt
SCIENTIFIC ENERGY SYSTEMS, INC.	Blake, D. O. Demler, Roger Friedman, Tizhak Hoagland, Dr. Lawrence Syniuta, Walter Vernon, Jack
SHELL OIL COMPANY	Abbin, Joseph Jr. Burstain, I. G. Curtis, J. R. Hendrickson, C. H. Yatsko, Edward

SOLAR, DIVISION OF INTERNATIONAL HARVESTER	Duffy, T. E. White, David
SUN COAST RESEARCH	Loomis, W. Warren
SUN OIL COMPANY	Toulmin, H. A.
SUNDSTRAND AVIATION	Adam, A. Warren Niggemann, Richard
TECTONICS RESEARCH	Braun, A. T.
TELEDYNE CONTINENTAL MOTORS	Blackburne, E. Karaba, Al Marks, D.
TEXACO, INC.	Hopkins, Stephen
THERMO ELECTRON CORPORATION	Armstrong, Jack Doyle, Ed Patel, Parimal Witzel, Walter
THERMO MECHANICAL SYSTEMS	Yano, Robert
TOYO KOGYO LTD.	Yamate, Noriaki
TOYOTA MOTOR CO.	Kinoshita, Takahiko Nakamura, Kenya Takagi, Hidemasa
TRACOR INC.	Gres, M. E. Kraus, James
TRW	Richardson, Neal
ULTRA ELECTRONICS	Court, D. J. Dent, John
UNITED AIRCRAFT OF CANADA	Stoten, Mike
UNITED AIRCRAFT RESEARCH LAB	Greenwald, Larry
UNITED PRESS INTERNATIONAL	Lechtzin, Ed
UNITED STIRLING	Ortegren, Lars
UNITED TURBINE	Haggblad, H. Kronogard, S. O. Malmrup, Lars
UNIVERSITY OF CALIFORNIA	Sawyer, Prof. Robert

UNIVERSITY OF MICHIGAN	Anderson, Dr. R. W. Bolt, Prof. Jay Lady, Edward R. Nichols, Prof. J. Arthur Yang, Dr. Wen
UNIVERSITY OF RHODE ISLAND	Brown, Dr. G. A.
UNIVERSITY OF UTAH	Zenger, Jerry
UNIVERSITY OF WISCONSIN	Myers, Phil
VOLKSWAGON	Bucheim, Rolf Walzer, Dr. Peter
WALLIS MOTOR RES.	Wallis, Marvin E.
WAYNE STATE UNIVERSITY	Singh, Dr. T.
WESTINGHOUSE	Johnson, R. H.
WHITE MOTOR CO.	Simpson, F. O. M.
XAMAG, INC.	Bentele, Dr. Max

APPENDIX C

DEVELOPMENT OF THE EPA COMPOSITE HIGHWAY DRIVING CYCLE

APPENDIX C

DEVELOPMENT OF THE EPA COMPOSITE HIGHWAY DRIVING CYCLE

Highway Driving Characterization: The Department of Transportation segregates road systems into either of two categories on the basis of principal area characteristics. The two categories are urban and rural (highway), which are differentiated because of functional differences in land use, road networks, and travel characteristics*. DOT experience indicates that this differentiation in characteristics occurs in places of 5,000 population. Rural (highway) road networks are adequate if place populations are less than 5,000 and urban traffic networks are required if the place populations exceed 5,000. In order to characterize road types within either category the Department of Transportation has developed a "Functional Classification Concept" which classifies each highway, road, or street according to the principal service that it renders. This system of classification develops a hierarchy of route types. Lowest in the hierarchy are the local roads and streets, where trips begin and end. These trip ends are characterized by low speeds, unlimited access, and penetration of neighborhoods. At the top of the hierarchy are the arterials designed to accommodate high volumes of through traffic. Intermediate facilities or collectors accommodate the necessary transition from local roads and streets to arterials. Outside urban areas, the main road type classifications are:

A. Principal arterial system
   a. Interstate
   b. Other principal arterials
B. Minor arterial system
C. Collector
   a. Major collectors
   b. Minor collectors
D. Local system.

The development of rural systems classification starts at the top of the hierarchy and works down. First the principal and minor arterial systems are developed on a statewide basis. Then the collector and local classifications are developed on a more localized (county) basis.

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*Part II of the 1972 National Highway Needs Report, House Document No. 92-266

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On the basis of the above classification scheme, the percent of total highway vehicle miles traveled has been calculated for each road type:

TABLE C-1

Type of Highway	Percent of highway vehicle miles traveled
A. Principal arterials	39.5
B. Minor arterials	22.4
C. Collectors	23.9
D. Locals	14.2
	100 %

Highway operation represents between 40 and 50% of total vehicle miles traveled, a value which continually decreases as urbanization increases. These percentages are the basis for constructing a composite highway driving cycle to simulate all types of highway operation.

For this study, five routes incorporating each road type to be traveled during the characterization were selected by EPA personnel. Figure C-1 is a map of the general area. Figure C-2 illustrates a sample route which was designed to cover a variety of road types for equipment check out tests. On the first run of this route the data recording equipment functioned properly, but the vehicle experienced a fuel system failure. The test equipment was transferred to the stand-by vehicle and the replacement vehicle and equipment were checked out on the dynamometer. Since the equipment had functioned properly on the sample route and everything functioned well when checked on the dynamometer, the route shown on Fig. C-3 was run first. This is primarily a type B (minor arterial) route with 61% type B roads, 28% type A (major arterial) roads and 11% type C (collector) roads. The second route, Fig. C-4, is a type A route with 100% type A roads. Figure C-5 illustrates a type C route with 44% type C roads, 22% type D (local) roads, 17% type A roads and 17% type B roads. The fourth data collection run was a rerun of the sample route, Fig. C-2. This route consists of 47% type D roads, 43% type C roads and 10% of type A roads. The fifth route was run on a freeway in Ohio subject to 55 MPH speed limits, consists of 100% type A roads (Fig. C-6).

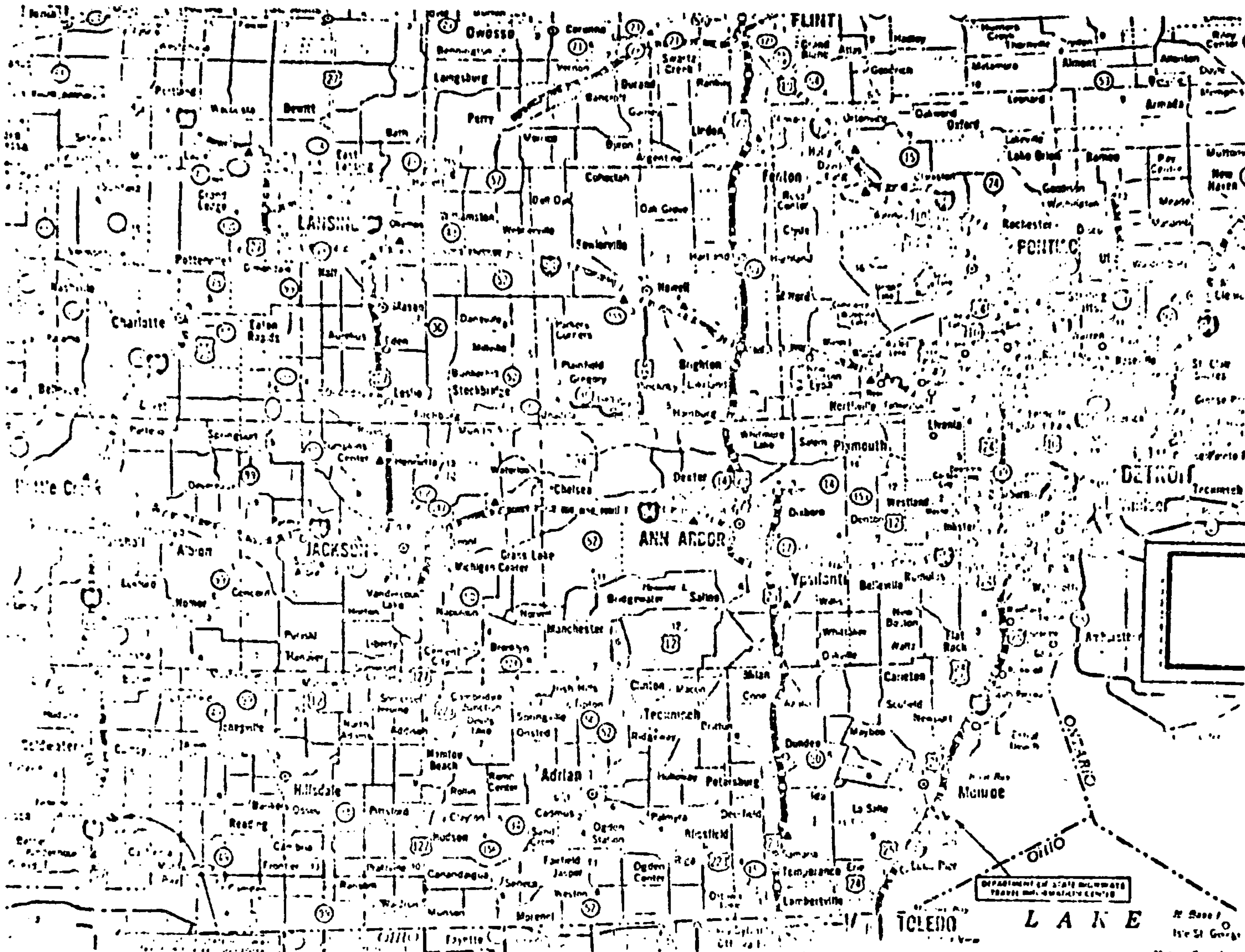

Fig. C-1 General Area Travelled

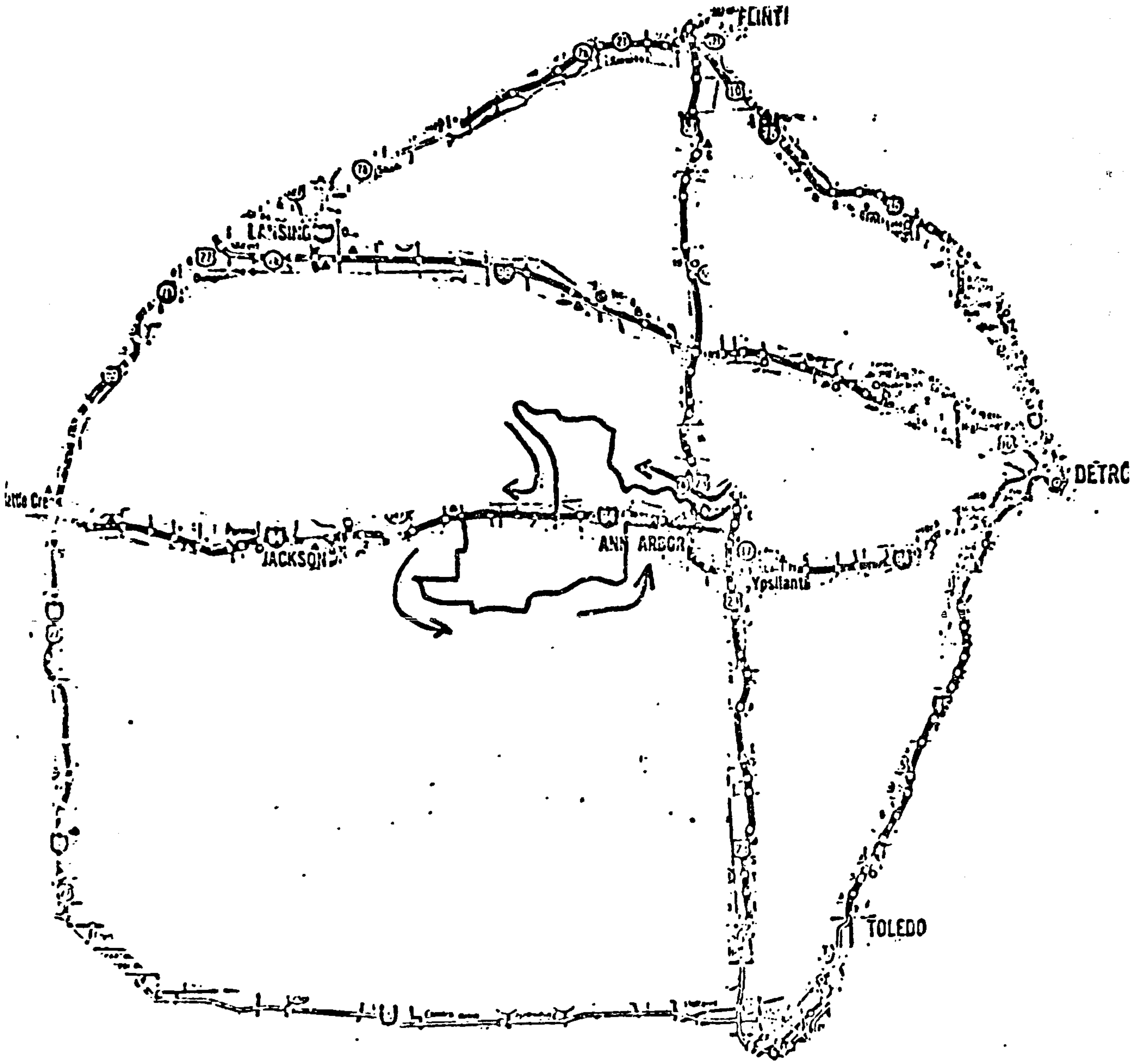

Fig. C-2 Sample Run "D" Route

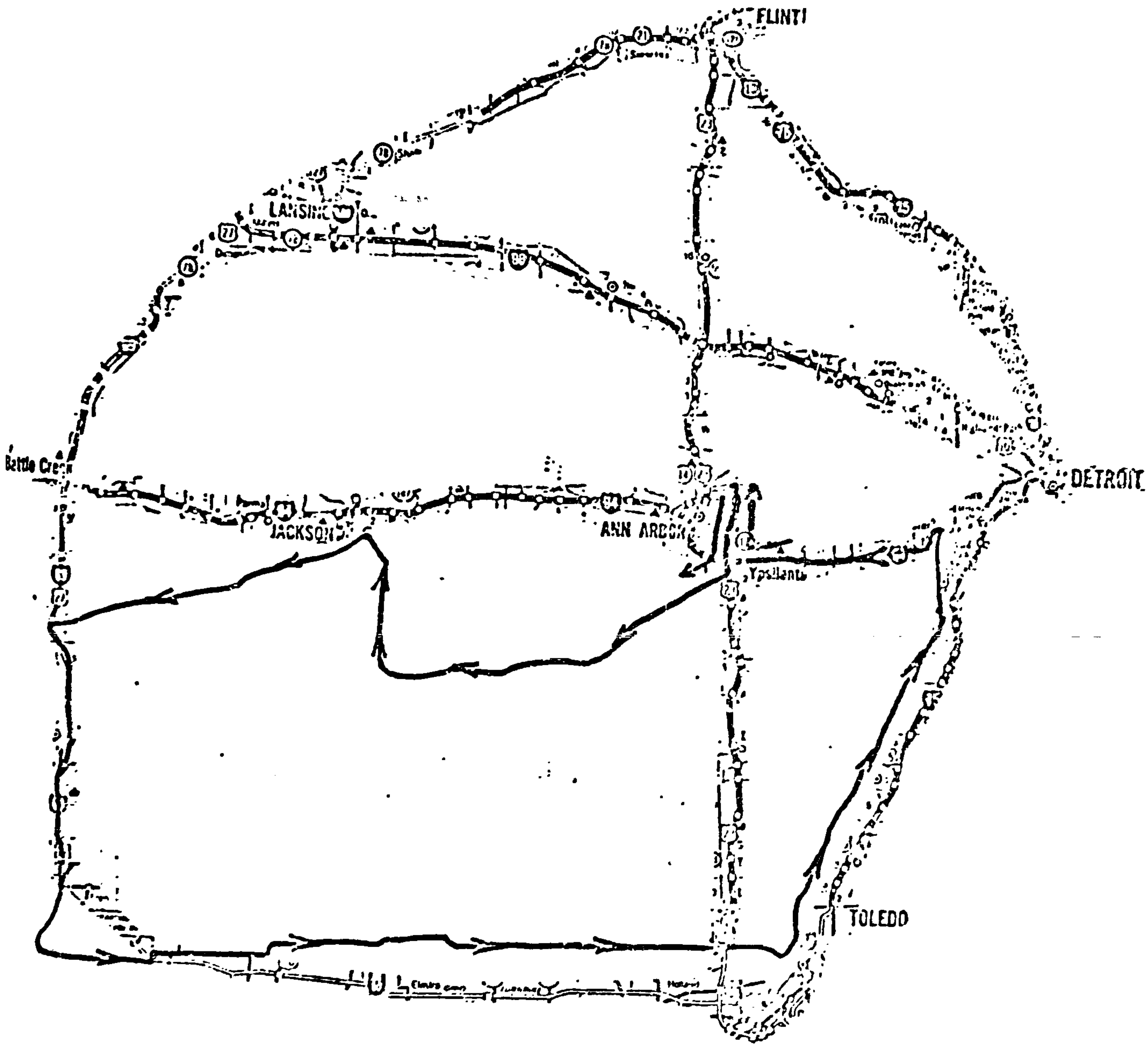

Fig. C-3 "B" Route

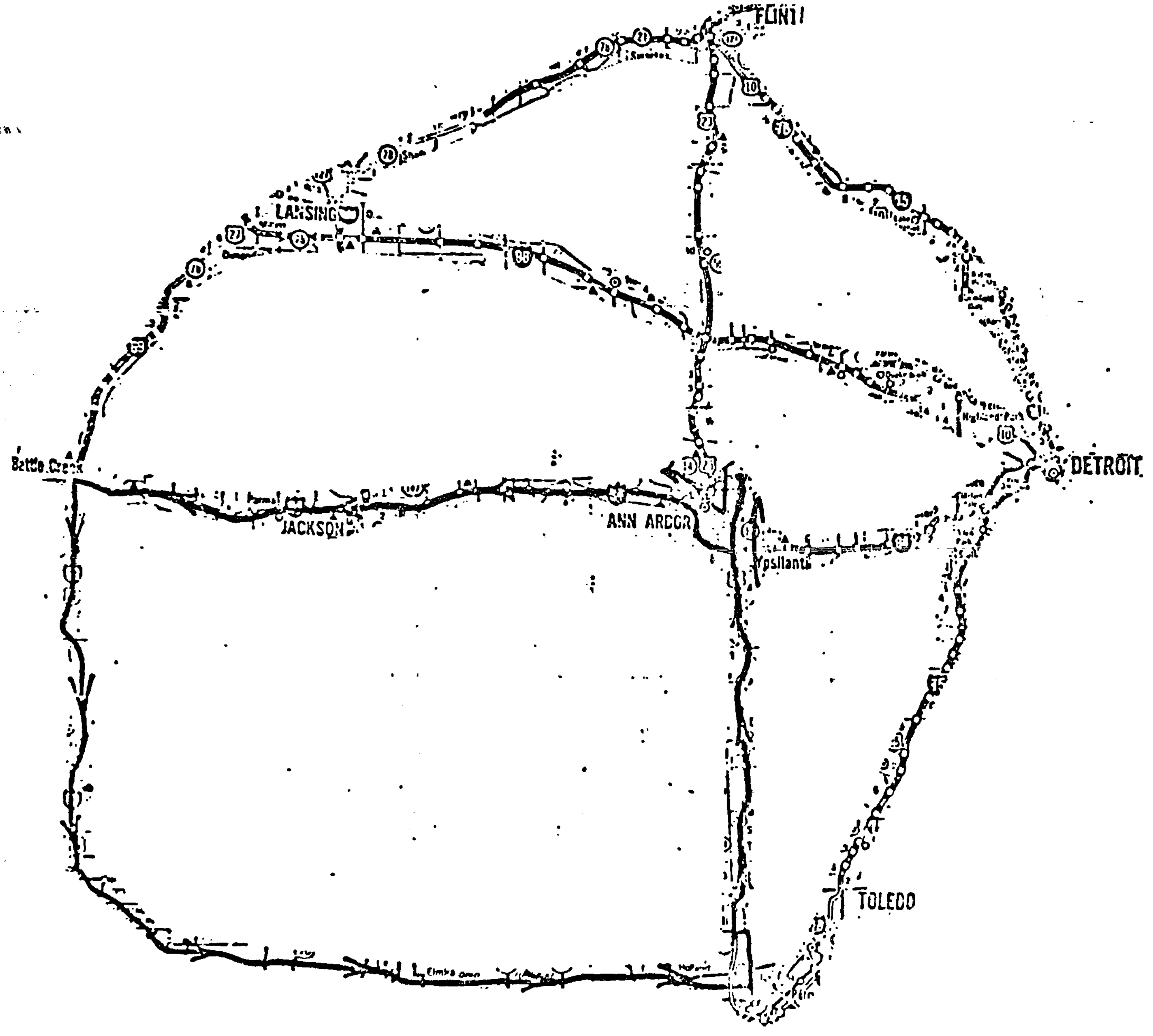

Fig. C-4 "A" Route

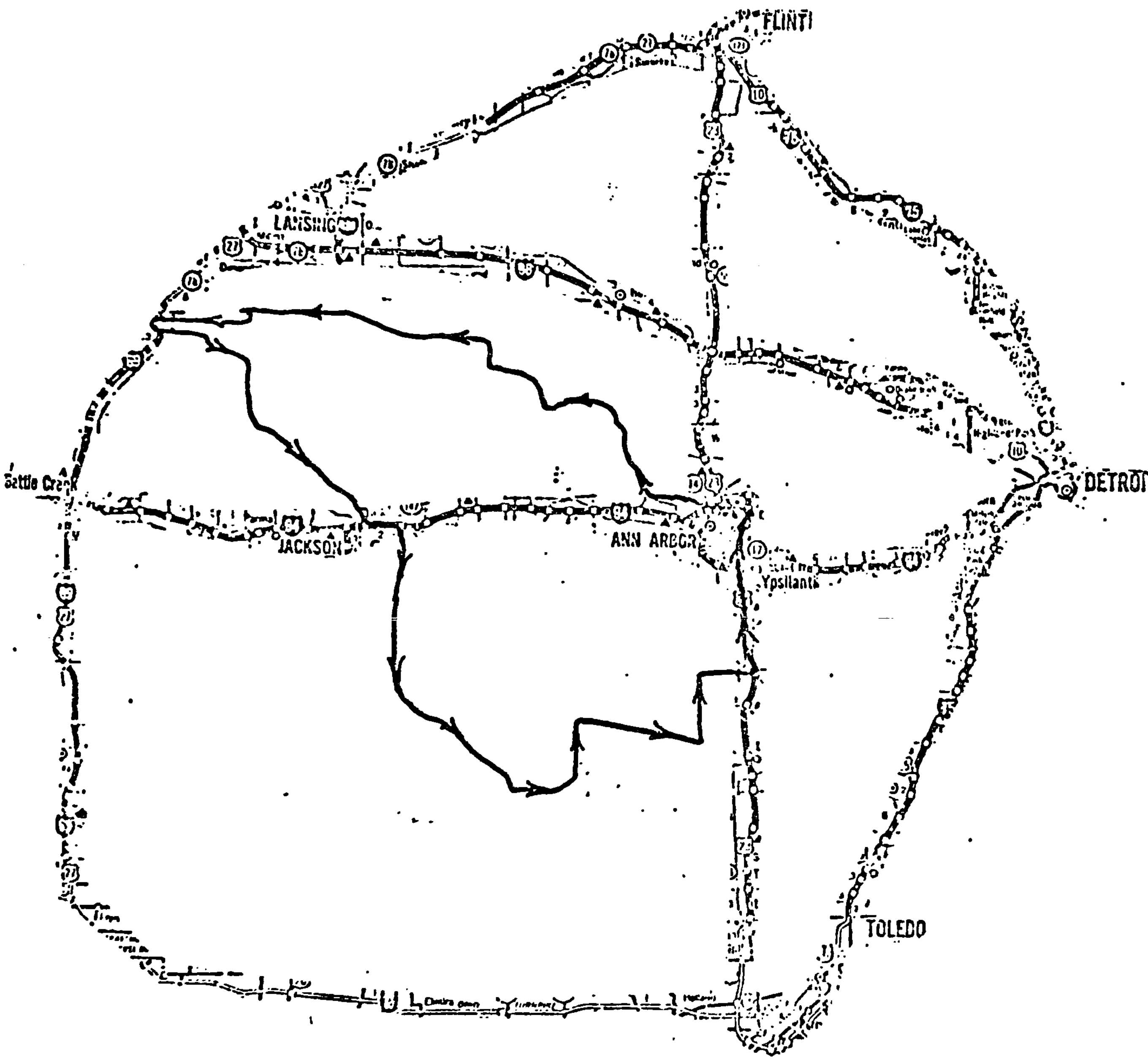

Fig. C-5 "C" Route

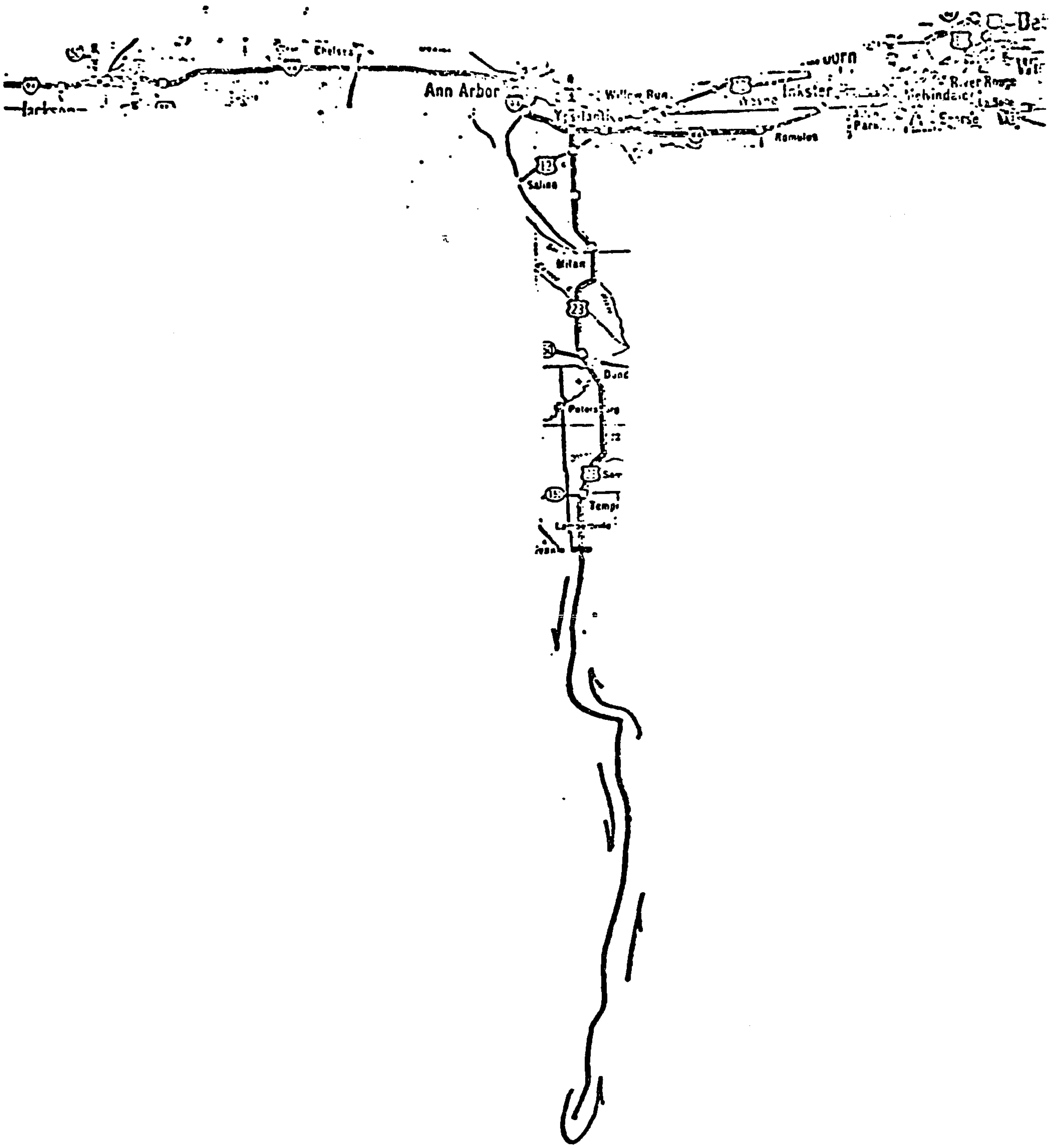

Fig. C-6 "A-55 MPH" Route

During this data collection process, 460 feet of chart were used, which at 4 inches of chart travel per minute represents about 23 hours of data, collected over a total distance of about 1050 miles. During all travel, an observer accompanied the driver to make notes about the trip and to log pertinent data.

Vehicle Instrumentation: The vehicle used to collect data in this program was a 1971 Ford Ranchwagon with a 429 CID-4V engine, 3 speed automatic transmission, and a 2.75 ratio rear axle. This vehicle had been previously instrumented for a study of vehicle operation and driving profiles. The instrumentation included a manifold vacuum transducer, digital timer (seconds), a driveshaft torquemeter, and driveshaft speed pickup. The signals from the driveshaft were scaled and recorded on a stripchart moving at a rate of 4 inches per minute to produce the same time base as the federal urban driving cycle. All of the instrumentation was calibrated and checked on a chassis dynamometer to verify true speed and torque readings. The vehicle contained a static inverter power supply to provide 120 volt, 60 cps electricity. This supply was used on all calibrations and testing.

The true road speed was checked against the vehicle speedometer to permit a quick calibration of the recorder on the road. A panel meter which indicated driveshaft speed also facilitated a third check on true speed and calibration stability. Calibration checks indicated good stability through the entire program.

The torquemeter had a shunt resistor which was used to calibrate the gain of the torquemeter. The torque readings were scaled to measure from -200 to +800 foot-pounds. Torque readings were used to assess the variation in throttle position for various velocity profiles. No problems were incurred with this measurement.

Data Verification and Analysis: For ease of analysis, the 460 feet of recorder chart gathered during this experiment were displayed on the walls of the office hallway at the EPA Ann Arbor laboratory. The charts were properly identified according to route number and were reviewed and verified by the route observers. There was one observer on each drive and three observers were used in the program. These observers reviewed their own traces and verified comments. They identified route segments according to type of road, A through D, determined which segments represented urban (population above 5,000) driving and deleted the urban segments. Data reduction consisted of tabulating route speeds at 15 second (1 inch) intervals to determine the maximum, minimum and average segment speeds. Total segment time, distance, number of stops, number of major speed deviations per mile for each segment were calculated. A speed deviation was defined as an excursion greater than + 5 mph from a line connecting end-point velocities on six inch intervals (1.5 min) of the entire segment.

These data were compiled from all of the charts for each road type and the average characteristics were determined for each road type. These data are presented in Table C-2.

Table C-2

Average Highway Characteristics

Road Type	Average Speed MPH	Stops/mile	Speed Deviations/ mile
A	57.16	0.0100	0.070
B	49.42	0.0575	0.439
C	45.80	0.1260	0.484
D	39.78	0.2360	0.598
Composite	49.43*	0.08	0.327

$$\text{*Composite Speed} = \frac{1}{(.395/A + .224/B + .239/C + .142/D}$$

(Also, see footnote on Page C-1.)

After these road type characteristics and the composite highway trip characteristics had been determined, a driving cycle selection committee was designated. This committee was composed of the three observers and three other EPA staff engineers. The committee reviewed the data, decided that a nominal 10 mile highway route would be optimum for laboratory testing and agreed on a method for obtaining the route. The committee split into three groups of 2 persons each, one observer and one other engineer. Each group was to select and combine the appropriate lengths and types of road segments to produce a route with characteristics equivalent to the actual composite characteristics. Each group traced the selected sections of the actual speed versus time charts to come up with the composite route. After the three candidate routes were prepared, the committee reconvened and evaluated the relative merits of each route. As might be expected, the three routes were quite comparable with each having special features which that group felt were particularly important. After a thorough analysis and discussion, the committee constructed a composite route which contained the best features of all three routes. Figure 181 (Section V-I) presents the average characteristics of the composite route. Figure 180 (Section V-I) is a photoreduction of the driving chart and represents a graphical illustration of the speed-time trace as read from right to left, because of the direction of chart paper travel.

Table C-3

Comparative Analysis of Cycle Characteristics

Road Type	Average Speed Goal	Actual	Diff.	% Miles Traveled Goal	Actual	Diff.
A	57.16	56.10	-1.06	39.5	38.8	-0.70
B	49.42	48.42	-1.00	22.4	24.7	+2.30
C	45.80	43.84	-1.96	23.9	20.6	-3.30
D	39.78	41.16	+1.38	14.2	15.9	+1.70
Composite	49.43	48.59	-0.84	100.0	100.0	0.00

Table C-3 compares the final characteristics of the Table in Fig. 181 (Section V-I) with the goals shown in Table C-2. It is readily apparent that the highway driving cycle closely approximates the real world conditions. All average speeds are within ± 2.0 MPH of the real world average and the percentages of the distance traveled in each segment are within ± 4% of the DOT values.

During the construction of this cycle, the committee decided to use actual on-road traces to represent each segment. This decision placed two restrictions on the end points of the segments; the slopes and speeds had to be continuous at the segment junctions. Furthermore the committee thought the most realistic sequence of road segments would be DCAB. The cycle would start from an idle, contain four speed deviations (one each in B and D, two in C) and end with a deceleration to a stop and idle. For the convenience of the driver, who also controls the CVS sampling, a 2 second idle period was included at the beginning and the end of the cycle. The on-road data indicated the average idle time was 0.063 minutes/mile for all road types traveled.

Obviously, a change in any of these criteria for one segment impacts on the characteristics of the adjacent segments as well as the overall composite cycle characteristics.

One general observation about the B and C segments should be made. It was sometimes difficult to distinguish whether a road was strictly a type B or type C. Since their characteristics are very similar, a rigid distinction and duplication in the cycle was not considered critical.

The driving cycle shown in Fig.181 (Section V-I) was constructed from all of these criteria and is considered to be an accurate representation of all the types of highway driving normally encountered.

The characteristics of this highway driving cycle were determined by tabulating the velocities at each 0.1 inch of chart which represents 1.5 seconds.

This tabulation was converted to a digital table which listed the highway driving cycle velocities for each of the 758 one second intervals. The trace was then scaled to the same chart paper used for the Federal Urban Cycle. The tabulation is shown in Table C-4.

TABLE C-4

EPA HIGHWAY FUEL ECONOMY DRIVING CYCLE
SPEED (MPH) VS TIME (SEC)

SEC	MPH	SEC	MPH	SEC	MPH	SEC	MPH	SEC	MPH	SEC	MPH	SEC	MPH	SEC	MPH
0	SAMPLE ON	50	38.6	100	48.5	150	44.1	200	43.4	250	48.0	300	33.4	350	59.0
1	0.0	51	39.3	101	48.9	151	44.3	201	43.2	251	48.0	301	35.6	351	58.9
2	0.0	52	40.0	102	49.1	152	44.4	202	43.2	252	48.0	302	37.5	352	58.8
3	2.0	53	40.7	103	49.2	153	44.6	203	43.1	253	48.1	303	39.1	353	58.6
4	4.9	54	41.4	104	49.1	154	44.7	204	43.0	254	48.2	304	40.2	354	58.4
5	8.1	55	42.2	105	49.1	155	44.9	205	43.0	255	48.2	305	41.1	355	58.2
6	11.3	56	42.9	106	49.0	156	45.2	206	43.1	256	48.1	306	41.8	356	58.1
7	14.5	57	43.5	107	49.0	157	45.7	207	43.4	257	48.6	307	42.4	357	58.0
8	17.3	58	44.0	108	49.1	158	45.9	208	43.9	258	48.9	308	42.8	358	57.9
9	19.6	59	44.3	109	49.2	159	46.3	209	44.0	259	49.1	309	43.3	359	57.6
10	21.8	60	44.5	110	49.3	160	46.6	210	43.5	260	49.1	310	43.9	360	57.4
11	24.0	61	44.6	111	49.4	161	46.9	211	42.6	261	49.1	311	44.3	361	57.2
12	25.8	62	44.9	112	49.5	162	47.0	212	41.5	262	49.1	312	44.7	362	57.1
13	27.1	63	45.0	113	49.5	163	47.1	213	40.7	263	49.1	313	45.0	363	57.0
14	28.0	64	45.1	114	49.5	164	47.0	214	40.0	264	49.0	314	45.2	364	57.0
15	29.0	65	45.4	115	49.4	165	47.4	215	40.0	265	48.9	315	45.4	365	56.9
16	30.0	66	45.7	116	49.1	166	48.0	216	40.3	266	48.2	316	45.5	366	56.9
17	30.7	67	46.0	117	48.9	167	48.0	217	41.0	267	47.7	317	45.8	367	56.9
18	31.5	68	46.3	118	48.5	168	47.9	218	42.0	268	47.5	318	46.0	368	57.0
19	32.2	69	46.5	119	48.4	169	47.8	219	42.7	269	47.2	319	46.1	369	57.0
20	32.9	70	46.8	120	48.1	170	47.3	220	43.1	270	46.7	320	46.5	370	57.0
21	33.5	71	46.9	121	47.7	171	46.7	221	43.2	271	46.2	321	46.8	371	57.0
22	34.1	72	47.0	122	47.4	172	46.2	222	43.4	272	46.0	322	47.1	372	57.0
23	34.6	73	47.1	123	47.3	173	45.9	223	43.9	273	45.8	323	47.7	373	57.0
24	34.9	74	47.2	124	47.5	174	45.7	224	44.3	274	45.6	324	48.3	374	57.0
25	35.1	75	47.3	125	47.8	175	45.5	225	44.7	275	45.4	325	49.0	375	57.0
26	35.7	76	47.2	126	47.9	176	45.4	226	45.1	276	45.2	326	49.7	376	57.0
27	35.9	77	47.1	127	48.0	177	45.3	227	45.4	277	45.0	327	50.3	377	56.9
28	35.8	78	47.0	128	47.9	178	45.0	228	45.8	278	44.7	328	51.0	378	56.8
29	35.3	79	46.9	129	47.9	179	44.0	229	46.5	279	44.5	329	51.7	379	56.5
30	34.9	80	46.9	130	47.9	180	43.1	230	46.9	280	44.2	330	52.4	380	56.2
31	34.5	81	46.9	131	48.0	181	42.7	231	47.2	281	43.5	331	53.1	381	56.0
32	34.6	82	47.0	132	48.0	182	41.5	232	47.4	282	42.6	332	53.8	382	56.0
33	34.8	83	47.1	133	48.0	183	41.5	233	47.3	283	42.0	333	54.5	383	56.0
34	35.1	84	47.1	134	47.9	184	42.1	234	47.3	284	40.1	334	55.2	384	56.1
35	35.7	85	47.2	135	47.3	185	42.9	235	47.2	285	38.6	335	55.8	385	56.4
36	36.1	86	47.1	136	46.0	186	43.5	236	47.2	286	37.5	336	56.4	386	56.7
37	36.2	87	47.0	137	43.3	187	43.9	237	47.2	287	35.4	337	56.9	387	56.9
38	36.5	88	46.9	138	41.2	188	43.6	238	47.1	288	34.7	338	57.0	388	57.1
39	36.7	89	46.5	139	39.5	189	43.3	239	47.0	289	34.0	339	57.1	389	57.3
40	36.9	90	46.3	140	39.2	190	43.0	240	47.0	290	33.3	340	57.3	390	57.4
41	37.0	91	46.2	141	39.0	191	43.1	241	46.9	291	32.5	341	57.6	391	57.4
42	37.0	92	46.3	142	39.0	192	43.4	242	46.8	292	31.7	342	57.8	392	57.2
43	37.0	93	46.5	143	39.1	193	43.9	243	46.9	293	30.6	343	58.0	393	57.0
44	37.0	94	46.9	144	39.3	194	44.3	244	47.0	294	29.6	344	58.1	394	56.9
45	37.0	95	47.1	145	40.1	195	44.5	245	47.2	295	28.8	345	58.4	395	56.6
46	37.0	96	47.4	146	41.0	196	44.9	246	47.5	296	28.4	346	58.7	396	56.3
47	37.1	97	47.7	147	42.0	197	44.8	247	47.9	297	28.6	347	58.8	397	56.1
48	37.3	98	48.0	148	43.1	198	44.4	248	48.0	298	29.5	348	58.9	398	56.4
49	37.8	99	48.2	149	43.7	199	43.9	249	48.0	299	31.4	349	59.0	399	56.7

TABLE C-4 (Continued)

SEC	MPH	SEC	MPH	SEC	MPH	SEC	MPH	SEC	MPH	SEC	MPH	SEC	MPH	SEC	MPH
400	57.1	450	58.2	500	54.7	550	55.8	600	48.3	650	50.2	700	54.2	750	26.6
401	57.5	451	58.1	501	54.6	551	55.6	601	48.0	651	50.7	701	54.5	751	24.5
402	57.8	452	58.0	502	54.4	552	55.4	602	47.9	652	51.1	702	54.8	752	21.5
403	58.0	453	58.0	503	54.3	553	55.2	603	47.8	653	51.7	703	55.0	753	19.5
404	58.0	454	58.0	504	54.3	554	55.1	604	47.7	654	52.2	704	55.5	754	17.4
405	58.0	455	58.0	505	54.2	555	55.0	605	47.9	655	52.5	705	55.9	755	15.1
406	58.0	456	58.0	506	54.1	556	54.9	606	48.3	656	52.1	706	56.1	756	12.4
407	58.0	457	58.0	507	54.1	557	54.6	607	49.0	657	51.6	707	56.3	757	9.7
408	58.0	458	57.9	508	54.1	558	54.4	608	49.1	658	51.1	708	56.4	758	7.0
409	57.9	459	57.9	509	54.0	559	54.2	609	49.0	659	51.0	709	56.5	759	5.0
410	57.8	460	58.0	510	54.0	560	54.1	610	48.9	660	51.0	710	56.7	760	3.3
411	57.7	461	58.1	511	54.0	561	53.9	611	48.0	661	51.1	711	56.9	761	2.0
412	57.7	462	58.1	512	54.0	562	53.6	612	47.1	662	51.4	712	57.0	762	0.7
413	57.8	463	58.2	513	54.0	563	53.3	613	46.2	663	51.7	713	57.3	763	0.0
414	57.9	464	58.3	514	54.0	564	53.1	614	46.1	664	52.0	714	57.7	764	0.0
415	58.0	465	58.3	515	54.0	565	52.9	615	46.1	665	52.2	715	58.2	765	SAMPLE OFF
416	58.1	466	58.3	516	54.0	566	52.6	616	46.2	666	52.5	716	58.8		
417	58.6	467	58.2	517	54.1	567	52.4	617	46.9	667	52.6	717	59.1		
418	58.9	468	58.1	518	54.2	568	52.2	618	47.8	668	52.7	718	59.2		
419	59.1	469	58.0	519	54.5	569	52.1	619	49.0	669	52.6	719	59.1		
420	59.4	470	57.8	520	54.8	570	52.0	620	49.7	670	52.3	720	58.8		
421	59.8	471	57.5	521	54.9	571	52.0	621	50.6	671	52.3	721	58.5		
422	59.9	472	57.1	522	55.0	572	52.0	622	51.5	672	52.4	722	58.1		
423	59.9	473	57.0	523	55.1	573	52.0	623	52.2	673	52.5	723	57.7		
424	59.8	474	56.6	524	55.2	574	52.1	624	52.7	674	52.7	724	57.3		
425	59.6	475	56.1	525	55.2	575	52.0	625	53.0	675	52.7	725	57.1		
426	59.4	476	55.9	526	55.3	576	52.0	626	53.6	676	52.4	726	56.8		
427	59.2	477	55.8	527	55.4	577	51.9	627	54.0	677	52.1	727	56.5		
428	59.1	478	55.5	528	55.5	578	51.6	628	54.1	678	51.7	728	56.2		
429	59.0	479	55.2	529	55.6	579	51.4	629	54.4	679	51.1	729	55.5		
430	58.9	480	55.1	530	55.7	580	51.1	630	54.7	680	50.5	730	54.6		
431	58.7	481	55.0	531	55.8	581	50.7	631	55.1	681	50.1	731	54.1		
432	58.6	482	54.9	532	55.9	582	50.3	632	55.4	682	49.6	732	53.7		
433	58.5	483	54.9	533	56.0	583	49.5	633	55.4	683	49.7	733	53.2		
434	58.4	484	54.9	534	56.0	584	49.3	634	55.0	684	49.6	734	52.9		
435	59.4	485	54.9	535	56.0	585	48.7	635	54.5	685	49.5	735	52.5		
436	58.3	486	54.9	536	56.0	586	48.2	636	53.8	686	49.5	736	52.0		
437	58.2	487	54.9	537	56.0	587	48.1	637	52.5	687	49.7	737	51.3		
438	58.1	488	55.0	538	56.0	588	48.0	638	50.2	688	50.0	738	50.5		
439	58.0	489	55.0	539	56.0	589	48.0	639	48.2	689	50.2	739	49.5		
440	57.9	490	55.0	540	56.0	590	48.1	640	46.5	690	50.6	740	48.5		
441	57.9	491	55.0	541	56.0	591	48.4	641	46.2	691	51.1	741	47.6		
442	57.9	492	55.0	542	56.0	592	48.9	642	46.0	692	51.6	742	46.8		
443	57.9	493	55.0	543	56.0	593	49.0	643	46.0	693	51.9	743	45.6		
444	57.9	494	55.1	544	56.0	594	49.1	644	46.3	694	52.0	744	44.2		
445	58.0	495	55.1	545	56.0	595	49.1	645	46.8	695	52.1	745	42.5		
446	58.1	496	55.0	546	56.0	596	49.0	646	47.5	696	52.4	746	39.2		
447	58.1	497	54.9	547	55.9	597	49.0	647	48.2	697	52.9	747	35.9		
448	58.2	498	54.9	548	55.9	598	48.9	648	48.8	698	53.3	748	32.6		
449	58.2	499	54.8	549	55.9	599	48.6	649	49.5	699	53.7	749	29.3		

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APPENDIX D

The Potential Health Hazard of Nickel Compound Emissions from Automotive Gas Turbine Engines Using Nickel Oxide Base Regenerator Seals

by

Robert B. Schulz
EPA - AAPS Division

April 1974

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FOREWORD

This study was begun as a result of a letter from Mr. Eberhard Tiefenbacher of Daimler-Benz Aktiengesellschaft, Germany, pointing out the carcinogenic hazard of nickel oxide exhaust from automotive gas turbine engines which use this material in their regenerator rubbing seals.

This report was prepared by Mr. Robert B. Schulz of the Alternative Automotive Power Systems Division, Office of the Mobile Source Air Pollution Control, Office of Air and Waste Management, Environmental Protection Agency. The author wishes to acknowledge that a major portion of the survey on the Carcinogenic Potential of Nickel Oxide and all of the related findings and recommendations were written by Dr. Michael D. Waters, Ph.D., Research Biochemist, Pathobiology Research Branch, Dr. Philip B. Kane, M.D., Research Pathologist, Pathobiology Research Branch, and Dr. David L. Coffin, V.M.D., Chief, Pathobiology Research Branch, all of the Experimental Biology Laboratory, National Environmental Research Center, Research Triangle Park, Environmental Protection Agency.

The atmospheric concentration analysis was performed by the Office of Research and Development, Environmental Protection Agency, and reported to the author by Mr. John B. Moran. The particulate measurement was performed by the Dow Chemical Company, Midland, Michigan under contract to the Emission Control Technology Division, Office of Mobile Source Air Pollution Control, Environmental Protection Agency. The author wishes to acknowledge the assistance provided by

Mr. Tony Ashby, the Emission Control Technology Division Project Officer and Mr. Otto J. Manary of the Dow Chemical Company for their assistance with the particulate measurement. The author also acknowledges the assistance of Mr. Clay Hubean of Williams Research Corporation, Walled Lake, Michigan in providing information about the WR-26 turbine engine.

1. INTRODUCTION

The potential public health impact of nickel oxide emissions from automotive gas turbine engines being developed for light and heavy duty applications has been investigated by the U.S. Environmental Protection Agency. A promising technological improvement for the gas turbine engine is to use ceramic regenerators (rotary heat exchangers) to achieve high efficiency. At present, the most widely known and used composition for the high temperature rubbing seals required by such regenerators contains NiO (nickel oxide) and CaF_2 (calcium fluoride). Since various nickel compounds are known or suspected carcinogens, this has raised the question of whether anticipated wear of those seals in use would lead to emission rates of NiO which could pose a new air pollution problem.

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2. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

These are included as Section III-K in the main body of this report.

3. CARCINOGENICITY OF NICKEL OXIDE

3.1 Survey of Effects

A survey on the carcinogenic potential of nickel oxide (with recommendations regarding its use in automobile gas turbine engines as a rubbing seal material), was conducted by Waters, Kane and Coffin (Reference 1) of the Pathobiology Research Branch, Experimental Biology Laboratory, National Environmental Research Center, Research Triangle Park. They were unable to find published reports that related directly to the potential carcinogencity of nickel oxide as it may be produced as an automobile exhaust product. The survey of Index Medicus from January 1963 to December 1970 and a National Library of Medicine Medline Search from January 1971 to June 1973 (pre-prints) yielded essentially the same information found by the author in a preliminary survey (Reference 3).

Nickel is classified as a recognized respiratory carcinogen based on the increased mortality from cancer of the nose and from cancer of the lung experienced by nickel refinery workers exposed to nickel carbonyl (Reference 4). Nickel Oxide should be classified as a potential respiratory carcinogen because the incriminating evidence is predominantly restricted to observations made in experimental animals.

Malignant tumors have been produced in different animal species by a variety of nickel compounds introduced by different routes (Reference 5). Intramuscular injection of nickel oxide dusts into C3H and Swiss Mice resulted in the development of sacromas (Reference 6).

NiO dust implanted in the muscle tissue of NIH black rats resulted in tumors (Reference 7). The less soluble nickel compounds, such as nickel oxide, have been found to have the higher carcinogenic potential. Human evidence is at present not available linking nickel oxides to the development of cancer of the respiratory system in man. Chronic exposure to nickel oxide fumes of metal dressers in a steelworks showed (Reference 8) no evidence of lung cancer after 19 years. NiO is included in a chronic exposure study (Reference 9) of the cocarcinogenicity of cigarette smoke and various industrial pollutants in hamsters. The above evidence supports the classification of NiO as a potential respiratory carcinogen, with further evidence needed to change the classification to suspected or recognized respiratory carcinogen. Being a potential respiratory carcinogen, however, is probably enough to cause serious concern about the level of NiO concentration in the exhaust of an automobile gas turbine engine.

At the present time, nickel oxide is implicated as a potential carcinogen principally through association with the group of nickel compounds whose carcinogenic properties are well documented by industrial experience and experimental investigation (References 10 and 11). In general, the forms found to be sparingly soluble in water at 37°C (nickel dust, nickel sulfide, nickel carbonate, nickel oxide, nickel carbonyl and nickelocene) have been identified as carcinogens. To quote Sunderman (Reference 10):

> "Intraosseous, intramuscular, subcutaneous and intrapleural injections of the insoluble nickel compounds have resulted in the development of osteogenic sarcomas, fibrosarcomas and rhabdomyosarcomas. It is significant that

induction of carcinomas of the histological types that occur among nickel workers (i.e. squamous cell and anaplastic carcinomas) has only been accomplished following exposures by the respiratory route."

3.2 Experimental Evidence

Aside from reports of induction of rhabdomyosarcomas by intramuscular implantation of nickel oxide (Reference 6 and 7), the most incriminating experimental evidence against this compound is that it may function as a cocarcinogen. Toda (Reference 12) has reported that intratracheal administration of a mixture of nickel oxide and methylcholanthrene to rats resulted in a much greater incidence of pulmonary carcinomas than in rats which received methylcholanthrene alone.

Other studies which are pertinent to the discussion are the following: Bingham, et al. (Reference 13) have shown that exposure of rats at approximately 1/10th of the current threshold limit value (TLV) ($1mg/m^3$) for nickel results in hypersecretion in the bronchial epithelium and focal infiltration by lymphocytes in the alveolar walls and perivascular spaces. Alveolar macrophages displaying an altered size distribution profile could be recovered by lavage in increasing numbers with repeated exposure to nickel oxide. Furthermore, focal thickened areas were evident in alveolar walls and occasionally in the respiratory bronchi. These changes, though not necessarily of pathologic significance or irreversible, occur at such low levels of exposure as to warrant further investigation. It should be clearly recognized that TVL's cannot be validly applied to the general population since they are intended to provide guidelines for industrial workday exposure of healthy individuals.

In agreement with the ICRP Committee II Task Group on Lung Dynamics (Reference 14), Wehner and Craig (Reference 9) have demonstrated that nickel oxide displays moderate lung retention. In their studies using Syrian golden hamster, "Nearly 20% of the inhaled nickel oxide was retained in the lungs after initial clearance, and 45% of this was still present after 45 days." Nickel oxide concentrations ranged from 10 to 190 μg/liter. The compound was not acutely toxic to hamsters at any level employed. However, prolonged lung retention increases the concern over the possibility of inducing chronic changes. The minimum latent period for induction of tumors by finely divided nickel is reported by Hueper (Reference 15) to be 6 months. It should be noted that some animals in the Wehner and Craig study (Reference 9) are being observed for chronic changes.

Sanders et al. (Reference 16) have shown that the degree of solubilization of nickel oxide particles in biological fluids (tissue culture medium 199) is slight but measurable. Their studies with Syrian golden hamsters demonstrated that more nickel oxide particles were found free in alveolar lumens when pulmonsary clearance was impaired by exposure to cigarette smoke. This effect might be expected to potentiate adverse responses to nickel oxide although none were described. It should be pointed out that many individuals within the general population will display impaired clerance mechanisms because of underlying broncho-pulmonary disease.

3.3 Industrial Experience

Nickel workers undoubtedly have a higher prevelance of nasal and respiratory cancer than the general population. Sunderman (Reference 10) concluded that the incidence of lung cancer among nickel workers ranged from 2.2 to 16 times the incidence in the general population, and the reported incidence of cancer of the nose and paranasal sinuses was 37 to 196 times the expected values. Despite the fact that nickel oxide is a usual component of refining dust it is difficult to define its relative role as a causative agent. Nickel oxide is a minor component of dust (e.g. 6.3%) as compared with nickel sulfide (e.g. 59.0%) and the latter has been shown to yield a significantly higher incidence of rhabdomyosarcomas in rats (Reference 6). Furthermore, it is often impossible to dissociate the carcinogenic properties of nickel compounds from those of other metals that are usually present. The recent report by Saknyn and Shabynina (Reference 17) on the increased mortality from cancer among workers exposed to nickel oxide and sulfide, for example, also mentioned the presence of arsenic and cobalt in the refining atmosphere.

3.4 Summary of Health Hazards

The principal concerns over the release of additional nickel oxide to the atmosphere relate to the following facts:

1. The compound produces muscle sarcomas when the injected into rats (Reference 6 and 7).
2. Nickel oxide may function as a cocarcinogen when introduced into the lungs with a known carcinogen (Reference 12).
3. Low level (100-150 $\mu g/m^3$) nickel oxide exposure may result in histological changes in bronchi and alveoli (Reference 13).

4. Nickel oxide is cleared relatively slowly from the respiratory tract (Reference 15).

5. Cigarette smoking may impair clearance of nickel oxide and potentiate tissue damage (Reference 16).

6. Nickel oxide has been implicated by association in the higher incidence of nasal and lung cancer observed among nickel workers (Reference 10, 11, 17).

4. PARTICULATE MEASUREMENT

The exhaust particulates from the Williams Research Corporation gas turbine powered AMC Hornet automobile were measured at The Dow Chemical Company in Midland, Michigan (Reference 18). This prototype vehicle was powered by the WR-26 gas turbine engine which utilized two ceramic disc regenerators. The flame sprayed regenerator rubbing seal material composition was 90 percent NiO and 10 percent CaF_2.

Vehicle testing was done on a dynamometer using the following vehicle driving test procedures:

MFCCS	Modified 1975 Federal Driving Cycle	Cold Start	41 min.
FCHS	1975 Federal Driving Cycle	Hot Start	23 min.
50MPHSS	Steady State 50 MPH	Hot Start	60 min.

Only one-half of the engine exhaust was measured. A 5-inch stainless-steel flexible tube was used to couple the exhaust pipe to the exhaust inlet of the dilution tube. A description of the particulate measurement methods is contained in Reference 19.

A summary of the measured total particulates, trace nickel and trace calcium is given in Table I. The total particulates reported in the table were collected with a millipore filter. The NiO emissions rate was determined from the percent nickel from emission spectroscope analysis of the total particulate and assumes all NiO.

It was discovered after the test that engine transmission oil was collected in the particulate sample. The oil vent pipe was connected into the exhaust pipe used for exhaust measurement. A trace element analysis of the synthetic ENCO Turbine Oil 274 gave a nickel concentration

TABLE D-1

PARTICULATE MEASUREMENT TEST RESULTS

WR-26 Gas Turbine Vehicle

Vehicle Test No.	Test Mode	Total Particulate[a] (Grams/mile)	Trace Ni[b] (Percent)	NiO[c] (Grams/Mile)	Trace Ca[b] (Percent)	CaF_2[c] (Grams/Mile)
260 A	MFCCS	.676	0.4	.0034	1.1	.015
260 B	FCHS	.288	0.7	.0025	3.4	.019
260 C	FCHS	.269	0.6	.0020	3.6	.019
260 D	50 MPH SS	.139	0.3	.0005	0.7	.019

[a] 142 mm millipore filter

[b] Trace metals analysis of exhaust particulate

[c] Assumes all NiO or CaF_2, 19.84 mph or 50 mph

of < 1 ppm and a calcium concentration of 7 ppm. It was concluded that the transmission oil probably did not affect the nickel particulate measurement, but did raise the total particulate measurements. It was planned to re-run the test series, however, before this could be done, the engine had to be overhauled.

After 68 hours of operation the WR-26 gas turbine engine was overhauled because of excess leakage through the regenerator seals. It was found that the high pressure hot side insulation had broken loose and lodged under the seals, causing the excess leakage, The insulation material was sodium silicate (water glass) and asbestos. Significant amounts of nickel have been found in other asbestos, and therefore the insulation could be a source of some of the nickel in the exhaust particulate. This was not investigated further because there was sufficient NiO/CaF_2 seal wear to account for the nickel emissions.

The extent of regenerator seal wear required seal replacement. In general, the wear was uneven, with little or no wear in some areas, and wear almost through to the base plate in other areas. The estimated average wear on the four high pressure seals was 0.009 inch. A detailed dimensional inspection of the seals was not made before engine running, so it was impossible to obtain accurate seal wear rates.

An attempt was made by analysis to correlate the estimated average seal wear rate with the particulates measured in grams/mile. There was good agreement between the calculated NiO emission rate of 0.040 grams/mile and the measured NiO emission rate given in Table I. The calculated

CaF_2 emission rate was 0.0045 grams/mile, which is much less than the measured CaF_2 emission rate. This may be because CaF_2 is the lubricant which flows under pressure from the NiO solid matrix during regenerator operation.

The measured NiO emission rate ranged from 0.0005 grams/mile for the 50 MPH steady state test to 0.0034 grams/mile for the modified federal driving cycle cold test. An estimate of 0.003 to 0.005 grams NiO per mile was given to the EPA Monitoring and Data Analysis Division, Source Receptor Analysis Branch to do their atmospheric concentration analysis. The somewhat higher estimate of the NiO emissions was made to be conservative and account for the lower power output of the WR-26 engine, rated at 80 horsepower compared to a more likely range of 100 to 150 horsepower if automobile gas turbines were used widely. This doesn't necessarily follow, however, as improvements in engine performance and seal design should go toward reducing the seal wear rate.

It is therefore important to obtain additional particulate measurements on gas turbine automobile and heavy duty vehicles. EPA intends to measure the particulates from the Chrysler Baseline Engine after it has been converted from metal to ceramic regenerators. Initial testing of the Baseline Engine will be done with NiO/CaF_2 seals, in order to obtain baseline seal and ceramic regenerator performance. It is, however, EPA's intention to develop an alternate seal material for the Baseline Engine that does not use NiO or other hazardous materials.

5. ATMOSHPERIC CONCENTRATION ANALYSIS

The industrial threshold limit values (TLVs) for nickel and its compounds are summarized as follows:

Material	TLV (mg/m^3)
Nickel carbonyl	.007 (7 $\mu g/m^3$)
Nickel, metal and soluble salts (as nickel)	1 (1000 $\mu g/m^3$)

This is the safe level for an 8 hour per day, 5 working day per week exposure. Ambient air quality standards for the general population would be set at much lower levels then this. Further, the data obtained with low level (100-150 $\mu g/m^3$) nickel oxide exposure suggest that the TLV may be too high. Also NiO is not a soluble salt, but rather is a nearly insoluble oxide, and therefore the TLV may not necessarily apply.

Ambient urban concentrations of nickel in 1968 varied from a low arithmetic mean of .006 $\mu g/m^3$ to a high of .224 $\mu g/m^3$ (Reference 20). The maximum concentration observed was in Portland, Maine (1.30 $\mu g/m^3$). The frequency distribution for nickel in Portland for 1968 was as follows:

Frequency Distribution, Percent

	Min.	10%	20%	30%	40%	50%	60%	70%	80%	90%	Max.
(Ni -$\mu g/m^3$)	.009	.009	.016	.02	.03	.052	.11	.13	.46	.73	1.3

The average arithmetic mean urban concentration of nickel from 84 urban NASN stations in 1968 was .036 $\mu g/m^3$. A typical distribution for the "average" urban site was as follows:

Oakland, California

Frequency Distribution, Percent

	Min.	10%	20%	30%	40%	50%	60%	70%	80%	90%	Max.
(Ni -$\mu g/m^3$)	.006	.01[illegible]	.013	.016	.017	.026	.03	.034	.037	.097	.140

The maximum yearly average urban nickel concentration for 1969 occurred in New York City (0.173 $\mu g/m^3$) with a quarterly composite maximum of 0.330 $\mu g/m^3$ which occurred for the 1st quarter of 1969.

Nickel has been determined as one of the trace metals in automotive exhaust particulate under contract programs conducted by both the EPA Office for Research and Development (ORD) and the EPA Office of Air and Water Programs (OAWP) over the last three years. A review of all related reports and prepared estimates of nickel (as the mono-oxide) emissions from various automotive power systems give the ranges and "best estimate" emission rates are summarized in Table II.

The concentrations of nickel in various fuels has been reported by Lee and von Lehmden (Reference 21) as well as the source emissions levels of nickel. These are summarized in Table III.

NiO exposures were estimated based upon the extensive projections developed by ORD which modeled sulfate exposures from oxidation catalysts on conventional piston engines. The projected exposures were made for NiO on and near major arterial throughways with the following assumptions:

1. 25% of vehicle miles with turbine engine vehicles,
2. Nickel mono-oxide emissions are .005 gm/mile from turbine engine vehicles and zero from the remaining vehicles.

TABLE D-II

NICKEL EMISSIONS FROM LIGHT-DUTY

MOTOR VEHICLES (CALCULATED AS NiO)

	NiO Emissions in grams/mile	
Vehicle System	Range	Best System
Conventional/current	.000009 - .00025	.00003
Conventional/oxidation catalyst	.000005 - .0001	.00001
Conventional/Quester catalyst	.0003 (1)	.0003
Conventional/thermal reacter	.00067 (1)	.0006
Diesel (LDMV)	.00008 (1)	.00008
Stratified Charge	.0002 (1)	.0002
Turbine (LDMV) (Williams)	.0005 - .0034	.005*

*OAWP data and estimate
(1) one data point only

TABLE D-III

CONCENTRATION OF NICKEL IN FUELS

Source		Concentration, wt. % of nickel
Fuels:	Gasoline (1)	.0003 - .0005
	Fuel oil	.0001 - .01
	Consumer purchased fuel additives	.00003
	Fuel additives (2)	0
Source Emissions:		
	Phosphate rock	.0001 - .01
	Zn/Cu Smelter	.0001 - .01
	Ferro alloy	.01 - .1
	Brass/bronze Smelter	.001 - .1
	Coal Flyash	.001 - .008
	Coal fired powerplant	.0001 - .01
	Pb Smelter	0 - .0001
	Cement plants	.01 - .1
	Fe/Steel foundry	.001 - .1
	Incinerator	.01 - .1

(1) Fuel Surveillance Program (F & FA) and Contract Program (CPS-22-69-145)

(2) Based upon current records in Office of Fuel and Fuel Additive Registration, ORD, NERC/RTP.

The results of the exposure analysis are as follows:

1 hour peak exposure (vehicle occupant, worst meteorology, worst wind condition)	12.4 μgm/m^3
1 hour peak exposure (pedestrian, worst meteorology, worst wind condition)	8.8 μgm/m^3
24 hour average exposure (as 1 hour conditions)	1.45 μgm/m^3
Incremental 24 hour exposure (as 1 hour conditions, commuter living near throughway)	0.88 μg/m^3

It is concluded that the emission of NiO from automotive turbine engines of .005 grams/mile and the attendant exposure of the public to the incremental increases of this metal oxide is an unnecessary risk. The evidence against nickel oxide is sufficient to warrant development of alternate materials for use in automobile turbine engine rubbing seals. Since urban ambient levels of nickel are relatively high at present, due consideration should be given to any sources likely to increase these levels.

6. NICKEL CARBONYL HAZARD

It is also possible that the operation of an engine which generates impure nickel and carbon monoxide from combustion might result in conditions favorable for formation of nickel carbonyl in the exhaust stream. Nickel carbonyl, $Ni(CO)_4$, may be present wherever carbon monoxide contacts nickel and nickel alloys. Therefore, if nickel oxide is to be considered further, it should be demonstrated that nickel carbonyl is not a combustion product. The case for extreme toxicity and carcinogenicity of nickel carbonyl is virtually unquestioned (Reference 10).

Reference 22 gives the equilibrium concentrations of $Ni(CO)_4$ as a function of temperature, total pressure, and CO concentration at levels of 0.0005 to 3.0 mole-percent in the feed gas. This would be an estimate of the maximum concentration of nickel carbonyl from a reacting system. Other data indicates that nickel carbonyl can be formed in significant concentrations at 120°F any time the concentration of carbon monoxide exceeds 100 ppm in the presence of finely divided nickel. The nickel carbonyl readily decomposes at temperature above 140°F and forms nickel oxide in dry air and/or nickel carbonate in moist air.

The WR-26 automotive turbine engine exhaust temperature is 200°F at idle to 500°F at full power. These temperatures are high enough to prevent the formation of nickel carbonyl. This should also be the case with other automotive gas turbine engines.

The actual presence of NiO in the WR-26 turbine engine exhaust has not been confirmed. Only a trace element measurement of nickel in the exhaust particulate has been made. Some of the nickel may be the more soluble nickel sulfate, $NiSO_4$, or possibly the very toxic form of nickel carbonyl, $Ni(CO)_4$. As the emission of nickel carbonyl would greatly increase the public health risk, it would be prudent to identify the form of the nickel compounds emitted.

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APPENDIX E

ALTERNATIVE AUTOMOTIVE POWER SYSTEMS DIVISION
ANNUAL, FINAL, AND SUMMARY REPORTS

MAY 1974

ALTERNATIVE AUTOMOTIVE POWER SYSTEMS DIVISION

ANNUAL, FINAL, AND SUMMARY REPORTS

MAY 1974

The attached list of publications are annual, summary and final reports of work performed under study and development contracts and interagency agreements funded by the Alternative Automotive Power Systems (AAPS) Program of the Office of Air and Water Programs (OAWP) of the U.S. Environmental Protection Agency.

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RELATED REPORTS

STRATIFIED CHARGE ENGINE

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APTD SERIES REPORTS

APTD - 0573
REPORT DATE: June 1970
CONTRACT NUMBER: CPA 22-69-132
CONTRACTOR: Thermo Electron Corporation
REPORT TITLE: "Conceptual Design Rankine Cycle Power System With Organic Working Fluid and Reciprocating Engine for Passenger Vehicles."
NTIS ACCESSION NUMBER: PB 193-418
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0574
REPORT DATE: June 1970
CONTRACT NUMBER: CPA 22-69-128
CONTRACTOR: The Marquardt Corporation
REPORT TITLE: "Study of Continuous Flow Combustion Systems for External Combustion Vehicle Powerplants."
NTIS ACCESSION NUMBER: PB 193-417
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0707
REPORT DATE: Undated
CONTRACT NUMBER: EHS 70-106
CONTRACTOR: Solar Division of International Harvester Company
REPORT TITLE: "Low Emission Burner for Rankine Cycle Engines for Automobiles."
NTIS ACCESSION NUMBER: PB 202-196
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0724
REPORT DATE: June 1, 1971
CONTRACT NUMBER: F04701-70-C-0059
CONTRACTOR: The Aerospace Corporation
REPORT TITLE: "Hybrid Heat Engine/Electric Systems Study." (Volume I)
NTIS ACCESSION NUMBER: PB 201-645
NTIS PAPER COPY PRICE: $6.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0725
REPORT DATE: June 1, 1971
CONTRACT NUMBER: F04701-70-C-0059
CONTRACTOR: The Aerospace Corporation
REPORT TITLE: "Hybrid Heat Engine/Electric Systems Study." (Volume II)
NTIS ACCESSION NUMBER: PB 201-646
NTIS PAPER COPY PRICE: $6.00
NTIS MICROFICHE PRICE: $1.45

APTD -0750
REPORT DATE: April 30, 1971
CONTRACT NUMBER: EHS 70-104
CONTRACTOR: Lockheed Missiles and Space Company
REPORT TITLE: "Flywheel Feasibility Study and Demonstration."
NTIS ACCESSION NUMBER: PB 200-143
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0762
REPORT DATE: April 1971
CONTRACT NUMBER: EHSH 71-002
CONTRACTOR: TRW Systems Group
REPORT TITLE: "Analysis and Advanced Design Study of an Electromechanical Transmission."
NTIS ACCESSION NUMBER: PB 203-463
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0875
REPORT DATE: July 1971 (Annual)*
CONTRACT NUMBER: W-31-107-Eng-38
CONTRACTOR: Argonne National Laboratory
REPORT TITLE: "Development of High-Energy Batteries for Electric Vehicles."
NTIS ACCESSION NUMBER: PB 205-254
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0957
REPORT DATE: January 28, 1971
CONTRACT NUMBER: EHS 70-107
CONTRACTOR: Minicars, Inc.
REPORT TITLE: "Emission Optimization of Heat Engine/Electric Vehicle."
NTIS ACCESSION NUMBER: PB 198-093
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0958
REPORT DATE: August 1971
CONTRACT NUMBER: EHS 70-115
CONTRACTOR: United Aircraft Research Laboratories
REPORT TITLE: "Manufacturing Cost Study of Selected Gas Turbine Automobile Engine Concepts"
NTIS ACCESSION NUMBER: PB 202-251
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0959
REPORT DATE: August 1971
CONTRACT NUMBER: EHS 70-123
CONTRACTOR: AiResearch Manufacturing Company
REPORT TITLE: "Compact Condenser for Rankine Cycle Engines."
NTIS ACCESSION NUMBER: PB 208-237
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0960
REPORT DATE: February 1972
CONTRACT NUMBER: EHS 70-111
CONTRACTOR: General Electric Company
REPORT TITLE: "Modeling, Analysis, and Evaluation of Rankine Cycle Propulsion Systems." (Volume I).
NTIS ACCESSION NUMBER: PB 209-277
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0961
REPORT DATE: February 1972
CONTRACT NUMBER: EHS 70-111
CONTRACTOR: General Electric Company
REPORT TITLE: "Modeling, Analysis, and Evaluation of Rankine Cycle Propulsion Systems." (Volume II).
NTIS ACCESSION NUMBER: PB 209-278
NTIS PAPER COPY PRICE: $6.00
NTIS MICROFICHE PRICE: $1.45

APTD - 0966
REPORT DATE: October 1971
CONTRACT NUMBER: F19628-71-C-0002
CONTRACTOR: The Mitre Corporation
REPORT TITLE: "Advanced Automotive Power System Structured Value Analysis Model."
NTIS ACCESSION NUMBER: PB 209-286
NTIS PAPER COPY PRICE: $6.75**
NTIS MICROFICHE PRICE: $1.45

*NOTE: See APTD-1126 for July 1970 Annual Report.

**Paper copy not presently available from NTIS.

APTD - 0980
REPORT DATE: July 1971
CONTRACT NUMBER: EHS 70-125
CONTRACTOR: Paxve, Inc.
REPORT TITLE: "Evaluation of a Low NOx Burner."

NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1121
REPORT DATE: February 25, 1972
CONTRACT NUMBER: 68-04-0034
CONTRACTOR: Sundstrand Aviation
REPORT TITLE: "Hybrid Propulsion System Transmission Evaluation."

NTIS ACCESSION NUMBER: PB 210-057
NTIS PAPER COPY PRICE: $6.00
NTIS MICROFICHE PRICE: $1.45

APTD - 1126
REPORT DATE: July 1970 (Annual)*
CONTRACT NUMBER: W-31-107-Eng-38
CONTRACTOR: Argonne National Laboratory
REPORT TITLE: "Development of High-Energy Batteries for Electric Vehicles."

NTIS ACCESSION NUMBER: PB 197-576
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 1154
REPORT DATE: May 5, 1972
CONTRACT NUMBER: EHS 70-102
CONTRACTOR: Thermo Electron Corporation
REPORT TITLE: "Detailed Design, Rankine-Cycle Power System With Organic-Based Working Fluid and Reciprocating Expander for Automobile Propulsion" (Volume I - Technical Report).

NTIS ACCESSION NUMBER: PB 210-836
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 1155
REPORT DATE: May 5, 1972
CONTRACT NUMBER: EHS 70-102
CONTRACTOR: Thermo Electron Corporation
REPORT TITLE: "Detailed Design, Rankine-Cycle Power System With Organic-Based Working Fluid and Reciprocating Expander for Automobile Propulsion" (Volume II - Appendices).

NTIS ACCESSION NUMBER: PB 210-837
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 1181
REPORT DATE: November 1971
CONTRACT NUMBER: 68-04-0033
CONTRACTOR: Mechanical Technology Incorporated
REPORT TITLE: "Feasibility Analysis of the Transmission for a Flywheel/Heat Engine Hybrid Propulsion System."

NTIS ACCESSION NUMBER: PB 212-097
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 1182
REPORT DATE: July 31, 1972
CONTRACT NUMBER: 68-04-0048
CONTRACTOR: Lockheed Missiles and Space Company, Inc.
REPORT TITLE: "Flywheel Drive Systems Study."

NTIS ACCESSION NUMBER: PB 213-342
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

*NOTE: See APTD-0875 for July 1971 Annual Report

APTD - 1226
REPORT DATE: August 1972
CONTRACT NUMBER: EHSH 71-003
CONTRACTOR: Thermo Mechanical Systems Company
REPORT TITLE: "The Study of Low Emission Vehicle Powerplants Using Gaseous Working Fluids."
NTIS ACCESSION NUMBER: PB 220-148
NTIS PAPER COPY PRICE: $6.00
NTIS MICROFICHE PRICE: $1.45

APTD - 1290
REPORT DATE: May 1972
CONTRACT NUMBER: 68-04-0013
CONTRACTOR: United Aircraft Research Laboratories
REPORT TITLE: "Automotive Gas Turbine Optimum Configuration Study."
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1291*
REPORT DATE: July 14, 1972
CONTRACT NUMBER: 68-04-0012
CONTRACTOR: AiResearch Manufacturing Company of Arizona
REPORT TITLE: "Automobile Gas Turbine Optimization Study"
NTIS ACCESSION NUMBER: PB 213-389
NTIS PAPER COPY PRICE: $6.00
NTIS MICROFICHE PRICE: $1.45

APTD - 1343
REPORT DATE: June 1972
CONTRACT NUMBER: 68-01-0406
CONTRACTOR: General Electric Company
REPORT TITLE: "Automobile Gas Turbine - Optimum Cycle Selection Study."
NTIS ACCESSION NUMBER: PB 213-370
NTIS PAPER COPY PRICE: $6.00
NTIS MICROFICHE PRICE: $1.45

APTD - 1344
REPORT DATE: March 1972
CONTRACT NUMBER: N00017-62-C-0604
CONTRACTOR: John Hopkins University - Applied Physics Laboratory
REPORT TITLE: "Heat-Engine/Mechanical-Energy-Storage Hybrid Propulsion Systems for Vehicles."
NTIS ACCESSION NUMBER: PB 213-417
NTIS PAPER COPY PRICE: $6.75
NTIS MICROFICHE PRICE: $1.45

APTD - 1345
REPORT DATE: April 1972
CONTRACT NUMBER: 68-04-0028
CONTRACTOR: TRW Systems Group
REPORT TITLE: "Develop High Charge and Discharge Rate Lead/Acid Battery Technology."
NTIS ACCESSION NUMBER: PB 213-257
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 1346
REPORT DATE: November 1971
CONTRACT NUMBER: EHSH 71-009
CONTRACTOR: Tyco Laboratories, Incorporated
REPORT TITLE: "Lead/Acid Battery Development for Heat Engine/Electric Hybrid Vehicles."
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

**NOTE:* APTD-1546 is a Summary of This Report.

APTD - 1355
REPORT DATE: April 1972
CONTRACT NUMBER: 68-04-0058
CONTRACTOR: TRW Systems Group
REPORT TITLE: "Cost and Emission Studies of a Heat Engine/Battery Hybrid Family Car."
NTIS ACCESSION NUMBER: PB 213-280
NTIS PAPER COPY PRICE: $3.00
NTIS MICROFICHE PRICE: $1.45

APTD - 1356
REPORT DATE: January 31, 1972
CONTRACT NUMBER: 68-04-0040 (Phase II)
CONTRACTOR: Cornell Aeronautical Laboratory, Inc.
REPORT TITLE: "An Evaluation of the Stratified Charge Engine (SCE) Concept."
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1357
REPORT DATE: December 1972
CONTRACT NUMBER: 68-01-0430
CONTRACTOR: Chandler Evans
REPORT TITLE: "Vapor Generator Feed Pump for Rankine Cycle Automotive Propulsion System (Chandler Evans)."
NTIS ACCESSION NUMBER: PB 222-849
NTIS PAPER COPY PRICE: $5.50
NTIS MICROFICHE PRICE: $1.45

APTD - 1358
REPORT DATE: December 1972
CONTRACT NUMBER: 68-01-0437
CONTRACTOR: Lear Motors Corporation
REPORT TITLE: "Vapor Generator Feed Pump for Rankine Cycle Automotive Propulsion System."
NTIS ACCESSION NUMBER: PB 222-871
NTIS PAPER COPY PRICE: $3.50
NTIS MICROFICHE PRICE: $1.45

APTD - 1359*
REPORT DATE: December 1972
CONTRACT NUMBER: 68-01-0405
CONTRACTOR: Williams Research Corporation
REPORT TITLE: "Automotive Gas Turbine Economic Analysis."
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1374
REPORT DATE: February 1973
CONTRACT NUMBER: 68-04-0014
CONTRACTOR: AiResearch Manufacturing Company of Arizona
REPORT TITLE: "Low NOx Emission Combustor Development for Automobile Gas Turbine Engines."
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1441
REPORT DATE: February 1973
CONTRACT NUMBER: 68-04-0016
CONTRACTOR: Solar Division, International Harvester Company
REPORT TITLE: "Low NOx Emission Combustor for Automobile Gas Turbine Engines."
NTIS ACCESSION NUMBER: PB 222-818
NTIS PAPER COPY PRICE: $7.25
NTIS MICROFICHE PRICE: $1.45

* NOTE: See Supplement Report EPA-460/9-73-001

APTD - 1454
REPORT DATE: February 1973
CONTRACT NUMBER: 68-04-0017
CONTRACTOR: Northern Research and Engineering Corporation
REPORT TITLE: "Low NOx Emission Combustor for Automobile Gas Turbine Engines (Northern Research and Engineering Corporation)."
NTIS ACCESSION NUMBER: PB 222-340
NTIS PAPER COPY PRICE: $11.25
NTIS MICROFICHE PRICE: $1.45

APTD - 1457
REPORT DATE: February 1973
CONTRACT NUMBER: 68-04-0015
CONTRACTOR: United Aircraft of Canada Limited
REPORT TITLE: "Low NOx Emission Combustor for Automobile Gas Turbine Engines."
NTIS ACCESSION NUMBER: PB 222-075
NTIS PAPER COPY PRICE: $6.75
NTIS MICROFICHE PRICE: $1.45

APTD - 1468
REPORT DATE: March 1972
CONTRACT NUMBER: Interagency
CONTRACTOR: Bureau of Mines
REPORT TITLE: "Emission Characteristics of Spark Ignition Internal Combustion Engines Used as the Prime Mover in a Hybrid System."
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1516
REPORT DATE: April 1973
CONTRACT NUMBER: EHS 70-117
CONTRACTOR: Battelle Columbus Laboratories
REPORT TITLE: "Low Emission Burners for Automotive Rankine Cycle Engines."
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1517
REPORT DATE: May 1973
CONTRACT NUMBER: 68-04-0033
CONTRACTOR: Mechanical Technology Incorporated
REPORT TITLE: "Transmission for Advanced Automotive Single-Shaft Gas Turbine and Turbo-Rankine Engine."
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1545
REPORT DATE: July 1972
PRIME CONTRACT NUMBER: 68-04-0004
PRIME CONTRACTOR: Steam Engine Systems Corporation
SUB CONTRACTOR: The Bendix Corporation
REPORT TITLE: "Steam Car Control Analysis."
NTIS ACCESSION NUMBER: PB 222-349
NTIS PAPER COPY PRICE: $11.25
NTIS MICROFICHE PRICE: $1.45

APTD - 1546
REPORT DATE: September 15, 1972
CONTRACT NUMBER: 68-04-0012
CONTRACTOR: AiResearch Manufacturing Company of Arizona
REPORT TITLE: "Automobile Gas Turbine Engine Study"
NOTE: This is a summary report of APTD-1291.
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1554
REPORT DATE: June, 1973
CONTRACT NUMBER: 68-04-0019
CONTRACTOR: University of Michigan
REPORT TITLE: "Heat Transfer and Flow Friction Performance of Heated Perforated Flat Plates"
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1558
REPORT DATE: December 15, 1972
CONTRACT NUMBER: 68-04-0034
CONTRACTOR: Sunstrand Aviation
REPORT TITLE: "Transmission Study for Turbine and Rankine Cycle Engines"
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1563
REPORT DATE: June 1973
CONTRACT NUMBER: 68-04-0030
CONTRACTOR: Monsanto Research Corporation/Sunstrand Aviation
REPORT TITLE: "Optimum Working Fluids for Automotive Rankine Engines, Volume I - Executive Summary"
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1564
REPORT DATE: June 1973
CONTRACT NUMBER: 68-04-0030
CONTRACTOR: Monsanto Research Corporation
REPORT TITLE: "Optimum Working Fluids for Automotive Rankine Engines, Volume II - Technical Section"
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1565
REPORT DATE: June 1973
CONTRACT NUMBER: 68-04-0030
CONTRACTOR: Monsanto Research Corporation
REPORT TITLE: "Optimum Working Fluids for Automotive Rankine Engines, Volume III - Technical Section - Appendices"
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

APTD - 1566
REPORT DATE: June 1973
CONTRACT NUMBER: 68-04-0030
PRIME CONTRACTOR: Monsanto Research Corporation
SUBCONTRACTOR: Sunstrand Aviation
REPORT TITLE: "Optimum Working Fluids for Automotive Rankine Engines, Volume IV - Engine Design Optimization"
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

EPA SERIES REPORTS

EPA - 460/9-73-001
REPORT DATE: July 1973
CONTRACT NUMBER: 68-01-0405
CONTRACTOR: Williams Research Corporation
REPORT TITLE: "Automotive Gas Turbine Economic Analysis, Investment Cast Turbine Wheel Supplement"
NOTE: This is a supplement to APTD - 1359.
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

EPA - 460/3-73-001
REPORT DATE: September 1973
CONTRACT NUMBER: 68-01-0461
CONTRACTOR: General Electric Company
REPORT TITLE: "Development of Low Emission Porous-Plate Combustor for Automotive Gas Turbine and Rankine Cycle Engines"
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

EPA - 460/3-73-003
REPORT DATE: October 1973
CONTRACT NUMBER: 68-01-0408
CONTRACTOR: General Electric Company
REPORT TITLE: "Design of Reciprocating Single Cylinder Expanders for Steam Final Report"
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
NTIS MICROFICHE PRICE:

EPA - 460/3-73-004
REPORT DATE: October 1973
CONTRACT NUMBER: 68-04-0036
CONTRACTOR: Solar Division International Harvester Company
REPORT TITLE: "Low Emission Combustor/Vapor Generator for Automobile Rankine Cycle Engines".
NTIS ACCESSION NUMBER:
NTIS PAPER COPY PRICE:
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APPENDIX

REPORTS RELATED TO THE AAPS PROGRAM

APTD - 69-51 — NTIS ACCESSION NUMBER: PB 192-321
REPORT DATE: October 1969 — NTIS PAPER COPY PRICE: $3.00
CONTRACT NUMBER: PH 86-67-109 — NTIS MICROFICHE PRICE: $1.45
CONTRACTOR: Battelle Memorial Institute
REPORT TITLE: "Study of Unconventional Thermal, Mechanical, and Nuclear Low-Pollution-Potential Power Sources for Urban Vehicles."

APTD - 69-52 — NTIS ACCESSION NUMBER: PB 194-814
REPORT DATE: October 1969 — NTIS PAPER COPY PRICE: $3.00
CONTRACT NUMBER: PH 86-67-108 — NTIS MICROFICHE PRICE: $1.45
CONTRACTOR: Arthur D. Little, Inc.
REPORT TITLE: "Prospects for Electric Vehicles, A Study of Low-Pollution-Potential Vehicles - Electric."