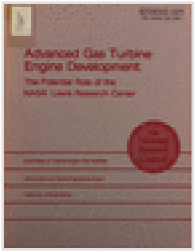

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ADVANCED GAS TURBINE ENGINE DEVELOPMENT: THE POTENTIAL ROLE OF THE NASA LEWIS RESEARCH CENTER

Turbine Engine Test Facilities Committee

Aeronautics and Space Engineering Board
Assembly of Engineering
National Research Council

National Academy of Sciences
Washington, D.C. 1977

NOTICE

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Washington, D.C. 20418

PREFACE

The superiority of American aircraft and aeronautical equipment, both military and civilian, has long been recognized by other nations. Aeronautical sales, worldwide, are the second most important factor in the nation's foreign trade after agricultural products. (See Figure 1.)

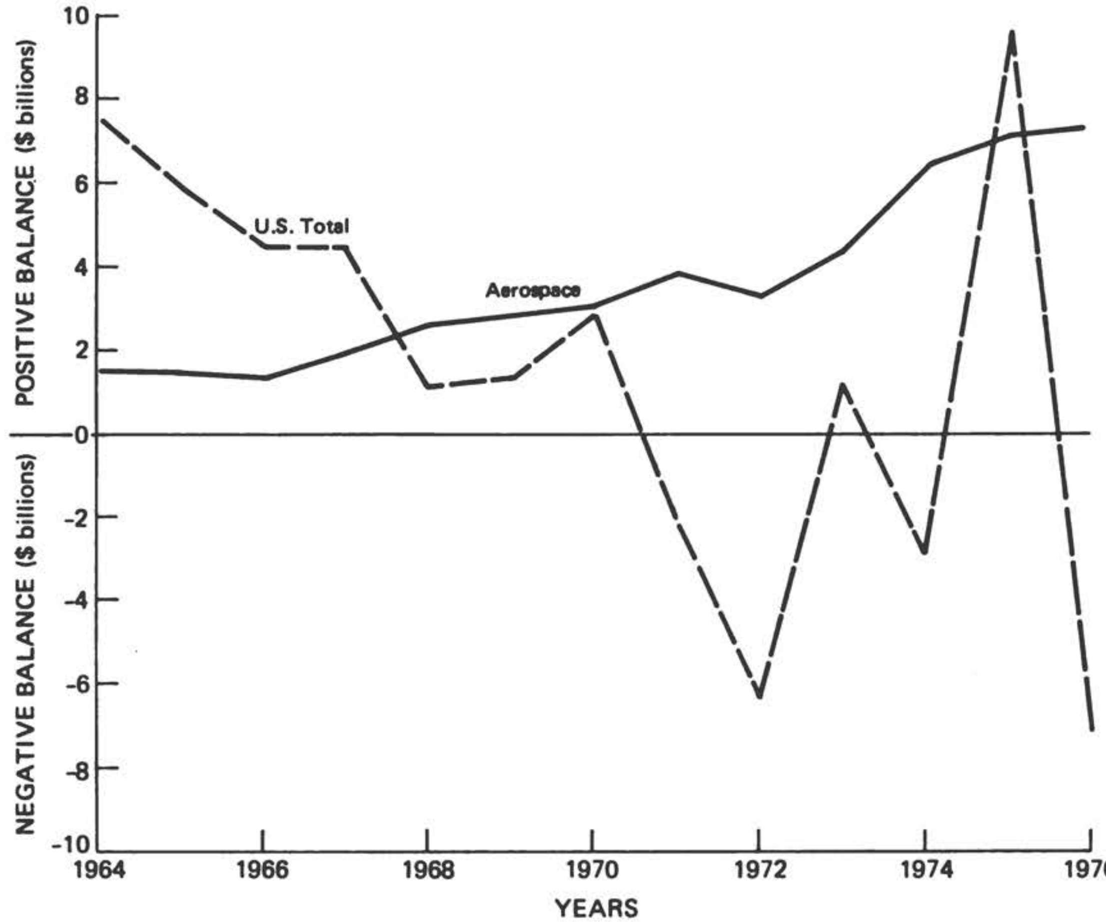
Since the early days of aviation, our nation's success in the aeronautical field has been due in large measure to public and Congressional support of the aeronautical research and development efforts of the National Advisory Committee for Aeronautics (NACA) and its successor agency, the National Aeronautics and Space Administration (NASA). Scientists and engineers in both the NACA and NASA, with their colleagues in the Department of Defense, in industry, and in universities, have created and utilized an extensive array of facilities essential to the testing of new aircraft concepts, advanced engines, and new equipment.

After conducting a thorough examination of proposed military and commercial aircraft and related engine requirements to the year 2000 and beyond, NASA requested the National Research Council to have the Aeronautics and Space Engineering Board (ASEB)* review the engine test facilities and related future plans for NASA's Lewis Research Center in Cleveland, Ohio. The purpose of the review was to determine the requirements for supporting research to facilitate the creation of advanced aircraft engines, and to suggest how the Lewis Research Center could contribute to the nation's energy needs. The ASEB formed an ad hoc Committee on Turbine Engine Test Facilities (TETF)** to study:

1. What the Lewis Research Center could do to advance the state of the art in aircraft propulsion, including the creation of related research and test facilities to support the aeronautical propulsion community.

2. How Lewis and the U.S. Air Force's Arnold Engineering Development Center (AEDC) at Tullahoma, Tennessee, could share

*See Appendix 1 for names of Board members.
**See p. vii for names of Committee members.



SOURCE: Aerospace Industries Association based on data from: Bureau of the Census, "U.S. Exports, Schedule B, Commodity and Country," Report FT 410; "U.S. Imports, General and Consumption, Schedule A, Commodity and Country," Report FT 135; "Highlights of U.S. Export and Import Trade," FT 900 (all are monthly publications).

U.S. Balance of Trade is the difference between exports of domestic merchandise, including Department of Defense shipments, and imports for consumption.

FIGURE 1 Aerospace and Total U.S. Balance of Payments responsibilities for engine testing, taking into consideration what the industry is capable of doing using its own facilities.

3. How Lewis could contribute to the nation's non-aeronautical energy efforts with its research facilities and personnel. The committee was specifically asked to consider how Lewis could best support the national energy program through the exploration and development of alternate energy conversion concepts.

The TETF reviewed NASA's current and proposed aircraft engine programs at Lewis concentrating on test and support facilities. The committee also considered ongoing work at Lewis and elsewhere in NASA to support the Energy Research and Development Administration (ERDA).

To ensure that a national view of available turbine engine test facilities was acquired, the committee visited the AEDC where the Air Force presented its current and planned aircraft and engine development programs as well as its proposals for new facilities to support future developments. During this meeting a briefing was provided on Navy activities, including plans and facilities of its Air Propulsion Test Center at Trenton, New Jersey. At the same meeting, the committee discussed the capabilities of a large-scale aircraft engine compressor research facility now under construction at Wright-Patterson Air Force Base (WPAFB), Dayton, Ohio.

Finally, during meetings held in Washington, D.C., today's industrial test facilities were described by representatives of the General Electric, Westinghouse, and Pratt & Whitney companies. At this meeting, the requirements and future plans for facility support of new, large, ground-based turbine installations for use in the electrical utility industry were considered by the committee and discussed with representatives from ERDA.

These meetings and briefings were supplemented by the following activities by individual committee members:

1. Reviews of the energy work completed and underway at the Jet Propulsion Laboratory, Pasadena, California, and the results of automotive engine studies done there under a Ford Motor Company grant;

2. Discussions with General Electric and Westinghouse on commercial prospects for ground power, particularly the Energy Conversion Alternatives Study (ECAS) done for Lewis;

3. Inspection of and a review of future plans for the compressor laboratory at WPAFB, Dayton, Ohio;

4. Discussions with the Deputy Director of the Southwest Research Institute, San Antonio, Texas, concerning the current management and use of ERDA laboratories, evaluated in a study done by Southwest Research Institute; and

5. Discussions with the President of the Electric Power Research Institute (EPRI), Palo Alto, California, concerning his views of the utility of demonstration ground power installations.

In each case a verbal report was made by the member involved at a subsequent meeting of the TETF committee.

TURBINE ENGINE TEST FACILITIES COMMITTEE
of the
AERONAUTICS AND SPACE ENGINEERING BOARD

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Lockheed Corporation

Hillard E. Barrett
Detroit Diesel Allison Division
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*Donald J. Jordan
Pratt and Whitney Aircraft Division (retired)

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*Chalmer G. Kirkbride
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Purdue University

*George S. Schairer
Boeing Company

Spiridon N. Suciu
General Electric Company

John M. Wild
General Dynamics Corporation

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*NAE member

TABLE OF CONTENTS

RECOMMENDATIONS OF THE TURBINE ENGINE TEST FACILITIES COMMITTEE

The TETF committee recognizes the continuing need for reducing aircraft fuel consumption, engine noise and engine emissions, and for maintaining the efficient performance of aircraft engines after many hours of use. The committee recommends that achievement of these goals should remain as NASA's highest priority mission for its Lewis Research Center.

- To accomplish these objectives, it is recommended that Lewis expand its efforts to stimulate the development of advanced concepts for both military and commercial engines, including those for use in general aviation and helicopters.

- To support this program, it is recommended that Lewis review its facilities requirements, de-emphasizing full-scale, complete engine testing in favor of expanding its component performance improvement tests. For complete engine testing, NASA should seek to establish agreements with the Air Force for reasonable use of the present or expanded facilities for full-scale engine testing at AEDC and the augmented compressor test facilities at WPAFB.

- Lewis should initiate a major activity to develop techniques for conducting research, at less than full-scale, on how engine installations interact with aircraft.

- Adequately trained and talented technical manpower is an essential element to the success of any research program. Because of the diversion of personnel to various space programs, and the aging and recent attrition of top level managers at Lewis, the laboratory should institute a personnel revitalization program that calls for new hiring, internal training programs, and increased interaction with universities.

- The importance of improving the correlation of results obtained from ground testing with those measured in flight, coupled with the ascending costs of testing full-scale engines in ground-based facilities, suggests the development of closer working relationships between Lewis and NASA's Dryden Flight Research Center (DFRC) in the fields of advanced flight test instrumentation and flight test techniques. Such an effort is necessary to find a practical means for determining the effects of engine-airframe interactions. There is a continuing need to improve upon the accuracy in estimating the performance of an installed engine based upon ground engine test data.

In considering the broader involvement of Lewis in national energy programs, the committee recommends that Lewis and NASA headquarters develop a definitive total mission proposal to be submitted to ERDA. The proposal should clearly define the areas of in-house research that Lewis is capable of fulfilling and those areas for which Lewis is capable of serving as the contracting or monitoring agent for ERDA, if such a role appears desirable to NASA as a policy.

If NASA headquarters and Lewis elect to make such proposals to ERDA, the committee recommends that alternatives be considered for Lewis, in the following order. Despite the new work proposed in these alternatives, the committee is convinced that no expansion of Lewis' responsibility should be permitted to diminish its efforts in the field of advanced aircraft engines.

<u>Alternative 1</u>: A limited expansion of research programs and facilities at Lewis beyond, but closely related to, aircraft engine research. This would logically include efforts in the energy field on the use of gas turbines as ground-based electric power generators, research on total ground power systems, on compressors, combustion, turbines, emissions, fuel systems for alternate fuels, bearings, cooling heat exchangers, materials, seals, and studies of the use of new concept gas turbines in advanced ground power systems.

<u>Alternative 2</u>: In addition to Alternative 1, Lewis could extend its research into the automobile engine field to parallel its work in small engines for helicopters and general aviation aircraft.

<u>Alternative 3</u>: The technical resources at Lewis could form the core for providing services to ERDA as an evaluator of new ground power concepts as well as planner and technical monitor of major demonstration ground power generation systems using gas turbine technology.

<u>Alternative 4</u>: Lewis could assume NASA-wide responsibility for technical support to ERDA by utilizing talent from all of NASA's research centers for research on such matters as cryogenic fuels, materials, aerodynamics (windmills), fuel cells, solar energy collection and conversion, and long-range transmission.

The committee suggests that NASA determine the role it believes is most suitable for Lewis' support to ERDA. Once agreement has been reached with ERDA on the work at Lewis, the need for new facilities should be defined and an appropriately increased manpower ceiling should be determined. If Lewis is given new responsibilities in energy research, the committee suggests that ERDA participate in a Center program planning advisory group that includes high level technical representatives from concerned organizations in government and industry.

LEWIS RESEARCH CENTER
HISTORY AND CURRENT CAPABILITY

In 1941 the National Advisory Committee on Aeronautics established what has become the Lewis Research Center in Cleveland, Ohio, to support the budding aircraft industry and the U.S. Army Air Service. Lewis' specific mission was to do research on aircraft engines and on interface phenomena involving airframe components and the engine. Early contributions of Lewis in association with the NACA's Langley Memorial Aeronautical Laboratory at Hampton, Virginia (now known as NASA's Langley Research Center), contributed significantly to the rapid improvement of aircraft performance during World War II.

Later, as the turbine became a potential engine for high performance aircraft, Lewis' efforts shifted to research on compressors, turbines, and burner elements. A major effort was begun in new high temperature materials essential to advance turbine engine performance. As with earlier reciprocating engines, the facilities necessary for testing were designed and installed and the personnel assigned to the tasks. Lewis also participated with government and industrial teams in developing and characterizing the fuels needed for these engines to operate at maximum efficiency.

NACA was reorganized into NASA in 1958 in recognition of the nation's space effort. Existing technical talent at Lewis was organized for needed work in fuels and hardware for advanced rocket engines, and major contributions were made to the space program. Lewis also became a contracting agency for end-use hardware, and specialized managerial talents were developed to conceive, develop, and produce operational equipment for space systems through major development and production contracts with industry.

Parallel with its space efforts, Lewis continued work in support of commercial and military aircraft but, in the view of some observers, essential work in compressors and turbines was neglected. Lewis expanded its capabilities in mechanical engineering, which led to work on drive shafts and transmissions and smaller-scale turbines, making contributions to the Army and the helicopter industry. Such small turbine research also supported the development of auxiliary ground power units for the military services and for many remote civilian installations.

Current Personnel

As the work evolved, Lewis assembled a complement of talented engineers and scientists engaged in turbine engine research, now totalling approximately 650. The TETF committee analyzed only the content of technical activities at Lewis and found the work to be distributed as follows:

- Conceptual studies; cycles, new engine concepts, propulsive lift, etc. — 18 percent
- Materials, mechanics, bearings, seals, etc. — 20 percent
- Engine dynamics and interactions; flutter, element distortion, engine performance. — 15 percent
- Basic engine elements and specialty efforts; compressors, combustors, fuels, pollution, turbines, inlets, nozzles, etc. — 35 percent
- Support to others: ERDA, Air Force, Army. — 12 percent

The opinion was offered by several observers that the capabilities of Lewis to accomplish turbine engine work suffered when NASA increased its emphasis on space programs in 1958, and that it has been only in the last ten years that Lewis has been reactivating its talent for air-breathing engine research and attempting to recruit young people into the field. Some TETF members felt that this situation was responsible for inconsistent progress in turbine component development. Lewis' management believes that it will still take several years to fill out the technologies needed and complete the modernization of the Center's functions (including the acquisition and assimilation of younger engineers to replace many who are reaching retirement age).

Current Facilities

Lewis' facilities have been maintained in excellent condition and are equivalent to modern research facilities elsewhere for engine and component testing and research. In particular, the instrumentation associated with the test stands, wind tunnels, and specialized test rigs appears to be fully adequate for research on modern aircraft engine concepts. The specific major equipment installations are summarized in Table I and described more fully in Appendix 2.

Essential to advanced propulsion system testing is the capability to handle and process large quantities of air and exhaust gases, either for operating engines or for engine element testing. The capacity of the air handling system at Lewis can be compared favorably to the capacity of the industrial facilities used by the major U.S. producers of gas turbine engines and to the current capacity of the Navy and Air Force test facilities which are involved in service and installation testing of new propulsion systems. This comparison is shown on Figures 2, 3, and 4. The test capability indicated by the dashed lines in these figures represents the proposed air handling capability for the new Air-breathing Systems Test Facility (ASTF) to be built at AEDC. Lewis has proposed a similar increase in air handling capacity to support its large engine test cells. The proposal to expand air handling was a major reason for the formation of the TETF committee. The committee's views are presented in the sections of this report on Potential Future Programs and Facilities Implications.

Existing facilities at Lewis are not completely suitable for an expanded role in automobile engine research. If Lewis were to accept such a role, small test cells, different instrumentation, and expanded component rigs will be required. The investment required for these facilities would be small, however, when compared to the expansion of air handling facilities for high altitude testing of large, high-bypass aircraft engines.

Table I

Major Facilities for Aeronautical
Propulsion Research
at the
Lewis Research Center

1. Systems Facilities

   a. 10' x 10' Supersonic Wind Tunnel (M=2-3.5) can operate as a closed return-type tunnel or open exhaust for propulsion testing

   b. 8' x 6' Supersonic Wind Tunnel (M=.4 to 2.0) can operate as a closed return-type tunnel or open exhaust for propulsion testing

   c. 9' x 15' V/STOL Wind Tunnel with capability to operate propulsion units in conjunction with aerodynamic surfaces

   d. Quiet Fan Test Facility with 35,000 hp drive

   e. Vertical Lift Fan Facility capable of testing "in-wing" fans or diverted thrust systems in the presence of a wing

   f. 6' x 9' Icing Research Tunnel can operate as a closed-throat return-type tunnel to test aircraft and components in the presence of ice

2. Propulsion Systems Facilities

   a. 2 - 10' dia. x 24' lg. total engine test chambers
   b. 2 - 24' dia. x 38' lg. total engine test chambers
   c. Noise reduction test facility for complete engines

3. Engine element test facility including air, fuel, and evacuation capability for altitude testing and for testing at elevated temperatures. The specialized facilities include:

   a. Single stage compressor facility (3,000 hp drive)
   b. Multistage compressor facility (15,000 hp drive)
   c. Turbine research facility with 10,000 hp dynamometer capacity
   d. Anechoic chamber for fan and jet noise experiments
   e. Combustor and turbine cooling research facility (with multi-fuel capability)
   f. High pressure and high temperature combustor and turbine research facilities
   g. Small engine test cells

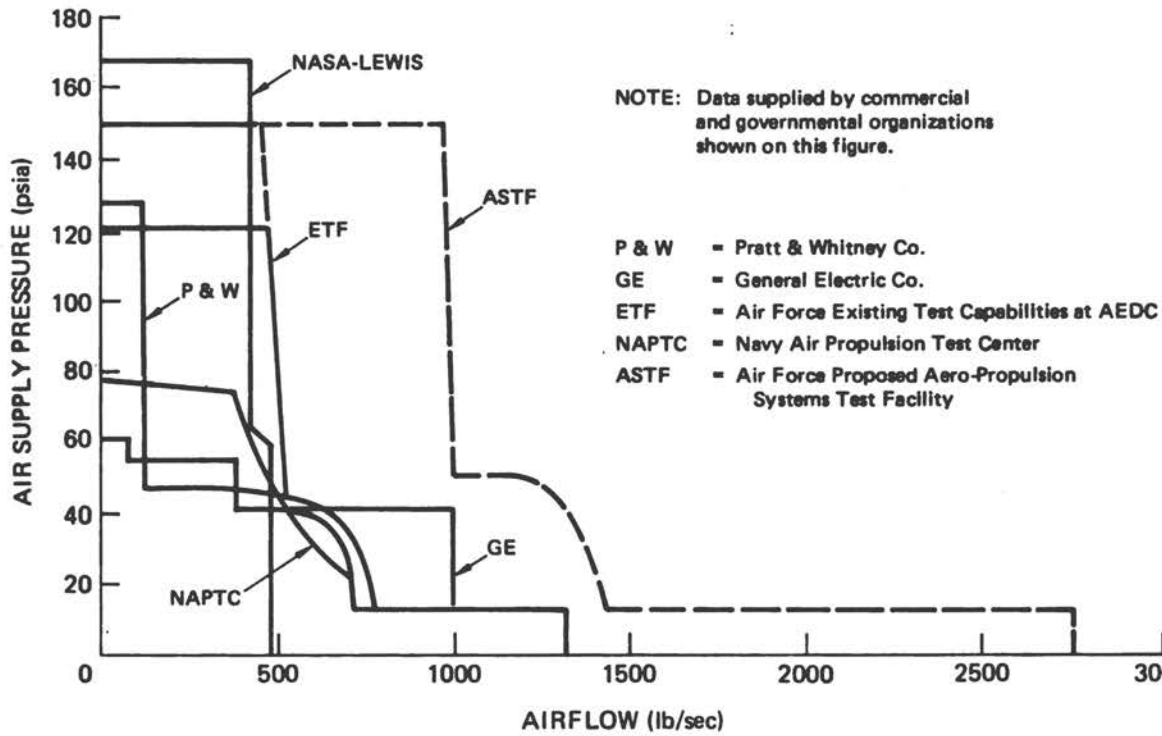

FIGURE 2 Air Supply Capability of U.S. Facilities

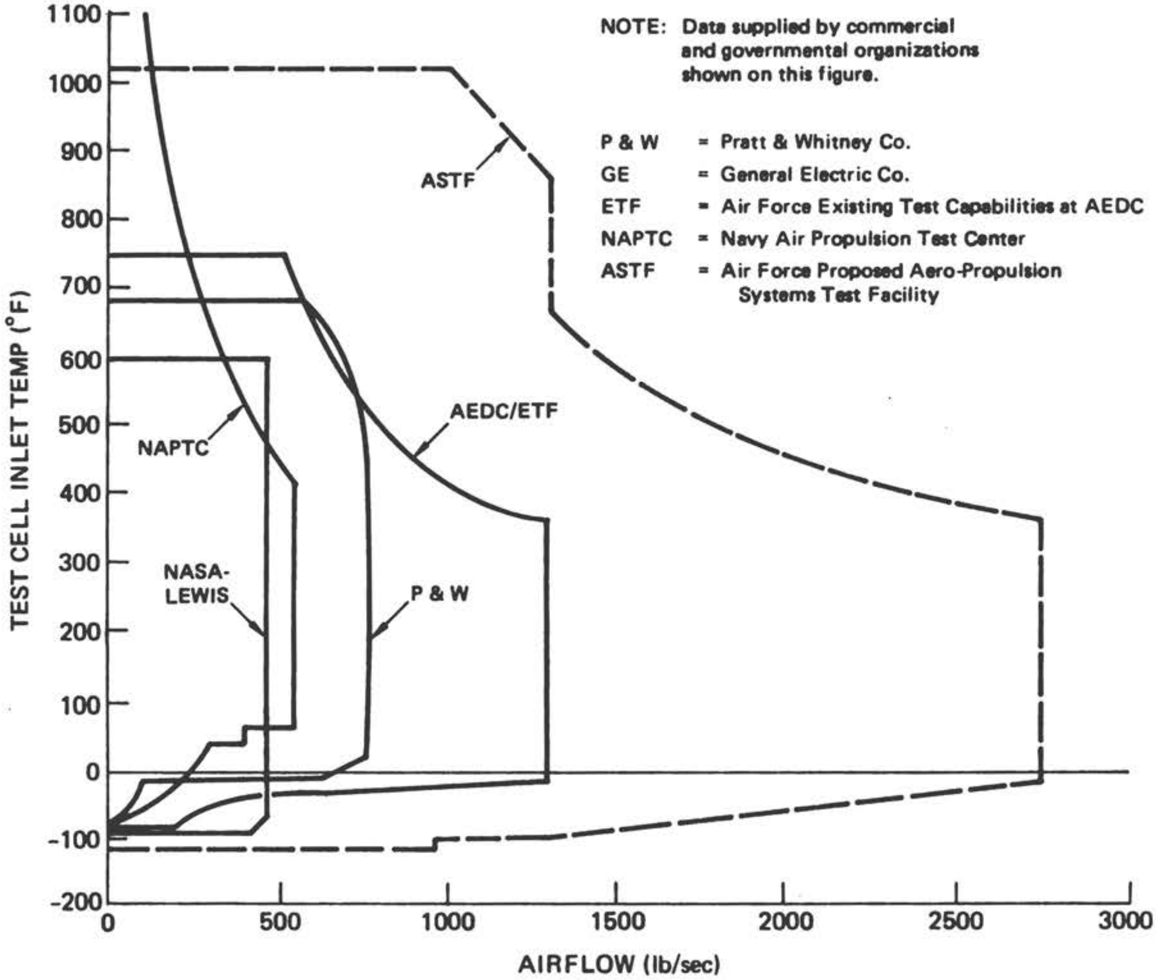

FIGURE 3 Temperature Capability of U.S. Facilities

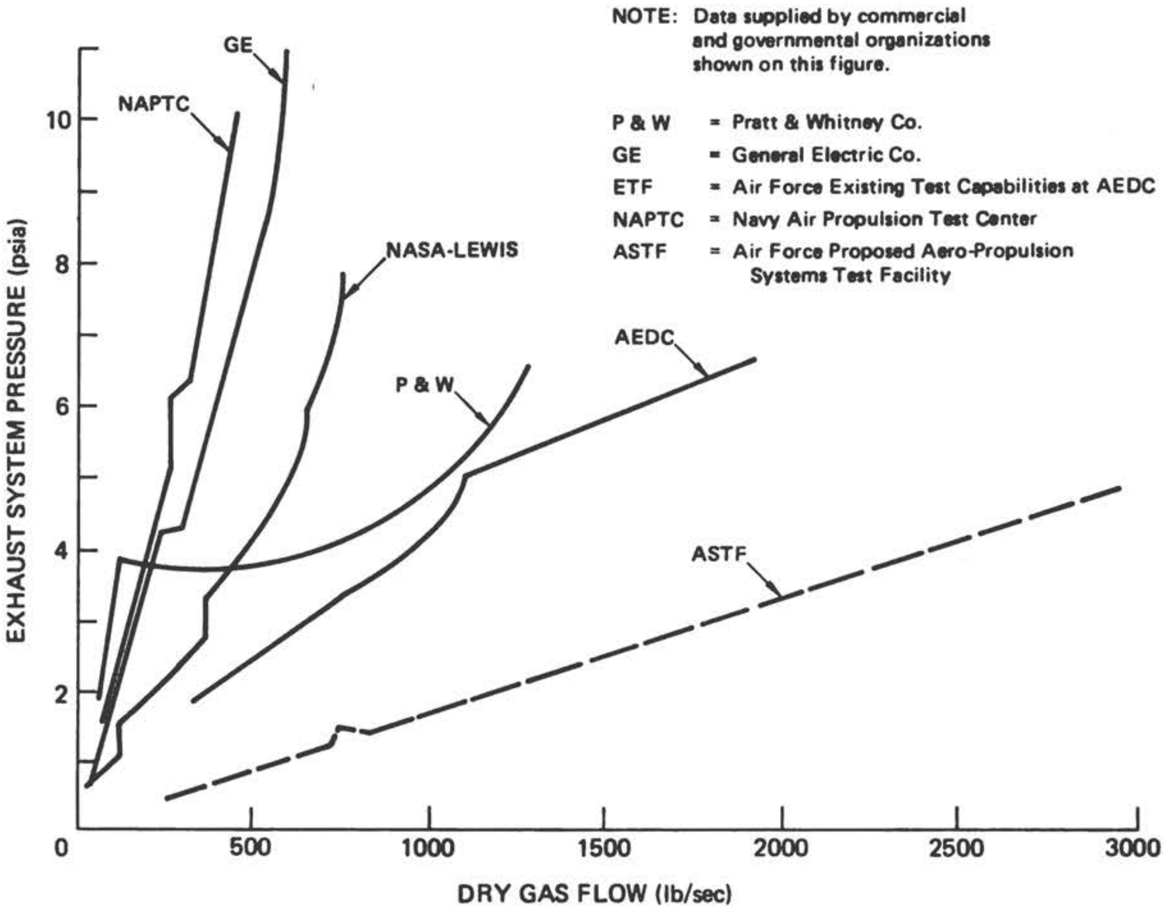

FIGURE 4 Exhaust System Capability of U.S. Facilities

POTENTIAL FUTURE PROGRAMS

Future goals suggest that research plans at Lewis be grouped into two major categories: (1) research that would support improvements for military and commercial engine performance, and (2) research (using the same kinds of technical talent) that could advance new energy systems.

Activities for Improving Aircraft Turbine Engine Performance

Any sound research program should permit and encourage creative engineers to conceive of systems that would make major improvements available to future systems users. In the past, the practice of soliciting new design concepts to advance the performance of both military and commercial aircraft has produced benefits. It is clear, however, that specific mission goals, although useful, are not essential to setting targets for research teams in specific disciplines. Lewis could create programs in at least the following areas, thereby offering the opportunity for any improvement in capability (or a step function in performance) to have a major impact in commercial or military systems:

1. Compressor efficiency;

2. Maximized stage loading to reduce the number of stages;

3. Compressor stability over a wide range of capacity and pressure ratio;

4. Techniques for controlling temperature distribution in burners, by cooling or controlled burning, to achieve fuel savings, enhance life, and reduce unwanted emissions;

5. Techniques for air cooling of turbine blades and discs, stator stages, and nozzle guide vanes and extending their operational life;

6. The use of cooling media other than air and particularly the use of coolants, such as hydrogen, which might also serve as fuel;

7. Aerodynamic seals, i.e., the maintaining of optimum clearances under all except the most unusual operating conditions over reasonable operating periods;

8. Prediction of flutter and element distortion to achieve improvements in performance of both the compressor and turbine;

9. Turbo-prop engines;

10. The prime problem now and in the foreseeable future for both commercial and military aircraft fleets is the reliability of hot section parts. In addition to the materials chosen and the methods of cooling used, great improvement is needed in the control of air and fuel in the burning process. This important problem should receive focused attention in Lewis' research. The development of analytic techniques and methods for obtaining optimum fuel and air introduction into burners can improve temperature distribution, reduce noise and undesirable combustion products, enhance fuel economy, improve performance, and decrease maintenance costs. Improvements in reliability will follow when designs for the hot sections are based on more precise knowledge of the burning process.

Along with research on any concept that has promise for major performance improvement should be a program to ensure that these improvements will survive repeated use of the components or exposure to adverse operating environments. The maintenance of high performance throughout the operational life of new engines should receive continuing emphasis in the planning of future research programs. Deterioration of compressor blades, wear of seals, clearance control, and bearing performance are as important to total energy conservation as the achievement of outstanding cycle performance and continuing high performance, and are fundamental to major improvement in aircraft engines, commercial or military. Thus, research in high temperature, long life, light weight material is as critical as any thermodynamic or systems concept in the achievement of higher levels of performance. Improvements in aerodynamic seals and the methodology for predicting flutter and distortion are worthy of considerably more effort.

Research in complex high performance aircraft engines demands facilities for conditioning, pumping, and controlling a variety of fuels for use in component and complete engine testing. Also needed is the sophisticated systems research to derive near optimum engine signals for adequate fuel control, and flexible computer facilities to experiment with response patterns to engine signals for the achievement of proper fuel flow commands. Potential changes in fuel characteristics, needed to enhance refining and permit the use of alternate fuels, impose more challenges on research in fuel systems, and specialized facilities will be required to pursue solutions.

The Air Force, through its development facilities proposals to the Administration and Congress, has emphasized the necessity for full-scale testing of developed hardware when controlled test conditions in ground-based facilities have heretofore provided substantial cost and diagnostic instrumentation advantages over flight testing. Furthermore, with adequate ground test facilities, sustained testing time at specific critical operating conditions can help confirm whether production and engineering development performance levels have been met. This kind of confirmatory test activity, essential to the military services, is not a responsibility of Lewis and, therefore, should not be the basis for NASA test facility requirements.

In spite of this fundamental difference in what Lewis does as compared to the Air Force, Lewis does need some access to full-scale engine test facilities in which complete engines can be operated under controlled conditions in environments that cannot be simulated in current Lewis facilities. This is essential to explore the interaction of engine elements, the characteristics of the total system at both on- and off-design conditions, and the effects of alternate interface configurations between engine elements on total performance. Thus, it seems essential that Lewis and the Air Force must continue a formal arrangement whereby complete engines can be obtained for testing within Lewis or Air Force facilities, and that Air Force facilities must be used by Lewis for complete engine testing when the environmental or air flow capacity requirements for any given test exceed those of existing NASA facilities.

The cost of facilities to properly simulate altitude conditions for the testing of very large engines makes it essential that such facilities not be duplicated. The facilities at AEDC should be managed as a national facility available for Lewis' use whether the engine tested is applicable to commercial or military aircraft or both. These suggestions closely parallel proposals made to NASA by its Research and Technology Advisory Council (RTAC) which recommended a joint AF-NASA-Navy committee to coordinate plans and set priorities for joint programs and individual use of the Air Force facilities.

The high cost of full-scale engine test facilities suggests another essential research program which appears to be primarily a NASA responsibility. This effort involves the development of methods for conducting research on inlets and nozzles in the presence of real engines. Research on the interaction of engines with inlets at varying airplane altitudes, attitudes and Mach numbers, and research on the effects of engine exhausts, under similar conditions, demand pumping capacities and environmental protection schemes that are likely to be extremely costly. The availability of relatively small engines with modern cycles suggests that valid small-scale simulation of full-scale interaction phenomena should be possible. The development of such simulation techniques should be high on the Lewis priority list. Such a program would benefit future military and commercial programs alike.

In a similar vein, Lewis and the Dryden Flight Research Center might jointly undertake a program to develop new techniques for exploring engine-airframe interactions in flight. The objective should be to develop techniques which would be more competitive with large ground test installations in terms of cost as well as in the quality and quantity of results. The Air Force successfully used such techniques in the early 1950's to supplement the testing done in ground-based facilities for the development of high Mach number, ramjet-airframe combinations. Similar techniques may be applicable to advanced turbine engines, ramjets, or mixed-cycle hypersonic thrust concepts demanding large airflows at high altitudes and speeds.

In studying what Lewis has been doing to advance commercial aircraft engines and what it might do in the future, a few policy directions and areas were suggested for program emphasis:

- Lewis should not relax its efforts in analyzing new concepts of engines and cycles for commercial aircraft.

- A similar conceptual emphasis on new cycles for small power conversion units may be required. High performance is required for aircraft auxiliary power units, light commercial aircraft, and helicopters. The information gathered in the development of small size aircraft propulsion elements may also be directly applicable to automotive engines.

- Although many new technologies exploited by the military may be directly applicable to commercial engines, the basic requirements of military and civil propulsion systems appear to be diverging. Thus, a specific Lewis research program designed only to support new commercial engine concepts seems justified.

- The prolonged testing of complete large engines is expensive and imposes major financial burdens if the facilities are provided to do such testing at the extremes of the operational environment. Performance testing of such engines to confirm their qualities should normally be left to the operators, manufacturers, or DoD.

- Full-scale programs directed toward improving the reliability of commercial engines should be approached carefully because of the difficulty in setting rational standards and the extremely high rate of operational time accumulated by the commercial airlines. The setting of standards for engine reliability is not a NASA responsibility. Testing of advanced materials, gears, pumps, bearings, lubrication, and new concepts of parts cooling all hold promise of contributing more to high reliability than prolonged testing by NASA of today's complex total systems or operational sub-systems.

- Many interface problems exist between elements of a large engine. Lewis can and should contribute to their solutions. Moreover, Lewis should concentrate on techniques for solving such problems without resorting to full-scale engine testing in the many environmental regimes within which these engines must operate. If such full-scale testing is necessary to address a critical interface problem and exceeds the capacity of present Lewis facilities, the work should be done in the Air Force's ASTF of the AEDC by Lewis personnel.

- The results of Lewis' work with the Army on small turbines and their accompanying transmissions and power shafts are applicable to small commercial aircraft engines. Lewis should explore the potentials in this field because the application of new technologies to general aviation engines has been slow. The emphasis on cost in the evolution of general aviation designs inhibits the use of many technologies now available. Thus, work on general aviation engines should be aimed at concepts that show promise of reducing costs as well as improving performance. Such emphasis is similar to the factors influencing research on automobile engines and, therefore, if Lewis is assigned to do research on automobile engines, the emphasis on cost should also benefit general aviation.

Possible Activities in Support of ERDA

In the government reorganization that created ERDA, 90 percent of the Atomic Energy Commission, all of the Office of Coal Research, half of the Bureau of Mines, all of the solar and geothermal research projects of the National Science Foundation, and a major project on advanced automobile propulsion of the Environmental Protection Agency (EPA) were consolidated into a single agency. As another independent agency, NASA has the potential to make major contributions to ERDA programs in at least three general categories:

- Direction of major systems programs demanding technological judgment;
- Conversion of chemical energy to power via turbine and other engine systems;
- Support of other high technology energy development needing special skills and knowledge in fluid mechanics, structures, materials, fuels, control systems, test techniques, related instrumentation, and knowledge of where supporting technology exists within industry and other government agencies.

Systems Direction or Integration

Lewis has already demonstrated its ability to examine major systems through the Energy Conversion Alternatives Study completed for ERDA in 1975. There are many similar conceptual and cost-benefit studies essential to the support of national energy policies that Lewis could manage. These include, for example, the systems to produce and use synthetic fuels based on coal and the location of major facilities to minimize transportation delays and safety hazards while optimizing energy usage.

In coordinating such elements in aeronautical propulsion as fuels, materials, interaction with airframe elements, maintenance, and noise suppression, Lewis has demonstrated its ability to manage complex research programs involving government and industry. This kind of management service should be helpful in other major energy programs. In supporting the nation's space effort, Lewis has acquired the professional talent, test competence, and research background in a number of areas directly related to future energy systems. These include solar energy, such small power sources as auxiliary power units and power cells, heat exchangers, such power storage devices as flywheels, and major development background in handling and using cryogenic fuels.

As a result of its support to the aviation industry and its continuing cooperation with DoT's Federal Aviation Administration, Lewis is familiar with advanced safety concepts developed for new transport aircraft. These include, for example, failure analysis of turbines; "multiple vote" control systems to preclude engine failures or to control them should they fail; "fail safe" and "fail operative" concepts of mechanical parts, structural elements, and control systems; and the long-life design of system elements exposed to varying loads. All of these rapidly developing systems concepts are directly applicable to energy systems.

Conversion of Chemical Energy to Power with Turbines

Lewis' effort in this field has contributed to the worldwide eminence of U.S. aircraft turbine engines. The performance demands upon such engines will continue to demand research well beyond the boundaries of current knowledge. Lewis' research programs in the following fields are directly applicable to ground power turbines and should provide the base for substantial performance improvements:

- Compressor and turbine aerodynamics
- Ceramic materials
- Liquid cooling of hot systems--burners, nozzle guide vanes and, perhaps, even turbine blades
- Air-cooled turbine blades
- Intercoolers and aftercoolers
- Exhaust emission control
- Digital (multiple safety) fuel controls.

The background on turbine and rocket engine operation with a variety of fuels and the understanding of combustion phenomena now available at Lewis can be used directly in the investigation of synthetic fuel application to ground power generation. The characteristics and specifications for new fuels to be used in ground power installations can be developed in the same manner as fuels for aircraft and automobiles. Accordingly, ground power installations may be developed to burn fuels with broader characteristics, thus leading to lower cost. "Fuel compatibility" is a unique technology which could be part of the Lewis mission. This is not meant to include fuel processing as in a "coal-to-fuel" or "well-to-user" processing system but only to the carefully developed specifications and tolerance margins of the end product. Lewis could provide important technical support to ERDA's Coordinating Research Council, an active interface for users with large fuel requirements in the automotive, aircraft, railroad, and petroleum industries, as well as in the military.

Support of Other High Technology Development

The current emphasis on fuel saving and emission control for automobile engines has had a slowing effect on alternate cycle research. Furthermore, rapid conversion of manufacturing capacity to new engine concepts would demand capital investments that could be prohibitive for even the largest of the nation's manufacturers. ERDA has explored a number of new automobile engine cycles and has considered several concepts for national research centers. Lewis should be able to engage in such activities to support ERDA, thus saving the cost of a new national center. If Lewis proposes such a supportive role to ERDA, it should design its programs and facilities to recognize a potential close relationship between future automobile engines and those suitable for private-owner aircraft. This relationship could accelerate work toward improved fuel consumption and exhaust emissions for small engines, suggest lighter weight approaches to automobile engines, and promote less expensive ones for the private-owner aircraft market.

Fuel systems for a wide variety of power installations have occupied Lewis through the aircraft turbine and space power portions of its history. Lewis is familiar with the fuel handling problems in cryogenic systems and the precise control of such systems to optimize performance.

The understanding of heat exchangers, as well as the promise and limits of their development, will be needed in fuel conservation work on ground power systems and certainly in automobile systems. Heat exchangers will also be an element in any fuel-based power cell. Lewis has such technological background.

Materials technology is essential to any power conversion system. Although Lewis is not the only NASA center--and certainly not the only national center--for materials development, its work has been concentrated on those materials most likely to enhance the performance of turbines and other engines--ceramics, stainless steels, other high temperature steels, casting techniques, and protective coatings to prevent high temperature erosion or corrosion. Of equal importance are the materials necessary to provide long life, such as seals, bearings, and gears--all subjects of major Lewis programs.

As higher levels of performance are sought, the dynamics of turbine elements occupy all aircraft turbine developers, and this will be an important concern in ground power turbines. Lewis brings a long history of accomplishment in this field which can be applied beyond aircraft engines.

Lewis has an essential and advanced capability in the design and application of instrumentation systems, including recording and data analysis. These techniques would be a valuable contribution to the development of new, complex energy conversion systems.

MANAGEMENT IMPLICATIONS

In reviewing the potential of the Lewis laboratory to continue serving the aircraft and space industry, while serving an expanded community in the energy field, the committee has posed a number of management questions.

National Decisions

Establishing new centers of technical excellence to solve the nation's energy problems should be unnecessary when the expertise already lies within existing government laboratories with extraordinary capabilities. Lewis can provide expertise outside the aircraft field in turbine engines, internal combustion engines, mechanical power transmissions, the use of alternate fuels, and the application of such power systems to stationary power generation, automobiles, and other ground transportation systems. If Lewis is assigned a major role in this field, manpower ceilings will need to be adjusted to prevent its research work in aircraft engines from being diverted.

The aircraft development and manufacturing industry is critically under-financed and dependent on expanding technology. It is characteristic that both commercial and military programs shift from one member of the industry to another. NASA aeronautical research provides an essential and stable base of technological growth for all members of the industry and the military. Such support is much more successful than direct government subsidy to many industries, as is exemplified by the maritime industry and passenger railway industry. Therefore, the promise of new technology lends urgency to the continuation and expansion of the Lewis aeronautical programs.

Joint Agreements with ERDA

NASA, in conjunction with Lewis, needs to present to ERDA a comprehensive plan proposing the use of NASA technological talent and facilities to support the nation's search for new energy alternatives and for converting old energy sources into new supplies of power. The proposal should identify those major energy needs that can be fulfilled by talent at Lewis. Present program-by-program proposals do not permit long range planning, nor do such proposals contain requirements for the total management of major energy tasks, technical direction of industry teams under contract, continuing sponsorship of university contributions in new technology, and education of new practitioners. Lewis has demonstrated outstanding performance in all these. Lewis needs a comprehensive mission assignment from ERDA to serve that agency properly and efficiently. ERDA could benefit from a proposal that showed how a major delegation of research responsibility could be accomplished at Lewis to the nation's benefit.

Technical research centers are most effective when the expertise and enthusiasm of the members can be maintained through challenging work. NASA has followed this precept by delegating the management of major technical efforts to its several research centers. If ERDA should decide to assign responsibility for specific energy efforts to NASA centers, the committee urges NASA to recommend that the same principle should be followed.

If NASA, specifically Lewis, is to assume a major management role for a portion of the nation's energy research, ERDA should participate in the management of Lewis. NASA should propose an in-house advisory group to assist in planning research programs at Lewis that includes high level technical representatives from NASA, ERDA, and from such potential users as the stationary power, ground vehicle, and aircraft industries. Such an advisory board can assess how Lewis is serving the potential users and provide them a communication channel with Lewis that could help guide specific programs and future research activities.

An important element of any NASA-ERDA agreement should be a clear understanding of the basic rules for laboratory management. One example is the permissibility of "across-the-board" use of a center director's fund based on the total activities of the center. This resource, under the director's control, is for the development of proposals based on internally generated ideas. Such a fund is believed to be essential for a center's continuing creative excellence.

Any assignment to NASA centers of major mission responsibilities for energy needs to be accompanied by an appropriate increase of manpower ceilings to help NASA do the required tasks and to recruit and train younger technologists to replace reassigned or retired NASA personnel.

Joint Agreements with the Air Force

In recommending that no major expansion of air handling capacity be considered for Lewis, the committee recognizes that a closer and more formal arrangement with the Air Force will be necessary. Planning for complete engine testing must be more long-range and formal than the planning for component testing. No critical priority justification should be imposed on Lewis to share the use of AEDC. It appears that ample facility time can be made available to NASA without conflicting with Air Force programs, and funding for such time should be included in NASA's budget.

The existing relationships between Lewis and WPAFB regarding component development, particularly for compressor testing, appear to be satisfactory. The committee has noted that added facilities for element testing may need to be created at centers for engine development in industry, within the Air Force, and at Lewis. Thus, some duplication may result and may be desirable.

Internal NASA Management Decisions

Competitive energy proposals from a number of NASA centers could lead to unjustified duplication of programs and, consequently, excessive costs. The specific assignment of energy responsibilities within NASA should be considered before defining Lewis' support to ERDA. Such an assignment could take the form of a lead role for Lewis in all NASA support to ERDA, or NASA could decide to divide the tasks for ERDA among separate centers or to specify the assignment of joint tasks. In any case, NASA and Lewis could make major contributions in:

1. Wind energy,
2. Solar conversion,
3. Geothermal,
4. Hydrogen,
5. Power cells,
6. Automobile systems--alternate cycles, alternate fuels, transmissions,
7. Aircraft power systems, and
8. Stationary power systems.

If the concept of major Lewis participation in the national energy program is accepted in principle by ERDA, a joint ERDA-NASA task force should be established to assign clear tasks to the research center.

NASA should not reduce the number of employees at Lewis working on research in aeronautical propulsion (about 1,300 persons out of a total of 2,600). In fact, manpower ceilings will need to be raised if important energy roles are accepted. This does not mean that talent should not be shifted. To the contrary, mature professionals should be utilized in establishing new programs in energy, while young development technologists and research people should be brought into NASA to participate in energy research as well as in the aeronautical field. A new mission assignment should give Lewis an excellent opportunity to acquire able young researchers and train them in programs directed by more experienced practitioners.

NASA should consider the phaseout of Lewis' support to future space systems. Sufficient talent is believed to exist elsewhere in NASA to support space activities now being performed at Lewis, and approximately 900 people now employed in such work could contribute to new energy programs. It is noteworthy to state here that all committee members did not agree on the desirability of such a phaseout. All of the committee members did agree that NASA should study such a phaseout, if a major energy responsibility were to be assigned to Lewis.

A critical review is suggested for the proposed work by Lewis in energy-conservation power systems for aircraft. Work on components for future engines could have substantially more potential benefit than complete new engine design and development. In particular, caution should be exercised in producing "demonstration" engines because they divert technical manpower from more fundamental research and tend to lead to considering the use of such engines on new (or old) aircraft before the economic justification for such an engine is established. Total new engine concepts are likely to result from the use of good basic cycle and component data when the combination of new market requirements and clear economic justification coincide. This comment is equally pertinent to automobile and ground power turbine engine concepts. Lewis should involve industry and the military in exploring new engine cycle and design ideas so that its research can support those concepts that appear to have the most promise.

FACILITIES IMPLICATIONS

In considering the future facilities at Lewis, the committee took the position that it must first assume alternative future roles for Lewis and then outline the facility implications of those new roles. New responsibilities that Lewis could undertake were assumed to be: aircraft only, aircraft plus automotive, and aircraft, automotive, and ground power, including turbine engines for electric power.

Aircraft Engine Facilities

The primary question of expanding Lewis' facilities for air handling in order to test larger complete engines at the speeds and altitudes for which they were designed was addressed thoroughly. The TETF committee recognized the desirability of such facilities and is fully aware of the fact that the current 50,000 lb. thrust engines are not the ultimate in engine development. It is also obvious that much higher altitudes will be reached in the future by both military and commercial aircraft. It is axiomatic, therefore, that some means must be found for adequate testing of such engines to confirm their overall performance and to explore the problems of their interaction with new concepts of airframes. Furthermore, current deterrents to the development of a supersonic transport--high costs, airport noise, effects, if any, on the atmosphere, and sonic signature--may be susceptible to technological advances, and research toward the solution of such problems should continue. Accordingly, research targets were the basis for proposing that arrangements be made for NASA to do full-scale testing at the AEDC.

The amount of such full-scale, high speed, high altitude testing in ground facilities will eventually be limited by the substantial costs involved. The nation cannot continue to expand its ground facilities to parallel the engine concepts that will be required. In addition to exploring how such testing can be combined with Air Force testing at AEDC, Lewis should, in conjunction with other NASA centers, develop techniques for engine research, particularly in the field of engine-airframe interactions, at reduced scale, so that current facility capabilities would not be exceeded and substantially more information could be obtained for a given budget level.

Moreover, in conjunction with NASA's DFRC, Lewis should explore new concepts of flight testing to evaluate engine-airframe interaction either with manned or unmanned vehicles, to improve the validity of the results, and to develop concepts to reduce costs and increase information achievable through such testing. This approach should be aimed at a substantial improvement in instrumentation and testing techniques so that critical data need not always be obtained from continuously larger and more expensive ground facilities involving the compressing, cooling, cleaning, and distribution of large quantities of air.

Improvements in the performance of future aircraft engines, particularly those improvements that lead to major conservation of fuel, are dependent on a multitude of small improvements within the components of future engines. A catalog of component test facilities and potential expansion and improvement of these facilities should be reviewed carefully. Changes in component test facilities are probably required at Lewis even if aircraft engines are to be the sole responsibility at the center. Component improvement will involve experiments at substantially higher temperatures, more detailed exploration of flow patterns and interstage phenomena, use of new cycle concepts, possibly involving intercoolers, and certainly new concepts of component cooling.

Also inherent in the development of advanced engines, particularly the more fuel-efficient concepts, will be advanced work in materials to withstand higher temperatures, better seals, different concepts of clearance, control, bearings, and detail dynamics of blades. Facilities for element research as well as for engine components should not constitute a major facility investment as compared to expanded full-scale total system testing and should be considered by Lewis for future capital expenditures.

Aircraft and Automotive Engine Facilities

If Lewis were to accept this combination of roles, the facilities implications are relatively modest from a financial standpoint--roughly analogous to the facilities additions necessitated by work on small turbine engines, transmissions, and drive mechanisms being done for the Army. The emphasis on cost and long life and the difference in the environment of use suggests that special facilities would probably be required to avoid conflicts in priorities. Furthermore, a number of different cycles should probably be investigated for automobile engines, many of which may need specialized facilities. The facilities in place today and those planned for the future for materials, bearings, heat exchangers, seals, and gear drive systems are equally applicable to automotive exploratory research and could be used for both purposes.

Facilities Implications of Ground Turbine Engine Research in Support of the Electric Utility Industry

The facilities required, if Lewis were to be given national responsibility in this broad energy field, will depend on many concomitant decisions, including:

- o To what extent the U.S. will sponsor demonstration power centers;
- o The nature of the alternate fuel program within the U.S. and where the alternate fuels will be compounded for early experimentation; and
- o Whether ERDA will sponsor ground power experiments for a number of alternate cycle concepts simultaneously.

The committee recognizes that these matters require policy decisions, but it is possible to suggest major areas of Lewis' possible contribution that might assist NASA in making policy proposals to support ERDA. Chauncey Starr, President of the EPRI, offered these opinions during an interview concerning Lewis' potential:

- o "Steam and gas turbine failures are the source of the largest number of power failures in the U.S."
- o "The entire industry needs a national source of valid information and technological advances in materials, bearings, anticorrosion, high temperature effects, combined cycles, chemical combustion from different fuels--slurries, synthetic fuels, etc."

There is a distinct and close relationship between these problems and those of advanced aircraft turbines. It is on this basis that NASA should include in any proposal to ERDA the use of Lewis' technological capability and management experience to create a national center for ground turbine power research and exploratory development.

The facilities implications of such a decision would certainly include:

- o Study of existing component facilities to determine if their expected workload and current scale permit substantive work in support of large ground power units.
- o Consideration of alternate component cooling systems and agents that are unique to ground-based turbines and require special experimental facilities.
- o Plans for developing alternate fuels and availability of such fuels via transport systems, pipelines, etc. Experiments with alternate fuels may dictate the location of a

ground power turbine research facility. The alternative is to propose gasification or other similar facilities near the site chosen for power experimentation with alternate fuels. Also implied is the expansion of deposition and erosion instrumentation, as well as a critical review of exhaust cleansing facilities.

- Power requirements for component testing and availability of such power on an intermittent basis. (The opposite of this requirement also exists--namely, the availability of a customer for excess power that may be developed in full-scale turbine testing.)

- Potential need for using different combustion and heat exchanger systems from those that are suitable for aircraft, such as fluidized beds and high temperature steam exchangers.

- Need for total system control concepts and simulation facilities necessary to explore alternate concepts. It appears that Lewis' capability developed during research on aircraft power systems should be directly applicable.

- Effects on the environment of Cleveland and its outlying communities as well as Lake Erie might be great if ground power experimentation expanded Lewis' power demand to a large degree.

Before the future of fossil fuel power conversion plants in the U.S. is defined, the question of government-sponsored large demonstration power stations will undoubtedly be considered. Any definition of such operational experiments could be a potential responsibility for Lewis. Its capability for conceiving and analyzing complex advanced systems would be valuable in any such programs. The TETF committee has taken no position on whether such demonstrations should be sponsored, but suggests that Lewis could make a contribution and should be limited to the conceptual phases of the program and to the function of technical monitor. No local facilities at the Lewis complex should be involved.

CONCLUSIONS

The availability of national funds for non-aeronautical energy programs should not divert NASA's attention from the research needs of the aeronautical community. This conclusion stems not only from the conviction that aeronautical engine research continues to be needed, but also from the conviction that new aircraft engine concepts represent the most demanding technical challenge and that successful research in this field will produce knowledge applicable to the entire national energy effort.

The performance promise of future aircraft depends critically on new engine research. The need for high and low altitude emission control, the potential for larger engines to make cargo aircraft more competitive with surface systems, the efficient use of fuel at supersonic speeds for long-range military aircraft, and the continued pursuit of lower noise levels all demand the highest quality of technical talent and continuing national support of aircraft engine research.

With respect to Lewis' activities in support of new aeronautical concepts, a critical review of past internal planning may be in order to set priorities. Three issues should be addressed:

First, the desire to demonstrate advances in the fields of sound suppression and fuel efficiency may put undue emphasis on the testing of complete engines to the detriment of work on advanced engine components; and the committee favors increased emphasis on the latter.

Second, advanced concepts for both commercial and military aircraft engines will face demands for improved fuel consumption, which, in turn, will require a shift in emphasis in many component research programs; and

Finally, the large cost of creating and operating essential air handling facilities and the need for even larger engines and higher performance aircraft virtually dictates that a major effort be directed toward developing new methods and techniques for exploring engine performance and engine-airframe interaction phenomena with scale-model testing rather than at full scale.

The management relations among interested NASA research centers, the Air Force's AEDC, and the Air Force's new compressor research facility at WPAFB are excellent. The programs planned for these centers, although overlapping in some limited areas, are not inefficiently duplicative.

Lewis could make major contributions to the solution of certain important non-aircraft energy problems. This center is unique in the U.S. in terms of its available knowledge and research capabilities in gas turbines, and its talent could be applied broadly to any fossil fuel energy conversion concept.

The application of Lewis' capabilities to help solve the nation's energy problems does not demand a major change in Lewis' relationship to NASA headquarters. NASA has properly delegated management responsibilities in the aircraft engine field to Lewis. This management experience can be applied to the management of any new efforts in energy conversion in much the same way that the technical team could be expanded to fulfill a broader energy role.

If its mission were expanded, Lewis' effective ongoing relationships with universities and the technical community are likely to contribute to the acquisition of young technical employees. Such relationships should be nurtured and expanded. The center also has developed efficient contractual relationships with industry and could readily expand contract efforts in new fields of heat engine research and development.

Lewis could provide ERDA with technology and management resources in support of many of the nation's energy programs. Specific contributions could include the exploration of new concepts for systems and such new critical components as:

- Heat engines for transportation systems;
- Heat exchangers for all energy applications;
- Burners and fuel systems based on new synthetic fuels, including compounds utilizing coal or high energy fuels, including hydrogen;
- Fuel energy conversion to electricity;
- Energy storage to satisfy peak electrical load demands;
- Automobile engine exhaust emission control, or new cycles which do not require such control;
- Fossil-fuel-fired electric generating system emission control;
- Large power conversion demonstration centers.

Lewis already has the talent to plan, develop, evaluate program proposals, and serve as the continuing technical monitor in most of the systems and components listed above. Any program of the importance and magnitude of a demonstration center would involve major responsibilities in systems concepts, evaluation, program definition, monitoring, and certification of progress and completion. NASA should consider suggesting to ERDA the use of Lewis' capabilities to fulfill the technical systems monitoring role for major power conversion demonstration centers.

APPENDIX 1

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APPENDIX 2

FACILITIES FOR AERONAUTICAL PROPULSION RESEARCH
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LEWIS RESEARCH CENTER

10 X 10 Foot Supersonic Wind Tunnel

The 10 X 10 Foot Supersonic Wind Tunnel has a Mach number range of 2 to 3.5 and can be operated throughout the entire Mach number range on either an aerodynamic cycle at various air densities or on a propulsion cycle at a fixed density as a function of Mach number. On the aerodynamic cycle, the tunnel operates as a closed return-type tunnel, and on the propulsion cycle it operates as an open non-return type tunnel.

The facility has the following capabilities:

Test Section	10' x 10' x 40' long
Stagnation Pressure	Approximately 200 to 5000 psf absolute (function of Mach number and type of operation cycle)
Stagnation Temperature	Minimum 100°F Maximum 300°F (up to 600°F for short time periods on propulsion cycle with some degradation of air flow)
Air Capacity	No. 1 compressor - 4,635,000 cfm No. 2 compressor - 1,350,000 cfm No. 1 compressor cooler 1880#/sec 650°F to 120°F No. 2 compressor cooler 2670#/sec 350°F to 120°F
Cooling Tower Capacity	1,104,000,000 BTU/hr. 433,700 hp
Air Dryer Capacity	1,440,000 cfm to .55 grs./lb. dry air (on propulsion cycle)
Air Dryer Time	1-2 hours summer to 8 hours winter
Fuels	Various gas and liquid systems

<u>Quiet Fan Test Facility</u>: The facility consists of an outdoor test stand capable of supporting an aircraft engine fan, including inlet and discharge ducting, 21 feet above grade and 120 feet from the nearest acoustical interference. The fan is powered by a 35,000 horsepower variable speed electric motor located in the 10 x 10 Supersonic Wind Tunnel through a speed increaser gear box and a 125 foot long shaft. Fan speeds up to 4700 rpm can be attained in either direction of rotation. Permanent microphone jacks are set on a 100 foot radius from the test fan and fan controls and instrumentation are provided

along with the acquisition and recording equipment for relevant research data.

8 X 6 Foot Supersonic Wind Tunnel

The tunnel has a Mach number range of 0.4 to 2.0 and can be operated throughout the entire Mach number range on either an aerodynamic cycle or on a propulsion cycle. On the aerodynamic cycle the tunnel operates as a closed return-type tunnel, and on the propulsion cycle it operates on an open non-return type tunnel.

The facility has the following capabilities:

Test Section	8' x 6' x 39' long divided into two sections, supersonic and transonic with the transonic section perforated.
Stagnation Pressure	Minimum 2400 lbs. per sq. ft. absolute. Maximum 3700 lbs. per sq. ft. absolute.
Stagnation Temperature	Minimum 132°F ± 50° Maximum 205°F ± 50°
Air Capacity	1,800,000 cfm to .50 grains/lb. dry air (propulsion cycle).
Air Dryer Time	1/2 hour summer to 12 hours winter.
Cooler	2500#/sec. maximum inlet 300°F, outlet 135°F.
Fuels	Various gas and liquid systems.

<u>9 X 15 Foot V/STOL Wind Tunnel</u>: This facility, used for scale model testing of propulsion systems and wings for vertical and short take-off and landing aircraft, consists of a rectangular test section 15 feet wide by 9 feet high built in the return leg of the 8 x 6 Foot Supersonic Wind Tunnel. Wind velocities up to 175 miles per hour can be provided with uniform velocity profile in the test area. Boundary layer control and elimination of recirculation are provided. There is no capability for altitude simulation. A 3000 psi air supply (for powering air turbine fan motors), remote model controls and extensive data acquisition systems are also incorporated. These systems are shared with the 8 x 6 Wind Tunnel. Because of limitations of the 3000 psi air, the duration and frequency of engine operating time is limited.

Propulsion Systems Laboratory Complex

Consists of four test chambers, control and data acquisition centers and supporting structures, such as cooling towers, air heaters, components, laboratory and equipment building. It is used to test full scale turbojet, ramjet or rocket engines under simulated altitude conditions with controlled temperature and pressure to determine such characteristics as thrust, fuel consumption, air flow, stall limits, blow-out limits, operating temperatures, acceleration characteristics, vibration and starting characteristics.

The complex has the following basic characteristics and capabilities:

Altitude Capability	5,000 ft. to 70,000 ft.
Test Section Dimensions	Chambers 1 and 2 - 10 ft. dia. x 24 ft. lg. Chambers 3 and 4 - 24 ft. dia. x 38 ft. lg. (see below).
Maximum Engine Thrust	Chambers 1 and 2 - 50,000 lbs. Chambers 3 and 4 - 100,000 lbs (see below).
Combustion Air	450 lb/sec at 60 psia.
Heated Air	375 lb/sec at 40^{o}-600^{o}F.
Dehydrated Air	250 lb/sec at 60 psia dried to 9 gr/lb.
Refrigerated Air	110 lb/sec to -50^{o}F
Altitude Exhaust	220 lb/sec at 50,000 ft.

Test Chambers 3 and 4: Consist of horizontal pressure tight cylindrical tanks equipped with a rigid circular diaphragm in which the research engine is mounted, making it possible to maintain a difference in pressure between the engine inlet air and the exhaust or engine back pressure at the tank discharge. Pressure, temperature, flow rate and back pressure can be independently varied to simulate, within the facility capacity, all combinations of flight speed and altitude for the research engine under test. Flow rates up to 450 pounds per second at 60 psia can be provided at temperatures up to 1200^{o}F. Exhauster capacity is 220 pounds per second at 50,000 feet equivalent altitude with coolers capable of cooling engine exhaust gases from 3500^{o}F.

Engine Research Building

The complex consists of fourteen structures housing 65 test cells and offices for research personnel. In the building tests are conducted of energy systems and system components including jet engines, compressors, turbines, combustors, automotive engines, bearings, seals, and lubricants and gears. The overall capability provided by the complex can be described as follows:

Central Air Supply Control Room
Refrigerated Air - Capacity 55 lb/sec at -20^{o}F
Dry Pressurized Air - Capacity 55 lb/sec at 1.5 grains H_2O/lb. air at varying pressures.
Service Air - 3 compressors at 3.2 lb/sec each at 125 psig.
Cooling (low pressure) Air - 900 hp fan with capacity of 50,000 ft^3/min at 56 in. H_2O.
Atmospheric Exhaust System - Center Section - 43,000 ft^3/min at 3 in. H_2O.
Compressor and Turbine Research Facility - 140,000 ft^3/min at 10 in. H_2O.
Southeast and Southwest Wings - 33,000 ft^3/min at 3 in. H_2O.

Six specialized test facilities within the Engine Research Building Complex are described in detail below:

Single-Stage Compressor Test Facility: This facility for fundamental research on single stage aircraft engine compressors consists of a large test cell equipped with a valved atmospheric inlet duct and a valved discharge duct that can be connected to either the atmosphere or to the center altitude exhaust system. The research compressor, connected to these ducts, is powered by a 3000 horsepower variable speed electric-motor and gear box capable of driving the compressor at speeds up to 20,000 rpm. Compressor performance maps covering a range of air densities, pressure ratios and speeds can be obtained. Extensive instrumentation is incorporated to make detailed measurements of research compressor performance.

Multistage Compressor Test Facility: The facility consists of a large test cell equipped with a valved atmospheric air inlet and a valved discharge that can be connected to either the center altitude exhaust system or to the atmosphere.

A 15,000 horsepower variable speed motor and gear box is installed to drive compressor at speeds up to 18,000 rpm and throughout a prescribed operating map covering variations in air density and pressure ratio.

Extensive instrumentation is incorporated to make detailed flow measurement of each blade row as well as overall compressor performance characteristics.

Turbine Research Facility: Implements fundamental research on aerodynamic performance of single stage aircraft turbines. Consists of a large test cell equipped with two 5,000 horsepower water-cooled dynamometers connected in tandem and coupled to the research turbine and rated at a maximum speed of 6,600 rpm. Air to drive the turbine can be supplied to the cell at a flow rate of up to 52 pounds per second, at pressure as high as 40 psi and a temperature of 300°F. Altitude exhaust is connected to the turbine discharge, thereby providing a wide range of pressure ratios through the turbine.

Engine Fan and Jet Noise Facility: Consists of an anechoic chamber approximately 60 feet by 50 feet by 21 feet high and equipped with acoustically treated inlet and exhaust. A variable speed 7,000 horsepower electric motor to power the experimental fan and a compressed air system (30 pounds per second at 40 psig) for nozzle and acoustic measurements.

Combustor and Turbine Cooling Research Facility: Consists of two test installations in one test cell: one station is available for fundamental research on aircraft engine combustors and the other is used for turbine cooling studies. Each installation is provided with combustion air at 450 psi that can be heated to temperatures up to 900°F at flow rates up to 35 pounds per second. Altitude exhaust connection is also available to provide independent variation of air density and pressure ratio during combustor test programs.

The capability is also provided to utilize various fuels, such as methane, propane, or hydrogen and also to run endurance or life tests at flight operating conditions on unique combustor configurations and turbine vanes and/or blades.

High temperature and High Pressure Turbine and Combustor Research Facility: Two test positions are provided, one for turbine research and one for combustor research. A common air supply is provided capable of delivering to either facility up to 200 pounds per second of clean air at a pressure up to 650 psi and a temperature as high as 1150°F. Coolers and scrubbers cool exhaust gases from a maximum of 4000°F to 100°F and remove all particulates and soluble components prior to atmospheric discharge.

Engineer Components Research Laboratory

Facility No. 1 provides for operational testing and evaluation of full-scale jet engine combustors under conditions simulating full engine power, aircraft velocity and flight altitude. Detailed and extensive provisions made for instrumentation, data acquisition and evaluation of test article and performance. The test article can be supplied continuously with unvitiated combustion air at flow rates up to 285 pounds per second, temperatures up to 1200 F and pressures up to 115 psia. Provisions are also made for supplying liquid or gaseous fuels at flow rates as high as 10.2 pounds per second at temperatures up to 750°F and pressures of 1000 psig.

Facility No. 2 consists of two separate test rigs. One is a modified J-75 jet engine that provides vitiated air at 45 psig and up to 2500°F for experimental turbine operation. The other is a cascade rig that can be supplied with up to 30 pounds per second of unvitiated air at 125 psi heated to 1200°F. Research vanes or blades having a span of about 4 inches and a chord of about 2 inches can be accommodated. Six hundred (600) data channels can be recorded in digital form.

Vertical Lift Fan Facility

This noise facility can accommodate two research configurations: one for a pancake-type within-winglift engine and another for a jet engine.

A stanchion assembly allows a within-wing engine having up to 30,000# thrust to be positioned at elevations between 8 and 18 feet above the ground, and to be rotated ±90° about the wing axis. Air at 150 psig is available from a 24-inch pipe to drive the engine.

An engine stand supports a jet engine (having up to 30,000# thrust) with its centerline 9 feet above the ground and can rotate the engine exhaust ±90° while measuring thrust. A wind carriage can move a vertically mounted wing to various positions relative to the engine exhaust, allowing over-the-wing and under-the-wing flap tests.

Both 100 foot radius and 50 foot radius microphone arrays are provided for obtaining acoustical data. A self-propelled weather housing can be quickly moved about 300 feet away from the engine prior to testing.

Noise Reduction Test Facility

Consists of an outdoor test bed on which is mounted an engine support stand capable of anchoring and supporting, during full power operation a 100,000 pound thrust engine with its centerline 13'-6" above grade. In addition to 300 pressure channels and 300 temperature channels associated with engine and component operation, there are 48 extremely accurate and sensitive acoustical channels whose pick-up microphones can be installed within the engine or immediately adjacent thereto as required. Permanent microphone stations are installed at 150 foot radius from the test engine.

Icing Research Tunnel

A single-return, closed throat tunnel, capable of controlled conditions of moisture, temperature, and air speed. Necessary instrumentation is available to monitor conditions imposed by the tunnel on the model.

Used to investigate icing of air inlets (engines, coolers, etc.); spinners--rotating and stationary, wings--convention, slotted, and swept, icing instrumentation, and temperature probes.

Test Section	6' x 9' x 20'
Maximum Air Speed	300 mph
Model Mounts	Floor turnable and wall trunnion mounts.
Heat Exchanger (Heating)	Steam, finned tube, 5,000,000 BTU/hr.
Heat Exchanger (Cooling)	2100 tons cooling; -40°C may be obtained.
Water Spray	6 horizontal spray bars give a uniform 3' x 5' liquid water cloud in the test section; 500 gal. per hr. demineralizer, 450 gal. storage tank.
Icing Protection Services	Heated air. 3 - 1000#/hr. exchangers at 80 psig at 500°F Electric. AC 115/208 volts at 200 amps. DC 28 volts at 50 amperes.
Combustion Air	80# per second at 125 psig.

APPENDIX 3

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