Compatibility of Alternative Fuels with Advanced Automotive Gas Turbine and Stirling Engines

A Literature Survey

James Cairelli and David Horvath
National Aeronautics and Space Administration
Lewis Research Center

May 1981

NOTICE

Compatibility of Alternative Fuels with Advanced Automotive Gas Turbine and Stirling Engines

A Literature Survey

James Cairelli and David Horvath
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

May 1981

N81-27604

SUMMARY

Advanced automotive gas turbine and Stirling engines are being developed as possible alternatives to conventional piston engines. These engines provide the potential of using a wide variety of fuels for transportation purposes. This report discusses alternative fuels for use with advanced automotive gas turbine and Stirling engines on the basis of a literature survey.

Two factors in the design of the advanced automotive alternative engines that will affect alternative fuels capability are the combustor design and the materials that make up the path of the combustion products. The gas turbine literature shows that lean, homogeneous mixtures of fuel and air increase combustor tolerance to low-hydrogen-content fuels. Low-hydrogen-content fuels can cause excessive radiant heating of the combustor. The literature also shows that the types of ceramics being developed for advanced engines are very tolerant to fuel impurities. Present metal engines are sensitive to such impurities as sulfur, sodium, potassium, lead, vanadium, and ash, all of which cause severe corrosion problems. The new ceramics, which will replace the metal components, show promise of being corrosion resistant. Some new advanced combustor designs use a lean, homogeneous mixture of fuel and air that should allow the use of low-hydrogen-content and broad-cut fuels.

Crude oils from coal and oil shale will require costly hydrotreating to produce transportation fuels. However, fuels for the advanced automotive gas turbine and Stirling engines should require less processing than fuels for conventional piston engines. Gas turbine and Stirling engines can be adapted to run very well on alcohols or blends of alcohols and fuel oils and thus can extend petroleum supplies. However, the extent of the adaptability of advanced automotive alternative engines to alternative fuels is still to be determined. Some key questions need to be answered through advanced component and engine research activities:

    (1) What is the allowable range of fuel composition (i.e., hydrogen-carbon ratio, aromatics, naphthalenes, etc.) for different combinations of combustors and fuel systems?

    (2) Will a low-heating-value fuel (such as methanol) affect the transient performance of an engine whose turbomachinery and fuel system were matched for a fuel with twice the heating value?

    (3) What effect will the introduction of ceramic components have on the engine's tolerance to fuel impurities?

    (4) What problems will be encountered with low-temperature starts?

The answers to these questions will affect fuel cost, the efficiency of fuel production, and the ability of advanced automotive gas turbine and Stirling engines to adapt to different fuels.

INTRODUCTION

A joint effort is being conducted by the Department of Energy (DOE) and NASA to find alternatives to the standard automotive spark ignition engine and vehicle system. Part of the overall effort that is funded by DOE is the development of an advanced automotive gas turbine (AGT) and an automotive stirling engine (ASE). Because of the need to extend petroleum supplies and to help this country become more energy self-sufficient, the DOE Advanced Automotive Heat Engine program has as its goal to develop and demonstrate

advanced gas turbine and Stirling automobile propulsion systems that meet
the following objectives:
 (1) At least 30 percent improvement in fuel economy (mpg) over a 1984
     production vehicle of the same class and performance powered by
     conventional spark ignition engines (based on equal Btu content of
     fuel used)
 (2) Emissions levels that meet or exceed the most stringent Federal
     research standards: 0.41 g/mile hydrocarbons (HC), 3.4 g/mile
     carbon monoxide (CO), 0.4 g/mile oxides of nitrogen (NO_x), and
     0.2 g/mile particulates
 (3) Ability to use a broad range of liquid fuels and blends derived
     from crude oil as well as synthetic fuels from coal, oil shale, and
     other sources
 (4) Suitability for cost-competitive mass production

The components and materials for the advanced engines are presently being
developed. This report combines information from these recent developments
with information given in the literature on alternative fuels. On the basis
of a literature survey a discussion is developed about the application of
various alternative fuels to advanced automotive gas turbine and Stirling
engines.

Because of currently evolving automotive technology an advanced automo-
tive gas turbine engine and a Stirling engine may become competitive alter-
natives to conventional piston engines. The ability for clean use of
alternative fuels is an important concept in favor of these alternative
engines. Before discussing fuels for these engines it is necessary to
briefly describe the AGT and ASE, although present work in the development
of components and engines will determine the exact configurations of the
advanced engines.

ADVANCED AUTOMOTIVE GAS TURBINE ENGINES

Automotive gas turbines use a regenerative Brayton cycle. Figure 1
shows the engine configurations schematically for the one- and two-shaft
designs. Within that general framework many options are open to advanced
component designs and engine configurations:
 (1) Compressor options
     (a) Axial or centrifugal
     (b) Single or multiple stages
     (c) Fixed- or variable-geometry diffuser
     (d) Fixed or variable inlet guide vanes
 (2) Heat exchanger options
     (a) Stationary recuperator
     (b) Rotating regenerator
     (c) Metal or ceramic components
 (3) Combustor options
     (a) Droplet diffusion
     (b) Premixed-prevaporized
     (c) Catalytic
     (d) Multielement
     (e) Fixed or variable geometry
     (f) Metal or ceramic
 (4) Turbine options
     (a) Radial or axial

2

(b) Single or multiple stages
            (c) Fixed or variable geometry
            (d) Metal or ceramic
        (5) Engine shaft arrangements
            (a) Single or multiple
            (b) Power transfer between shafts
These advanced concepts are described by Evans and Miller in reference 1.

        Some of these advanced concepts have already been introduced into
operating automotive gas turbine engines. The Chrysler upgraded engine,
which is described in reference 2, has a centrifugal compressor with vari-
able inlet guide vanes, a ceramic regenerator, and a premixed-prevaporized
combustor. The Chrysler upgraded engine was developed as a part of the
Baseline Gas Turbine Development program, which was funded by the Environ-
mental Protection Agency, then by the Energy Research and Development
Administration, and finally by DOE. The Chrysler upgraded engine is shown
schematically in figure 2.

        Detroit Diesel Allison Division of General Motors is presently using
a gas turbine engine to advance the use of ceramics in the hot gas path.
Under the Ceramic Applications in Turbine Engines (CATE) project a heavy-
duty engine is being progressively retrofitted with ceramic components to
permit increased cycle temperature and engine efficiency. The project,
which is funded by DOE, is described in reference 3. The engine used in the
CATE project, designated as the GT404/505-4, is shown with the ceramic com-
ponents pointed out in figure 3.

        Presently there are three principal Government contractors developing
AGT vehicle systems: the AiResearch Manufacturing Company teamed with the
Ford Motor Company, DDA Division of General Motors teamed with the Pontiac
Division of GM, and the Chrysler Corporation teamed with the Williams
Research Corporation. The development effort includes the use of ceramics
to increase cycle temperature and efficiency and some use of variable geome-
try to improve off-design operating efficiency. As examples of likely AGT
configurations, all three concepts are briefly summarized in table I and
shown in figure 4 (ref. 4), figure 5 (ref. 5), and figure 6 (ref. 6).

ADVANCED AUTOMOTIVE STIRLING ENGINES

        The automotive Stirling engine is a closed-cycle, external combustion,
reciprocating piston machine that operates on a modified Stirling cycle.
(Fig. 7, obtained from ref. 7, describes the ideal Stirling cycle.) Many
different engine configurations, either single acting or double acting, can
be used to produce the Stirling cycle. Some of these are shown in figure 8
(ref. 8). Of the possible configurations, the Rinia double-acting arrange-
ment has been chosen for the automotive Stirling engine because of its rela-
tively high specific power and low specific weight. Figure 9 shows the
three mechanical drive arrangements that have been considered for the auto-
motive Stirling engine. The V-drive and the swashplate drive have been used
and tested in experimentally evaluated vehicles. The current P-40 engines,
built by United Stirling of Sweden under the DOE Automotive Stirling Engine
program, have a U-drive configuration with two parallel crankshafts con-
nected by gears to an output drive shaft.

        Since the Stirling engine uses a closed cycle, the combustion process
is separate from the thermodynamic cycle and is continuous. Two Stirling
external combustion systems are shown schematically in figure 10 with ex-

3

haust gas recirculation (EGR) and in figure 11 with combustion gas recirculation (CGR). The options that are open to Stirling engine combustion system configurations and components are

(1) Preheater options
    (a) Stationary recuperator
    (b) Rotating regenerator
    (c) Metal or ceramic
(2) Combustor options
    (a) Droplet diffusion
    (b) Atomizer
    (c) Premixed-prevaporized
    (d) Two stages
    (e) Catalytic
    (f) Multielement
    (g) EGR or CGR
    (h) Metal or ceramic

The technology involved with advanced Stirling engines is discussed in reference 9.

Development of the automotive Stirling system in the United States originated with Ford Motor Company (ref. 10) and was partially funded on a cost-sharing basis by DOE from 1977 until Ford decided to terminate its Stirling activities in 1978. Since 1978 the automotive Stirling engine development in this country has been totally funded by DOE.

This effort is directed to the development of an advanced experimental Stirling engine for automotive application that will meet the program goal and to the transfer of Stirling engine technology to U.S. manufacturers. The work (refs. 11 and 12) is being conducted by a team comprising Mechanical Technical Incorporated (MTI), United Stirling of Sweden, and AM General (AMG) - a wholly owned subsidiary of American Motors Corporation - under a contract inititated on March 22, 1978. MTI is responsible for overall program management, development of component and subsystem technology, and transfer of Stirling engine technology to U.S. manufacturers. United Stirling is primarily responsible for engine development. AMG is responsible for engine vehicle integration, testing, and evaluation. In addition, it is intended to add to the project team during the course of development a U.S. engine manufacturer who will be licensed to produce the Stirling automotive engine and will be an additional recipient of the technology transfer.

The Ford fuel economy assessment studies and reference engine design studies by MTI and United Stirling indicate very good potential for meeting and exceeding the 30-percent fuel economy improvement goal. Key approaches to achieving the improved fuel economy designs include

(1) Optimizing engine efficiency in the low part-power regions most critical to drive-cycle fuel economy
(2) Increasing mean heater tube temperatures and minimizing tube temperature variations
(3) Reducing engine and vehicle auxiliary and accessory losses through improved drive systems and better matching to real needs
(4) Minimizing conduction losses through cylinder and regenerator walls
(5) Improving controls to provide more efficient part-power operating modes in order to improve durability and transient exhaust emissions
(6) Reducing external heating system losses through use of a more effective air preheater and reducing combustion system flow losses

4

Ceramics can be used in the Stirling engine if ceramics technology becomes significantly advanced; however, the use of ceramics is not required to meet the fuel economy goal as it is for the gas turbine.

COMBUSTOR OPERATING REQUIREMENTS

The combustors for the AGT and ASE must perform to the same emissions and particulate limits (0.41 g/mile HC, 3.4 g/mile CO, 0.4 g/mile NO_x, and 0.2 g/mile particulates). The combustors for the AGT systems must stay below these emission limits while operating over the range of airflows, pressures, and temperatures matched to the aerodynamic and heat transfer components in the cycle. Minimizing the level and variation of pressure drop across the combustor is also essential to maintain the performance and stall margin of the compressor over its operating range. Uniquely the Stirling combustor operates in a separate combustion air-loop at pressures slightly above ambient and over a range of airflows and temperatures that do not match those of the primary working fluid of the engine but are controlled by the heat input required for the engine.

As a result, the combustor operating parameters for the two engine types differ considerably, as shown in table II. The Stirling combustor operates over a wide range of the flow parameter $w\sqrt{T}/P$ but at a nearly constant fuel-air ratio. The gas turbine operates over a wide range of fuel-air ratio but at a relatively constant flow parameter. However, the combustor primary-zone flame temperature and flame residence times must be controlled to within approximately the same limits for both engine types in order to assure that emission limits are not exceeded. Also, primary-zone fuel-air ratios and flow velocities must be high enough to avoid lean stability limits and flashback, respectively, within the operating range of the combustor. These limits vary somewhat with combustor type, combustor inlet temperature, and inlet pressure, but representative values are noted in table III.

Finally the thermodynamic efficiency of the gas turbine and Stirling engines in an automotive duty cycle depends directly on the amount of exhaust heat returned to the cycle. In the gas turbine cycle the exhaust heat return is limited by the effectiveness of the regenerator and the minimum sink temperature to which it operates, in this case the compressor discharge temperature. Additional regeneration (such as through the use of an exhaust-gas-to-inlet-air heat exchanger) and recirculation of the exhaust gas (EGR) to the compressor inlet (to control NO_x emissions) are not practical because of their large impact on compressor materials and specific work and the increase in flow sizing required for the engine components.

Although the efficiency of the Stirling cycle does not depend on the external combustion system efficiency, the overall engine efficiency is directly related to how efficiently the fuel energy is transferred into the Stirling cycle by the combustion system. Therefore the waste heat energy contained in the exhaust is extremely important and must be minimized. To avoid corrosion of the stainless-steel air preheater. The exhaust temperature of the present Stirling systems is limited by the condensation temperature of sulfuric acid (400° F; 200° C). This temperature limitation also limits the effectiveness of the combustion air preheater. As a result, control of Stirling NO_x and CO emissions by using very lean combustion is impractical because of the required large mass flow and attendant large flow of heat energy out the exhaust. For this reason Stirling engines use a com-

5

bination of a near-stoichiometric, lean-fuel-air-ratio mixture to control CO and external exhaust gas recirculation (EGR) or internal combustion gas recirculation (CGR) to control NO_x. The exhaust flow rate is independent of the amount of EGR or CGR and is only slightly more than that required for ideal combustion. Therefore the exhaust heat flow is considerably less than with very lean combustion only. The net difference in fuel consumption can be as much as 4 to 5 mpg.

The primary options that affect fuel selection and specification in both engines are the combustor design and the materials in the path of the combustion products. In the AGT the components in the path of the combustion products will be high-temperature, high-strength alloys and ceramics. An ultimate goal in the AGT development is to raise the turbine inlet temperature to 1370° C (2500° F) in order to increase overall cycle efficiency. This can be done without expensive cooling if ceramics are used for the hot flow path components. Silicon nitride and silicon carbide are the candidate materials for the combustor, turbine stage, and ducting because of their strength and corrosion resistance. Regenerators will be made mainly from aluminum silicates because they can be used to fabricate very thin, compact structures and have better heat transfer properties than silicon carbide and silicon nitride.

The Stirling engine combustion chamber is formed primarily by the engine heater tubes, which are made of high-temperature alloy. The entrance section of the combustor is cooled by the incoming combustion air and therefore is made of stainless steel. The uncooled base of the combustion chamber is made of ceramic to withstand the maximum flame temperature, and the air preheater is made of stainless steel.

FUEL PROPERTIES

Although most of the thermodynamic and transport properties of potential alternative engine fuels are noncritical, density, boiling range, and viscosity can be important combustion characteristics. Octane and cetane rating are of no importance. Volatility need only be sufficient to allow ignition during cold weather. The boiling range must not extend so high that it hinders premixing and prevaporizing in an advanced combustor or so low that the fuel is vaporized in the fuel system. The fuel must not be so viscous that it is difficult to pump and to atomize during cold weather. And it must be dense enough and have a high enough heating value that the volume and weight of the fuel are not prohibitive for a compact automobile.

It is of primary importance that gas turbine and Stirling engine fuels in general be purified of certain elements and compounds. Some impurities can cause severe problems with exhaust emissions, corrosion, erosion, carbon buildup, and residue, that is, costly maintenance problems with the gas turbine combustor and turbomachinery and the Stirling air preheater and combustor. As the concentration of certain impurities in the fuel increases, combustor life, turbine life, and air preheater life will suffer and engine performance will degrade with time. Purification of the fuel is then an important feature of the refining process.

Health and safety factors are also a concern for fuels of very high aromatic content. Large concentrations of benzene and polynuclear aromatic compounds are known to be toxic and carcinogenic, and care must be taken to avoid prolonged and repeated exposure. The health and safety factors are discussed in detail in references 13 and 14.

Depending on combustor types, the hydrogen content of the fuel may be an important factor that affects combustor life. The hydrogen content affects the luminosity of the flame within the combustor. Low hydrogen content corresponds to high flame luminosity and radiation (refs. 15 to 18). A highly radiant flame can cause overheating and distortion of the combustor materials.

Figure 12 shows the structures of different hydrocarbon fuel constituents and compares hydrogen-carbon ratios. Aromatic compounds typically have low hydrogen content and produce smoke. They are undesirable constituents for gas turbine fuels. For this reason aromatic content and smoke point are part of the specifications (ASTM D-1655) for aviation fuels. Figure 13 (ref. 19) is an approximate correlation between fuel aromatics content and hydrogen content for jet fuels.

The effect that a given hydrogen content of the fuel has on burner liner temperature is influenced by pressure and the structure of the aromatic components in the fuel (ref. 17). The high combustor liner temperatures, which come with a very luminous flame, are caused by the infrared portion of the flame and not the visible component. Visible flame radiation gives little energy at hydrocarbon-air flame temperatures, but carbon particles in the flame can radiate as black bodies in the infrared region. At high pressures the carbon particles tend to grow in size enough to increase the radiant heating. Radiant heating contributes to distortion, metal erosion, and durability problems (refs. 17 and 18). This effect is more pronounced with polycyclic aromatics than with monocyclic aromatics (ref. 17). Reference 20 presents data showing the effect on combustor temperature and exhaust emissions of different hydrogen content fuels.

Figure 14 shows the effect that hydrogen content has on combustor liner temperatures (ref. 16). The shaded area represents a band of data taken from tests of various aircraft combustors with pressure-atomizing fuel systems. The next lower line represents data from an advanced General Electric CF6-50 combustor that uses air-blast fuel injection to allow a leaner mixture in the primary combustion zone. The NASA Experimental Clean Combustor program (ECCP) engine, which is described in reference 21, is a more advanced design. The test conditions in this figure simulate cruise conditions, about 8 atmospheres and 547 to 756 K combustor inlet temperature. Since the difference between the maximum combustor liner temperature for a fuel with the reference hydrogen content (14.5 percent) and the combustor inlet temperature ($T_{LO} - T_I$) could be of the order of 300 K, the variation in liner temperature represented by the shaded area could be an important consideration when designing automotive combustors for use with low-hydrogen-content alternative fuels. However, the leaner air-blast combustor (CF6-50 in fig. 14) shows great tolerance to low hydrogen content. This demonstrates that leaning out the primary combustion zone can very significantly decrease the radiant heating of the combustor liner.

Although it has not been demonstrated, it may be possible to use a radiant flame to advantage in the Stirling engine. Since the heat from the combustion gas must be transferred to the heater tubes, any heat transfer that can be gained through radiation will improve the heater effectiveness. This radiation to the heater should also tend to reduce the peak flame temperature and thereby lower NO_x emissions.

The existence of nitrogen-containing compounds in the fuel is also un-
desirable because a high percentage of the fuel-bound nitrogen converts to
NO_x during combustion (refs. 18, 22, and 23). Figure 15 indicates conver-
sion rates for NO_x formation from fuel-bound nitrogen. It is shown that
the percentage of conversion decreases with increasing combustor inlet tem-
perature and nitrogen content. The combustor inlet temperatures in advanced
automotive gas turbine engines will be greater than the temperatures shown
in figure 15. The conversion rate of fuel-bound nitrogen to NO_x is not
significantly affected by pressure or flame temperature but decreases as
combustor outlet temperature increases (ref. 22). Test show that, depending
on the conditions described, between 20 and 100 percent of the fuel-bound
nitrogen is converted to NO and NO_2 in the exhaust.

Since it is the NO_x level and not the conversion rate of fuel-bound
nitrogen that is of direct importance, the limits on the amount of fuel-
bound nitrogen will be imposed by combustor type, vehicle fuel economy, and
emissions regulations. NO_x emissions are reduced by lowering flame tem-
perature, and flame temperature can be lowered by leaning out and premixing
the primary combustion zone. Figure 16 shows the NO_x emissions index ver-
sus primary-zone equivalence ratio for different combustor designs described
in references 1 and 23. A horizontal line representing the NO_x emissions
index limit (2.8 g NO_x/kg fuel) is also shown in figure 16. This limit is
based on a vehicle fuel economy of 20 mpg and a NO_x emissions limit of
0.4 g NO_x/mile. Lean blowout limits for the premixed and ceramic element
combustors are also shown. Note that for the premixed combustor the equiva-
lence ratio must be maintained below about 0.46 if the emissions index is to
be limited to 2.8. However, the equivalence ratio must be maintained above
about 0.3 if lean blowout is to be avoided. This narrow range of equiva-
lence ratio (0.3 to 0.46) could be maintained over the entire engine operat-
ing range by using variable geometry to control the fuel-air ratio. This
concept is planned in the design of the advanced gas turbine engines.

As discussed earlier, the Stirling engine combustor operates over a
wide range of flows and near stoichiometric fuel-air ratios, and it makes
use of either EGR or CGR to reduce NO_x emissions. Figure 17 shows the
effect of EGR on the NO_x emissions index. For the case shown in fig-
ure 17, about 57 percent EGR is required to meet the 2.8 g NO_x/kg fuel
emissions index limit.

Figure 18 shows the influence of fuel-bound nitrogen on NO_x emissions
index for various conversion rates. The emissions indices of figures 16 and
18 can be combined additively and used to approximate maximum allowable
fuel-bound nitrogen for a given gas turbine combustor and vehicle fuel
economy. For example, if it is assumed that a variable-geometry, premixed-
prevaporized combustor can keep the average equivalence ratio at about 0.4,
then figure 16 shows that the NO_x emissions index for no fuel-bound nitro-
gen will be about 1.5. This leaves an emissions index limit of 1.3 (2.8 -
1.5) for fuel-bound nitrogen. If further assumptions are a 20-mpg vehicle
fuel economy and a conversion rate of 50 percent, then figure 18 shows that
the maximum allowable amount of fuel-bound nitrogen for an emissions index
of 1.3 is about 0.08 percent by weight. By the same reasoning, catalytic
and surface combustors would allow about 0.17 percent fuel-bound nitrogen by
weight for the 20-mpg vehicle. If the vehicle fuel economy is 40 mpg
instead of 20 mpg, the corresponding NO_x emissions index limit is 5.6 g
NO_x/kg fuel. The maximum allowable fuel-bound nitrogen would be 0.25 per-
cent by weight for the lean, premixed combustor and about 0.32 percent for
the catalytic combustor.

8

The allowable fuel-bound nitrogen for a Stirling engine depends on the amount of EGR or CGR. As the amount of EGR increases beyond 55 percent, the allowable fuel-bound nitrogen also increases.

Effect of Impurities

Sulfur and sulfur compounds in the fuel will also lead to engine problems (refs. 15 and 24). Besides adding to emissions the sulfur forms some compounds (fluxes) that have melting points in the gas turbine and Stirling operating range and some compounds (acids) that have dewpoints in the operating range of the Stirling engine air preheater. These compounds can cause severe corrosion of the metal turbine blading and the Stirling engine metal heater head and metal air preheater. Total sulfur should be limited in the fuel to about 0.5 percent, and mercaptan sulfur (organic compounds of the form RSH) to 0.003 percent by weight (refs. 15 and 24).

Vanadium, sodium, and potassium, if present in certain quantities, can all form compounds during combustion that cause corrosion (refs. 15 and 24) of weld joints. These elements should also be of limited concentration in the fuel. Adding magnesium to the fuel can minimize the effect of vanadium. However, if lead is also present in the fuel, it will not only hinder the effect of magnesium, but also cause corrosion of weld joints. Table IV gives the ASTM D2880-78 recommendation for trace metal limits in the fuel.

It is also important that the fuel have a low gum content. Gum causes varnishlike deposits to form in the fuel system. The presence of sulfur and nitrogen in the fuel has a significant influence on gum formation (ref. 25). A limit that is typically imposed on aviation turbine fuels is an existing gum content of 7 mg/100 milliliters of fuel (refs. 15 and 24).

Ash is also to be avoided in automotive alternative engine fuels. Ash, the noncombustible portion of the fuel, can take the form of solid particles or metallic compounds that are dissolved in the fuel or in any water that has become mixed with the fuel. The particles can cause wear and plugging of the fuel system, and the metallic compounds (typically those previously described) can cause corrosion of engine components (refs. 15 and 24). The ASTM D2880-78 recommended limitation for ash content in gas turbine fuel oils is 0.01 percent by weight.

The composition of the fuel must also be acceptable for use with advanced ceramics. Parts of the combustors, regenerators, and first turbine stages of the advanced automotive gas turbine engines will be made of ceramics. Impurities in the fuel may corrode these parts. However, silicon carbide and silicon nitride, which are the most promising ceramics structurally, do not appear to be significantly affected by sulfur and trace metal content in the fuel under simulated gas turbine operating conditions (ref. 26). Therefore the use of these ceramics will probably impose no additional restrictions on fuel content.

Because of the great change in temperature as the combustion products pass through the turbine engine regenerator or Stirling engine air preheater, corrosive compounds may condense and attack the matrix material. This will be of concern in specifying limitations on fuel impurities. For example, recent experience with lithium aluminum silicate (LAS) regenerators shows a great sensitivity to chemical attack from sodium and sulfur (refs. 27 and 28).

Sulfur in the fuel causes oxides of sulfur to form during the combustion process. Some of these oxides form sulfuric acid and attack the re-

generator surface. The lithium ions in the LAS material are leached by the sulfuric acid, causing the thermal expansion characteristics of the regenerator material to change. Thermal stresses build up and eventually the regenerator fails as cracks form (refs. 27 and 28).

Sulfuric acid presents a similar problem in the Stirling engine air preheater, which is typically made of stainless steel. The sulfuric acid causes corrosion particularly in the areas near welds and also precludes use of less costly alloys.

Sodium oxide, which results from contaminated fuel or road salt being ingested by the engine, attacks the hot side of the LAS regenerator. The thermal expansion characteristics change as with the sulfuric acid attack, but failure of the regenerator happens faster (refs. 27 and 28).

Advanced ceramic regenerator materials are being developed to minimize this problem. The chemical attack described above can be avoided by leaching the LAS regenerator in sulfuric acid to remove the lithium ions prior to assembly in the engines. Another advanced material is magnesium aluminum silicate (MAS), which is also highly resistant to chemical attack. However, the maximum allowables for fuel impurities for these regenerator materials have not yet been determined (refs. 27 and 28).

Transport Characteristics

Although most of the thermodynamic and transport properties of potential alternative engine fuels are noncritical, density, boiling range, and viscosity can be indications of some other important combustion characteristics (refs. 15 and 24). In general for transportation fuels, more dense fuels produce more luminous and radiant flames because of their low hydrogen content. If the boiling range of a fuel extends to relatively low temperatures, there is a volatile constituent of the fuel that will aid starting during cold weather. A high viscosity will hinder the fuel pumping and atomization necessary for clean combustion. It will therefore be necessary to limit the fuel viscosity to about 10 centistokes (ref. 24) at the coldest ambient temperature that the automobile will operate at. This limit was selected in an attempt to assure fuel atomization. This could allow the use of a more viscous fuel during warm weather but require a less viscous fuel during cold weather. Figure 19 shows the relation between temperature and kinematic viscosity for some typical petroleum-based fuels. Based on the 10-centistoke limit, a fuel similar to number 2 fuel oil should be adequate for warm climates, and number 1 fuel oil should be adequate for all seasons.

Boiling range is important because the final boiling point is related to the viscosity and freezing point of liquid fuels (ref. 19). Figure 20 shows the boiling range of various petroleum products. Number 2 fuel oil, which has a high but marginally acceptable viscosity, has a final boiling point of about 345° C. Also, as figure 21 shows, a high final boiling point also gives a high freezing point. As the fuel approaches the freezing point, waxlike particles begin to build up in the fuel system. Based on figures 19 to 21, it is apparent that a wide-boiling-range petroleum fuel with a final boiling point of about 370° C or less is likely to satisfy viscosity and freezing point requirements for automotive fuels.

TYPES OF ALTERNATIVE FUELS

A gas turbine engine or Stirling engine can use a relatively wide variety of fuels because the performance of the engine is independent of many of the fuel characteristics that conventional piston engines require. The important factors that must be considered when choosing a fuel are

    (1) Availability
    (2) Cost
    (3) Energy efficiency
    (4) Volume and weight
    (5) Safety
    (6) Combustion characteristics, including emissions
    (7) Compatibility with materials that could be used in mass-produced engines

The candidate fuels may be liquid or gaseous, petroleum or nonpetroleum, natural or synthetic, hydrocarbon or nonhydrocarbon. However, the fuel must be safely packaged for a small vehicle, and the fuel and fuel system must be light enough so that the vehicle rolling resistance and inertia are within reasonable limits. Also, there may be certain constituents of a fuel that will cause corrosion or emissions problems.

The use of alternative fuels for automobiles could help ease this country's dependence on petroleum. The use of broader cuts of petroleum fuels will increase liquid fuel yields. Also, the use of non-petroleum-based fuels from oil shale, coal, or biomass could stretch and eventually replace petroleum-derived fuels. The automotive gas turbine and Stirling engine can be made to readily accept alternative fuels.

The ability of alternative engine combustors to accept low-hydrogen-content fuels is a key economic issue for the use of alternative fuels from coal and shale oil. It is expensive to hydrotreat synthetic oils to increase hydrogen content. Figure 22 (ref. 19) shows the relative hydrogen content of crude oils. It is apparent that coal especially needs a great deal of hydrotreating. Figure 23 (ref. 29) shows that the cost of hydrogen needed to transform coal into a barrel of oil that has a hydrogen-carbon ratio of 2 (14.3 percent H) would be about \$30 at 1980 prices, whereas to achieve a barrel of coal-derived synthetic oil with a hydrogen-carbon ratio of only 1.5 (11 percent H) would cost only about \$13 per barrel. Therefore, if a conventional engine required a fuel with an H/C ratio of 2 and a gas turbine or Stirling engine could use a fuel with an H/C ratio as low as 1.5, the fuel cost could be reduced by \$17 per barrel by using the alternative engine.

In 1976, Chrysler built an alternative fuels demonstration rig as a part of the Baseline Gas Turbine Development program (for ERDA, now DOE) (refs. 30 and 31). It consisted of six safety cans of fuel strapped to the front bumper of a gas turbine automobile with diesel number 1 in the vehicle fuel tank, making a total of seven fuels:

    (1) Diesel number 1
    (2) Nonleaded gasoline
    (3) A relatively broad-cut distillate (boiling range 40° to 230° C) similar to JP3 or JP4
    (4) An unrefined, low-hydrogen, high-ash, coal-derived fuel
    (5) Ethanol
    (6) 60/40 Diesel/isopropenol
    (7) 60/40 Gasoline/methanol

11

The fuels were dyed different colors and were valved through a clear plastic fuel line for visualization.

The demonstrations were at idle, switching between fuels with the engine running. The demonstrations showed that at idle the automotive gas turbine could switch between radically different fuels with no modifications at all and no apparent changes in performance. However, Chrysler notes that for optimum transient operation and exhaust emissions, the engine's combustor, fuel system, and control system would require adjustment for each fuel.

Chrysler also found that the unrefined coal liquid (which was derived from pyrolysis with no hydrotreating) was a poor fuel (ref. 31). This is not surprising considering the information listed in the section on fuel properties of this report and the composition of the fuel given below:

Carbon, percent 83.0
Hydrogen, percent 8.4
Nitrogen, percent 1.1
Oxygen, percent 0.4
Sulfur, percent 7.1

They concluded that this fuel required more refinement and that the liquids made for catalytic hydroliquifaction of coal would be more suitable.

It is important to note, however, that more advanced automotive gas turbine engines should be more tolerant to less refined fuels than the engines and combustors that were used in Chrysler's demonstration. It is likely that variable-geometry, premixed-prevaporized combustors and catalytic combustors will be able to take relatively low-hydrogen-content fuel and that advanced ceramics will be able to accept relatively high sulfur and other impurities. However, emissions consideration will dictate the degree of processing required to achieve low nitrogen and sulfur contents. Also, high ash content will still cause harmful deposits.

Multifuel demonstrations have been performed by United Stirling with a Stirling-powered Opal automobile on several occasions, but performance and emissions data have not been published.

Researchers at the Bartlesville Energy Research Center tested a single-cylinder nonautomotive Stirling engine to compare synthetic gasoline having an octane rating in the low 70's and a reference 84 octane gasoline (ref. 32). The results showed no significant difference between the two fuels in fuel consumption or exhaust emissions at a given engine setting.

Petroleum Derivatives

Petroleum supplies for transportation could be extended by several percent if broad-cut fuels were produced along with gasoline and diesel fuel. A broad-cut fuel is typically defined as a product of primary distillation that has a wide boiling range (final boiling point about 350° C) and no octane or cetane rating. Producing broad-cut fuels requires less energy than producing gasoline and diesel fuel. Maximizing the yield of broad-cut and/or diesel fuel increases the total liquid yield. It is a goal that automotive gas turbine, Stirling, and direct-injected, stratified-charge piston engines readily accept broad-cut fuels.

In a study of the refining industry (mentioned in ref. 33) for the Department of Transportation, Bonner and Moore Consultants considered ways of maximizing diesel fuel production. They concluded that increasing diesel

fuel production increases refinery efficiency if the amount of diesel fuel produced does not exceed 50 percent of the light-duty transportation fuels. They also concluded that refinery efficiency could be increased even further if broad-cut fuel was produced along with the gasoline and diesel fuel. For a 10/70/20 split of gasoline/diesel/broad-cut fuel, a supply of petroleum crude could be extended by 3.5 percent, raising the refinery efficiency to about 95 percent.

Texaco conducted another study that showed the benefits of producing diesel and broad-cut fuels over gasoline (ref. 34). They considered four cases that would produce a different mix of transportation fuels. For all four cases, refinery output of all other petroleum products was held the same as for the base case, which represented the U.S. refinery industry in 1972. The four cases are defined in table V. Table VI summarizes the yield of transportation fuels and energy needed to operate the refinery for each of the four cases. It shows that case D, which produces mostly broad-cut and some diesel fuel, would give a significantly better refinery output over case A (the base case). The benefits would be a 25-percent reduction in energy needed at the refinery and an almost 3-percent increase in the yield of transportation fuels.

Coal Derivatives

The depletion of domestic petroleum resources and the desire for U.S. energy self-sufficiency have enhanced the technological and economic attractiveness of coal liquifaction. Because of this, some advanced processes for large-scale commercial coal liquifaction are presently under development in the United States. These processes are improvements over the methods used by Germany during World War II to make transportation fuel from coal. The thermal efficiencies of these new processes are 60 to 70 percent (refs. 35 and 36), but despite good technological progress the economic incentives are still lacking.

Without extensive hydrotreating, coal liquids are low in hydrogen content. Therefore the unrefined coal liquids have likely applications in boilers and heavy-duty gas turbines where residual fuel oils can be used. However, with the added cost of hydrotreating (shown in fig. 23), transportation fuels can be produced from crude coal liquids.

The problem of coal liquifaction has been approached by several different methods. These methods vary in liquid yield and thermal efficiency. These processes are discussed briefly here, but more detailed summaries are given in references 36 to 38. In the Fischer-Tropsch process the coal is first gasified to form synthesis gas (H_2 and CO), which is then desulfurized and catalytically reacted to form a mixture of liquid hydrocarbons. This process was used by Germany during World War II and is presently used in a commercial plant in Sasolburg, South Africa, that produces 2000 barrels of gasoline per day. The process has a relatively low thermal efficiency (40 to 45 percent) as compared with the more advanced processes that are still under development. However, an advantage to this process is that it allows in-situ gasification of the coal. Also, a very similar process can be used to make methanol.

Most modern processes under development use direct hydrogenation of the coal to produce hydrocarbon liquids. The coal is pulverized and mixed with a solvent that can be obtained as a byproduct later on in the process. The slurry is mixed with hydrogen and fed into a reactor vessel at temperatures

greater than 430° C and at extreme pressures. Particulate matter must be removed and a significant portion of the coal must be used for the generation of the hydrogen used in the process, but the thermal efficiency of fuel oil by this type of process will be 60 to 70 percent. Gulf Solvent Refined Coal (SRC), Exxon Donor Solvent (EDS), and Hydrocarbon Research, Inc. (HRI) H-Coal are candidate processes for coal liquifaction.

Table VII compares petroleum crude oil to H-Coal and SRC. The H-Coal, which is produced by catalytic hydroliquifaction, is much lighter than the SRC, which is produced by a noncatalytic process. Also, more broad-cut fuels (100° to 650° F boiling range) can be produced from a given supply of H-Coal syncrude than from both SRC and petroleum crude oil. The cost of coal-derived syncrude has been estimated to be between $20 and $30 per barrel for commercial scale plants (ref. 36).

Another problem is with impurities, such as trace-metal, and nitrogen contents in the crude oils. Trace-metal content, which is of major concern to the life expectancy of metal components, will vary with the origin and processing of the coal and will be a problem with certain coal products. Excessive nitrogen content, typically encountered in coal-derived crude oils, will cause problems with meeting vehicular emissions requirements. Figure 24 (ref. 38) shows that the heavier fractions (lower API gravity) of synthetic crude oils tend to have low hydrogen content. Figure 25 shows that the fractions that have low hydrogen content also tend to have excessive nitrogen content. Figure 26 shows how the heat of combustion for these fuels varies with hydrogen content. The data points in figures 24 to 26 represent various fractions of synthetic crudes derived from different processes. These problems can of course be alleviated by refining the coal-derived crude oils.

Oil Shale Derivatives

Western oil shale in Colorado, Wyoming, and Utah can potentially supply hundreds of billions of barrels of shale oil. Production of oil from oil shale will probably be more economical than coal liquifaction. However, there are important environmental, economic, and political problems that come with establishing a major industry in an unpopulated, very dry region. These problems will require careful solution. More detailed coverage of the topic of shale oil is given in references 37, 39, and 40.

Oil shale is really a base material of marlstone containing an organic solid called kerogen. The oil shale contains about 14 percent kerogen by weight and, upon pyrolysis, may yield 25 to 40 gallons of shale oil per ton (ref. 39). The shale is heated to over 900° F so that pyrolysis of the kerogen will produce hydrocarbon compounds that can be condensed into liquids.

The present method of obtaining shale oil is to mine the oil shale, crush it, and then transport it to the retort facility for processing. Since so much shale is required to produce a barrel of oil, this activity involves the rearrangement of a great deal of landscape. The spent oil shale occupies 10 to 30 percent more volume than it did before it was mined. Disposal of the spent oil shale becomes a very significant problem because it requires large quantities of water from a generally arid area. Efforts are under way to reduce the water required in the process and to minimize the effects on the ecology.

When the retorting is accomplished in the ground, it is known as an in-situ process. The oil shale formation is first made permeable by drilling and causing horizontal faults by explosion, hydraulic fracturing, or leaching. A fire is started or hot gases are then circulated within the formation in order to decompose the kerogen and form hydrocarbon fluids that can be collected. This has advantages since most of the oil shale never leaves the ground, greatly lessening the environmental impact and making the operation more economical in principle. However, the yield of hydrocarbon liquids is not nearly as great.

Crude shale oils are highly unsaturated and high in ash, nitrogen, sulfur, and trace elements. This and the high viscosity of the shale oil make it difficult to transport by pipeline. These problems can be alleviated by mild hydrotreating of the crude shale oil.

The properties and composition of shale oil differ with location and process. Table VIII (ref. 41) shows the elemental analysis for dry shale oil from different locations. The nitrogen and sulfur contents of the oil vary greatly with location, and the carbon-hydrogen ratio is typically about 7. Table IX shows the properties of distillates from the Paraho Oil Shale project in Anvil Points, Colorado. These can be compared with values in table X, which shows some of the properties of Occidental shale oil produced from an in-situ process. The properties vary significantly. The distillates produced from the in-situ process are lower in nitrogen and sulfur. Also, only 28 percent of the Paraho distillates fall in the 100° to 650° F boiling range that is considered suitable for broad-cut fuels, but 46 percent of the distillates from the in-situ process fall into that category. The heavy oils would require further processing in order to make them less viscous and suitable for automotive applications.

Alcohol Fuels

Alcohols have potential for extending petroleum supplies significantly by substitution for and blending with petroleum fuels. The industry for producing alcohol fuels is already developing, and therefore the ability to use alcohols is an important advantage for advanced engines. Certain Governmental incentives are also helping to encourage rapid growth of the alcohol fuels industry (ref. 42).

The alcohols that are being considered for automotive fuels are primarily methanol and ethanol. Methanol will come mainly from liquifaction of synthesis gas from coal, as described in an earlier section of this report. The synthesis gas can also come from gasifying biomass and organic refuse and waste. Ethanol will come primarily from yeast fermentation of certain agricultural and food byproducts that contain carbohydrates. Research is also being conducted in cellulose conversion to fermentable products. Therefore ethanol can come from renewable resources, since the photosynthesis that produces the raw materials uses sunlight and recycles the carbon dioxide in the atmosphere. Much more information on the use and production of alcohol fuels is contained in references 37 and 42 to 45.

Alcohols are good gas turbine and Stirling engine fuels and have the advantage of being nonpetroleum and clean-burning fuels. Lower NO_x emissions result from alcohol's significantly lower flame temperatures as compared with gasoline and diesel fuel. Also, they can be blended with other fuels to stretch a given fuel supply.

However, there are some disadvantages to using alcohols as alternative engine fuels. Since alcohols are infinitely soluble in water, they are also susceptible to contamination by salts that may be dissolved in the water. This can cause severe corrosion problems within the gas turbine and Stirling engines themselves and the fuel systems. Other disadvantages are their relatively low heating value and chemical attack upon certain materials (refs. 46 and 47). Because of the lower heating value, fuel systems must be designed for higher volumes and flow rates. This may make it impossible to use alcohols and petroleum-like fuels interchangeably without modifying the fuel system when switching between one and the other. Corrosion problems are encountered with low-carbon steel, aluminum, brass, zinc, and magnesium, and therefore these metals should not be used in the fuel systems. Alcohols are also strong solvents that can soften and swell certain types of plastics and rubbers. Thus a disadvantage of alcohol fuels is that the fuel systems must be designed specifically for alcohols.

Blends of alcohols and broad-cut hydrocarbon fuels may be an excellent option. Since the blend would have a heating value closer to that of the broad-cut fuel, modifications of the fuel system when changing fuel may not be necessary. The potential problems of corrosion and salt contamination would not be as great for blends as for straight alcohols. However, when a certain amount of water is introduced into these alcohol-hydrocarbon fuel blends, there is a phase separation. The water tolerance of a blend can be enhanced by the addition of certain stabilizers and aromatics to the fuel. Tables XI and XII indicate the relation between water tolerance, aromatic content, stabilizers in methanol-gasoline blends. The haze point shown in tables XI and XII is the point at which phase separation occurs. Figure 27 shows the relation between water tolerance, blend ratio, and temperature for ethanol-gasoline mixtures. A comparison of this figure with tables XI and XII shows that ethanol-gasoline blends tolerate much more water than methanol-gasoline blends if no stabilizers are used.

Tests of gas turbine and Stirling engines using methanol fuel show no decrement in performance when switching from diesel fuel or gasoline to methanol. Reports show both a significant reduction in NO_x emissions because of a lower flame temperature and an increase in CO (refs. 44 and 48). However, increasing the atomization of the fuel in a diffusion flame combustor can help greatly to reduce the carbon monoxide emissions (ref. 48).

In summary, the major disadvantages to using straight alcohols as a fuel are the low heat of combustion and the danger of contamination by salts dissolved in water. Also, alcohol fuel blends must be kept relatively dry to prevent phase separation.

Hydrogen Fuel

The use of hydrogen as a fuel is a long-range concept that is presently under investigation (ref. 49). Hydrogen may become an important fuel for many applications because it can be safely stored as metal hydrides and produces a very clean flame. Hydrogen can be produced by the electrolysis of water or can be made from a catalytic process that uses coal and steam to produce hydrogen and carbon oxides. The large amounts of electric power required for electrolysis would conceivably come from nuclear powerplants, perhaps fusion plants, or from a combination of renewable energy resources (solar, wind, ocean, and biomass). It is likely that the use of hydrogen can become an effective method of replacing and extending natural gas sup-

plies. More information on the production and use of hydrogen can be found in reference 49.

However, the use of hydrogen as a vehicular fuel, particularly for automotive gas turbine and Stirling engines, poses some special problems. The main problem involves the volume and weight of the hydrogen storage systems (refs. 50 and 51). Hydrogen can be stored as a compressed gas, cryogenically as a liquid, as a metal hydride, or in liquid chemical compounds. Storing the hydrogen as a compressed gas on a vehicle is dangerous, and the idea is generally not considered. Liquefying and storing the hydrogen cryogenically requires a significant amount of energy and results in loss due to boiloff. Safety is a concern, also. Storing the hydrogen as a metal hydride is relatively safe, compact, and efficient, but there is a vehicle weight penalty of at least several hundred pounds. The most promising metal hydride based on fuel storage weight, magnesium hydride, requires dissociation temperatures that are typically greater than the exhaust temperatures of automotive gas turbine or Stirling engines, especially at part power. This means that the dissociation would probably require the use of more fuel. Storing the hydrogen in liquid compounds would result in less weight penalty than with metal hydride storage, but it takes a significant amount of energy to reform the hydrogen. Storage in liquid compounds is also illogical for gas turbine or Stirling vehicles because the hydrogen-containing compounds used to store the hydrogen would usually make excellent fuels themselves. Table XIII, taken from reference 50, summarizes a comparison of different hydrogen storage methods.

Hydrogen is a very clean fuel. It produces no hydrocarbons, carbon monoxide, smoke, or sulfur dioxide. Nitrogen oxides and harmless water vapor are the only combustion products. Nitrogen oxides can be very low for hydrogen-air flames, depending on the combustor design.

The key to producing minimum NO_x levels in a hydrogen continuous-combustion system is a lean, thoroughly premixed flame (ref. 52). The lean flammability limit for hydrogen and air occurs at a flame temperature of about 1200 K as compared with about 1800 K for hydrocarbon fuels at advanced automotive gas turbine combustor inlet temperatures. This large reduction in flame temperature can reduce NO_x emissions by more than an order of magnitude. Since the range of turbine inlet temperature in the advanced engines will be below 1650 K, it should be possible to eliminate the need for adding secondary air within the combustors.

However, combustion of a nonhomogeneous mixture causes hot regions, and this can negate the beneficial effect of an overall lean hydrogen-air mixture. Also, a hydrogen flame is difficult to stabilize because the flame speed is almost seven times faster than the flame speed for hydrocarbon fuels. A premixed hydrogen flame is prone to flashback into the non-homogeneous premixed region, causing high NO_x emissions and burnout problems. Prevention of this problem may require a pressure drop within the combustor, and this is impractical.

As discussed earlier, the automotive Stirling engine uses EGR or CGR to control NO_x. For a given equivalence ratio, hydrogen burns with a higher flame temperature than conventional hydrocarbon fuels. Thus additional EGR/CGR flow will be required to maintain low NO_x emissions. Heat transfer requirements dictate that the combustion temperature be higher for the automotive Stirling engine than for the advanced automotive gas turbine. The maximum Stirling engine combustion temperature is typically 2275 K. When conventional hydrocarbon fuels are used in the Stirling engine, a sub-

stantial portion of the heat transfer to the heater head is by radiation. The low radiation of the hydrogen flame will necessitate a higher flame temperature or greater heat transfer area to achieve the required heat transfer. Therefore NO_x emissions may be difficult to control.

FUTURE RESEARCH EFFORTS AT LEWIS

Although it is certain that advanced automotive gas turbine and Stirling engines will be able to accept a wide variety of fuels, the extent is still to be determined. Key unanswered questions are

(1) What is the allowable range of fuel composition (i.e., H/C ratio, aromatics naphthalenes, for different combustor and fuel system types?

(2) Will a low heating value fuel (such as methanol) affect the transient performance of an engine whose turbomachinery and fuel system were matched for a fuel with twice the heating value?

(3) What effect will the introduction of ceramic components have on the engine's tolerance to fuel impurities?

(4) What problems will be encountered with low-temperature starts? These are important questions because the answers will strongly affect fuel cost, the efficiency of fuel production, and the ability of an automotive alternative engine to adapt to different fuels. These questions will be studied at NASA Lewis for both the automotive gas turbine and Stirling engines in steady-state and transient engine test facilities. Both types of facilities will handle a large number of engine performance parameters, and the transient facility will also impose speed demands on the engines and simulate road loads. Test rigs are being used to evaluate advanced combustor concepts and components.

The Chrysler upgraded automotive gas turbine engine will be used for the gas turbine studies at Lewis. The engine is a two-shaft configuration with a fixed-geometry, premixed-prevaporized combustor. The present gas turbine engine test plan involves steady-state testing of both high- and low-hydrogen-content fuels and transient testing with methanol. The temperature at the hottest point on the combustor will be monitored to determine the effect of H/C ratio on radiant heating. For the transient tests, engine response time and compressor surge margin will also be studied to determine if the engine can readily accept both high- and low-heating-value fuels for road-cycle types of conditions.

The initial alternative fuels studies with the Stirling engine will be done with the United Stirling P-40 engine. This engine has a two-crankshaft, U-configuration with a stationary stainless-steel air preheater.

The automotive Stirling engine test plan will involve steady-state and transient engine testing with both high- and low-hydrogen-content fuels and with alcohols. Exhaust emissions will be studied to determine the effect of H/C ratio and to evaluate combustor performance. The effects of molecular bonded nitrogen atoms, sulfur, and vanadium will be evaluated, along with the effects of unsaturated chemical structure. Transient tests will be done to study engine control response and emissions effects with various fuels for road cycle types of conditions.

It is hoped that these studies will help to pin down the acceptable ranges of requirements for good automotive alternative engine fuels. On the basis of the literature summarized in this report, a first cut can be taken to identify the fuel requirements. Table XIV summarizes these requirements.

18

CONCLUSIONS

A wide variety of fuels are adaptable to gas turbine and Stirling engines but must satisfy certain requirements to insure proper operation, maintain engine life, and help satisfy emissions standards. These requirements depend on fuel system and combustor design and the materials that make up the path of the combustion products. Because of the types of combustors and engine materials being developed for use in advanced automotive gas turbine and Stirling engines, it is likely that a much greater tolerance to alternative fuels will be realized than in present-day engines. Advanced combustors will allow the use of relatively low-hydrogen-content and broadcut synthetic and petroleum fuels. This has been demonstrated with advanced aircraft combustors. Introduction of ceramics into the hot gas path will not only allow a hotter, more efficient thermodynamic cycle, but may also greatly decrease the engine's sensitivity to impurities in the fuel. These advantages would help to minimize the extent of costly hydrotreating and additional processing of synthetic fuels.

Although it is certain that advanced automotive gas turbine and Stirling engines will be able to accept a wide variety of alternative fuels, the extent of their adaptability is still to be determined. Key unanswered questions are

(1) What is the allowable range of hydrogen-carbon ratio for different combustor types?

(2) How does a wide range of fuel heating values affect engine performance under the highly transient demands of an automobile?

(3) To what extent will the introduction of ceramic components alter the engine's tolerance to fuel impurities?

(4) What problems will be encountered with low-temperature starts?
These are the questions that should be addressed by component and engine research activities. The answers will affect fuel cost, the efficiency of fuel production, and the ability of advanced automotive gas turbine and Stirling engines to adapt to different fuels.

REFERENCES

1. Evans, D. G.; and Miller, T. J.: An Overview of Aerospace Gas Turbine Technology of Relevance to the Development of the Automotive Gas Turbine Engine. NASA TM-73849, 1978.
2. Ball, G. A.; Gumaer, J. I.; and Sebestyen, T. M.: The ERDA/Chrysler Upgraded Gas Turbine Engine Objectives and Design. SAE Paper 760279, 1976.
3. Rockwood, F. A.: Ceramic Applications in Turbine Engines. Highway Vehicle Systems Contractors Coordination Meeting. CONF-791082, Dept. of Energy, 1979, pp. 192-208.
4. Conceptual Design Study of an Improved Gas Turbine (IGT) Powertrain. Phase I - Final Report. (Ford Motor Co. and AiResearch Mfg. Co.; NASA Contract DEN3-37.) DOE/NASA/0037-79/1, NASA CR-159580, 1979.
5. Helms, H. E.: Advanced Gas Turbine Powertrain System Development Project. Fifth International Symposium on Automotive Propulsion Systems. CONF-800419, Vol. 1, Dept. of Energy, 1980, pp. 158-180.

6. Wagner, C. E.; and Pampreen, R. C.: Conceptual Design Study of an Improved Automotive Gas Turbine Powertrain. (Chrysler Corp., DOE Contract DE-AC02-76CS-52749.) DOE/NASA/2749-79/3, vol. 3, COO-2749-40, NASA CR-159672, 1979.

7. Walker, G.: Stirling-Cycle Machines. Clarendon Press, Oxford, 1973.

8. Conceptual Design Study of an Automotive Stirling Reference Engine System. (MTI-79ASE53RE1A, Mechanical Technology, Inc.; NASA Contract DEN3-32.) DOE/NASA/0032-79/1, NASA CR-159605, 1979.

9. Assessment of the State of Technology of Automotive Stirling Engines. (MTI-79ASE77RE2, Mechanical Technology, Inc.; NASA Contract DEN3-32.) DOE/NASA/0032-79/4, NASA CR-159631, 1979.

10. Kitzner, E.: Ford Stirling Engine Powertrain Development. Highway Vehicle Systems Contractors Coordination Meeting. CONF-78-1050, Dept. of Energy, 1979, pp. 291-302.

11. Decker, O.: MTI Stirling Engine Powertrain Development. Highway Vehicle Systems Contractors Coordination Meeting. CONF-781050, Dept. of Energy, 1979, pp. 303-319.

12. Beremand, Donald G.: Stirling Engines for Automobiles. NASA TM-79222, 1979.

13. Biomedical Studies on Solvent Refined Coal (SRC-II) Liquefaction Materials: A Status Report. PNL-3189, Pacific Northwest Laboratory, 1979.

14. White, Otto, Jr., ed.: Proceedings of the Symposium on Assessing the Industrial Hygiene Monitoring Needs for the Coal Conversion and Oil Shale Industries. BNL-51002, Dept. of Energy, 1979.

15. Sawyer, John W., ed.: Sawyer's Gas Turbine Engineering Handbook. Volume II - Applications. Second ed. Gas Turbine Publications, 1972.

16. Blazowski, William S.: Fundamental Characterization of Alternate Fuels Effects in Continuous Combustion Systems. TID-28463, Dept. of Energy, 1978.

17. Schirmer, R. M.; McReynolds, L. A.; and Daley, J. A.: Radiation from Flames in Gas Turbine Combustors. SAE Trans., vol. 68, 1960, pp. 554-561.

18. Blazowski, W. S.: Combustion Considerations for Future Jet Fuels. Sixteenth Symposium (International) on Combustion. The Combustion Institute, 1977, pp. 1631-1639.

19. Longwell, J. P.; and Grobman, Jack S.: Alternative Aircraft Fuels. NASA TM-73836, 1977.

20. Butze, H. F.; and Ehlers, R. C.: Effect of Fuel Properties on Performance of a Single Aircraft Turbojet Combustor. NASA TM X-71789, 1975.

21. Gleason, C. C.; and Bahr, D. W.: Experimental Clean Combustor Program - Alternate Fuels Addendum. Phase II - Final Report. (R76AEG268, General Electric Co.; NASA Contract NAS3-18551.) NASA CR-134972, 1976.

22. Dilmore, J. A.; and Rohrer, W.: Nitric Oxide Formation in the Combustion of Fuels Containing Nitrogen in a Gas Turbine Combustor. ASME Paper 74-GT-37, Mar. 1974.

23. Rudey, Richard A.; et al.: Emissions Control for Ground Power Gas Turbines. Aircraft Engine Emissions. NASA CP-2021, 1977, pp. 203-242.

24. Standard Specification for Gas Turbine Fuel Oils. Am. Soc. Test. & Mater. D2880-80, 1980.

25. Hazlett, R. N.; Hall, J. M.; and Solash, J.: Properties and Composition of Jet Fuels Derived from Alternate Energy Sources - Part I. Background and N-Alkane Content. Conference on Composition of Transportation Synfuels: R&D Needs, Strategies, and Actions. CONF-7810176, Dept. of Energy, 1979, pp. 99-111.

26. Singhal, S. C.: Corrosion Resistant Structural Ceramic Materials for Gas Turbines. Proceedings of Nineteenth Gas Turbine Materials in the Marine Environment Conference, J. W. Fairbanks and I. Machlin, eds., Battelle Columbus Labs., MCIC-75-27, 1975, pp. 311-334.

27. Anderson, D. H.; et al.: Automotive Gas Turbine Ceramic Regenerator Design and Reliability Program. First Quarterly Progress Report. Prepared for EPA Contract No. 68-03-2150, Jan. 15, 1975.

28. Anderson, D. H.; et al.: Automotive Gas Turbine Ceramic Regenerator Design and Reliability Program. COO-2630-8, Energy Research and Development Adm., 1976.

29. Uyehara, O. A.: Transportation Fuels - 1978 Crude Oil Scene. Conference on Composition of Transportation Synfuels: R&D Needs, Strategies, and Actions. CONF-7810176, Dept. of Energy, 1979, pp. 223-251.

30. Schmidt, F. W.; and Wagner, C. E.: Baseline Gas Turbine Development Program. COO-2749-14, Energy Research and Development Adm., 1976.

31. Schmidt, F. W.; and Wagner, C. E.: Baseline Gas Turbine Development Program. COO-2749-15, Energy Research and Development Adm., 1976.

32. Bechtold, R. L.; and Flemming, R. D.: Performance of Gasoline and Diesel Fuels Produced from COED Syncrude. BERC/R1-78/2, Dept. of Energy, 1978.

33. Hurn, R. W.: Forces at Work Affecting Liquid Synfuels Development. Conference on Composition of Transportation Synfuels: R&D Needs, Strategies, and Actions. CONF-7810176, Dept. of Energy, 1979, pp. 49-53.

34. Johnson, E. M.; Tierney, W. T.; and Crawford, N. R.: An Opportunity for Maximizing Transportation Energy Conservation. Future Automotive Fuels: Prospects, Performance, and Perspective. J. M. Colucci and N. E. Gallopoulos, eds., Plenum Press, 1977, pp. 73-95.

35. Stebar, R. F.; et al.: Matching Future Automotive Fuels and Engines for Optimum Energy Efficiency. Future Automotive Fuels: Prospects, Performance, and Perspective. J. M. Colucci and N. E. Gallopoulos, eds., Plenum Press, 1977, pp. 96-120.

36. Stewart, J. F.; and Klett, M. G.: Converting Coal to Liquid/Gaseous Fuels. Mech. Eng., vol. 101, June 1979, pp. 34-41.

37. Identification of Probable Automotive Fuels Composition: 1985-2000. HCP/W3684-01/1, Dept. of Energy, 1978.

38. Reynolds, T. W.; Niedzwiecki, R. W.; and Clark, J. S.: Literature Survey of Syncrudes and Synfuels Derived from Coal. NASA TM-79243, DOE/NASA/2593-79/8, 1980.

39. Gary, J. H.: Motor Fuels from Oil Shale - Production and Properties. Future Automotive Fuels: Prospects, Performance, and Perspective. J. M. Colucci and N. E. Gallopoulos, eds., Plenum Press, 1977, pp. 136-148.

40. Alley, S. K.: Production of Liquid Fuels from Oil Shale. Conference on Composition of Transportation Synfuels: R&D Needs, Strategies, and Actions. CONF-7810176, Dept. of Energy, 1979, pp. 163-185.

41. Duvall, J. J.; and Bartke, T. C.: Comparison of Shale Oils from Different Sources Produced by Controlled-State Retort. Intersociety Energy Conversion Engineering Conference, 13th, Vol. 1. Society of Automotive Engineers, Inc., 1978, pp. 336-341.

42. The Report of the Alcohol Fuels Policy Review. DOE/PE-0012, Dept. of Energy, 1979.
43. Grain Motor Fuel Alcohol Technical and Economic Assessment Study. HCP/J6639-01, Dept. of Energy, 1979.
44. Hagen, David LeRoy: Methanol: Its Synthesis, Use as a Fuel, Economics, and Hazards. Thesis, University of Minnesota, 1976. Energy Research and Development Adm., NP-21727, 1976.
45. Ecklund, Eugene E.; et al.: The Status of Alcohol Fuels Utilization Technology for Highway Transportation. Intersociety Energy Conversion Engineering Conference, 13th, Vol. 1. Society of Automotive Engineers, Inc., 1978, pp. 226-232.
46. Patterson, D. J.: Engine Modification for Use of Mechanol and Methanol Gasoline Blends. Highway Vehicle Systems Contractors Coordination Meeting. CONF-7805102, Dept. of Energy, 1978, pp. 609-620.
47. Keller, James L.: Solving Alcohol Fuel Problems by Fuel Modification. Highway Vehicle Systems Contractors Coordination Meeting. CONF-7805102, Dept. of Energy, 1978, pp. 620-626.
48. Huellmental, L. W.; Liddle, S. G.; and Hammond, D. C.: Combustion of Methanol in an Automotive Gas Turbine. Future Automotive Fuels: Prospects, Performance, and Perspective. J. M. Colucci and N. E. Gallopoulos, eds., Plenum Press, 1977, pp. 235-262.
49. McLean, W. J.; et al.: Hydrogen as a Reciprocating Engine Fuel. Future Automotive Fuels: Prospects, Performance, and Perspective. J. M. Colucci and N. E. Gallopoulos, eds., Plenum Press, 1977, pp. 297-319.
50. Ecklund, Eugene E.; and Kester, Frank L.: Hydrogen Storage on Highway Vehicles: Update '76. First World Hydrogen Energy Conference, Vol. 2, T. N. Veziroglu, ed., Pergamon Press, 1976, pp. 3B-3 to 3B-29.
51. Rohy, D. A.: Automotive Hydrogen Storage with Magnesium Hydride. Tenth Summary Report ERDA-76-136, Energy Research and Development Adm., 1976.
52. Anderson, David N.: Emissions of Oxides of Nitrogen from an Experimental Premixed-Hydrogen Burner. NASA TM X-3393, 1976.

TABLE I. - ADVANCED AUTOMOTIVE GAS TURBINE CONCEPTS

Detroit Diesel Allison - Pontiac	Ford - AiResearch	Chrysler - Williams Research
Two shaft with power transfer	Single shaft	Single shaft
Centrifugal compressor with variable inlet guide vanes (VIGV)	Centrifugal compressor with VIGV and variable diffuser	Centrifugal compressor with VIGV
Premixed-prevaporized, varible-geometry ceramic combustor	Premixed-prevaporized, varible-geometry ceramic combustor	Premixed-prevaporized or catalytic ceramic combustor
Ceramic rotating regenerator	Ceramic rotating regenerator	Dual ceramic rotating regenerators
Ceramic radial turbines	Ceramic radial turbine	Ceramic radial turbine

TABLE II. - COMBUSTOR OPERATING PARAMETERS

	Overall fuel-air ratio range		Flow parameter, $w \sqrt{T}/Pa$		Pressure drop, $\%(\Delta P/P)$	
	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
Current turbines - no variable-geometry combustor						
Upgraded engine	0.01	0.003	0.67	None	2	None
CATE (1406 K)	.013	.003	1.7	None	---	None
Advanced turbines - variable-geometry combustor						
AiResearch	0.014	0.003	0.40	0.33	3	None
Detroit Diesel	.014	.003	.38	.19	2.5	1.7
Stirling engines - no variable-geometry combustor						
Ford (with exhaust gas recirculation)	0.55	None	0.82	0.12	5	0.06
P-40 (with combustor gas recirculation)	.55	0.04	----	----	5	.06

^{a}Where w is weight flow in kg/sec; T is temperature, and P is pressure.

TABLE III. - REPRESENTATIVE COMBUSTOR OPERATING LIMITS

Flame temperature, K:	
Maximum NO_x limit	1920
Minimum CO/HC limit	1310
Primary-zone, lean-stability-	~0.020
limit fuel-air ratio	

TABLE IV. – ASTM D2880-78 TRACE-METAL LIMITS FOR

FUEL ENTERING TURBINE COMBUSTORS

[From ref. 24.]

ASTM fuel designation	Vanadium	Sodium plus potassium	Calcium	Lead
	Trace-metal limits (maximum), ppm by weight			
0-GT 1-GT 2-GT 3-GT 4-GT	0.5 ↓ (a)	0.5 ↓ (a)	0.5 ↓ (a)	0.5 ↓ (a)

aConsult turbine manufacturers.

TABLE V. – TEXACO REFINERY STUDY

[From ref. 34. Refinery charging 100 000 barrels per calendar day of crude oil, maximum transportation fuel production.]

	Case			
	A (base case)	B (Research octane number, 91; motor octane number, 83)	C (maximum diesel)	D (maximum, 100°-650° F)
	Yield, barrels per calendar day			
Refinery fuel:				
Fuel gas	1 461	1 649	1 172	975
Propane and propylene	191	2 420	88	-------
No. 6 fuel oil	4 526	3 568	4 150	4 005
Fluid-coking coke (400 lb/barrel)	1 575	1 652	1 094	1 041
Subtotal	7 753	9 289	6 504	6 021
Transport fuels:				
Premium gasoline	20 910	-------	18 389	-------
Regular gasoline	33 944	-------	29 853	-------
Lead-free gasoline	-------	52 759	-------	-------
Diesel fuel	10 131	10 131	17 349	10 131
100°-650° F end-point fuel	-------	-------	-------	56 609
Subtotal	64 985	62 890	65 591	66 740
Protected products:				
Aviation jet fuel	9 100	9 100	9 100	9 100
Home heating oil	13 651	13 651	13 651	13 651
Petrochemicals and special naphthas	3 400	3 400	3 400	3 400
Lubrication oils and wax	1 800	1 800	1 800	1 800
Asphalt and road oils	3 300	3 300	3 300	3 300
Subtotal	31 251	31 251	31 251	31 251
Other fuels (coke, liquefied petroleum gas, and #4, #5, #6 fuel oils)	8 392	8 561	8 378	8 388
Total	112 381	111 991	111 724	112 400

TABLE VI. - REFINERY YIELD

[From ref. 34.]

Case	Transportation fuels output, barrels/day	Energy required at refinery, Btu/barrel
A	64 985	502 000
B	62 890	575 000
C	65 591	433 000
D	66 740	376 000

TABLE VII. - COMPARISON OF PETROLEUM AND SYNTHETIC CRUDE OIL CHARACTERISTICS

[From ref. 36.]

	Distillation yields									Gravity, °API
	Gasoline, C5-400° F, vol %	Kerosene, 400°-525° F, vol %	Heating oil, 525°-650° F, vol %	Fuel oil, 650°-975° F, vol %	Residuum 975° F+, vol %	Sulfur, wt %	Hydrogen, wt %	Oxygen, wt %	Nitrogen, wt %	
East Texas crude	40	14	12	20	14	0.33	14	----	0.09	38
H-Coal syncrude	37	26	17	20	--	.19	10.9	0.6	.1	23
SRC-1	10	--	12	6	72	.4	6.6	3.5	1.8	-6

TABLE VIII. - ELEMENTAL ANALYSIS OF DRY SHALE OILS

[From ref. 41.]

Shale	Carbon	Hydrogen	Nitrogen	Sulfur	Oxygen[a]	Carbon-hydrogen ratio
	Elemental analysis, wt %					
Lean Colorado	84.1	12.1	1.56	0.57	1.67	6.95
Average Colorado	84.3	11.8	2.00	.66	1.24	7.14
Rich Colorado	84.2	12.0	1.76	.83	1.21	7.02
Utah	84.7	12.0	2.09	.62	.59	7.06
Antrim (Michigan)	83.8	10.6	.74	1.83	3.03	7.91
Moroccan	80.7	10.8	1.45	7.11	[b]-0.06	7.32

[a]Determined by difference.
[b]High values for one or more of the other determinations.

TABLE IX. – PROPERTIES OF DISTILLATES FROM PARAHO SHALE OIL

[From ref. 37.]

Property	Naptha				Middle distillation							
					Kerosene				Heavy oils			
					Temperature, K							
	347-367	378-411	411-444	444-467	467-522	522-544	544-588	588-617	617-644	644-672	672-700	700-722
Cumulative middle distillates, vol %	0.66	1.61	2.62	3.65	8.07	14.10	20.92	28.27	34.52	41.68	50.36	61.33
Crude, vol %	0.97	0.93	1.09	0.97	7.87	4.20	9.43	5.28	7.22	7.10	10.25	11.70
Cumulative crude, vol %	1.14	2.07	3.16	4.13	12.00	16.20	25.63	30.91	38.13	45.23	55.48	67.18
Gravity, °API	35.6	38.0	38.1	34.9	31.7	28.9	27.4	23.6	22.2	19.7	19.0	17.7
Specific gravity at 60° F	0.8468	0.8348	0.8343	0.8504	0.8670	0.8822	0.8905	0.9123	0.9206	0.9358	0.9402	0.9484
ASTM D-86 distillation, °F:												
Initial boiling point	175	200	180	330	398	462	522	562	608	561	556	554
10 Percent	196	235	293	348	412	477	530	589	640	694	769	809
30 Percent	206	256	315	352	420	482	540	595	642	707	782	822
70 Percent	218	273	322	356	426	487	546	601	646	716	785	828
80 Percent	236	288	330	360	436	491	551	605	650	722	791	835
90 Percent	270	306	340	370	452	499	564	616	664	728	799	841
Final boiling point	296	324	364	388	472	517	580	628	688	734	806	849
Amount recovered, percent	96.0	97.0	97.0	96.0	99.0	99.0	99.0	99.0	99.0	95.0	98.0	98.0
Amount residual, percent	4.0	3.0	3.0	4.0	1.0	1.0	1.0	1.0	1.0	5.0	2.0	2.0
Vanadium content, ppm	------	------	------	------	------	------	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Nickel content, ppm	------	------	------	------	------	------	0.04	0.04	0.03	0.04	0.19	0.24
Iron content, ppm	------	------	------	------	------	------	2.7	2.7	0.71	1.3	9.7	21.0
Viscosity at 100° F, cS	------	------	------	------	------	------	6.07	11.09	23.03	41.2	110	360
Viscosity at 100° F, SUS	------	------	------	------	------	------	45.8	62.7	110.9	192.2	510	1668
Viscosity at 210° F, cS	------	------	------	------	------	------	1.67	2.38	3.42	4.88	6.50	7.37
Viscosity at 210° F, SUS	------	------	------	------	------	------	------	34.1	37.6	42.3	47.5	50.3
Total sulfur content, wt %	1.93	1.67	1.45	1.15	0.96	0.91	0.75	0.78	0.73	0.72	0.64	0.55
Mercaptan sulfur content, ppm	140	10	100	20	60	40	60	30	19	36	52	68
Total nitrogen content, wt %	0.10	0.57	1.24	1.62	1.15	1.46	1.71	1.80	2.00	2.25	2.14	1.89
Paraffin content, wt %	------	------	------	------	3.04	33.4	36.3	31.2	33.8	26.8	24.1	19.7
Naphthlene content, wt %	------	------	------	------	16.6	18.6	19.7	20.8	15.2	16.2	27.9	37.3
Aromatics content, wt %	------	------	------	------	34.0	29.0	28.0	31.0	33.0	35.0	32.0	28.0
Olefins content, wt %	------	------	------	------	19.0	19.0	16.0	17.0	18.0	22.0	16.0	15.0

TABLE X. - PROPERTIES OF DISTILLATES FROM OCCIDENTAL SHALE OIL

[From ref. 37.]

Property	Naphtha			Middle distillation								Whole crude
				Kerosene			Gas oils					
	Boiling range, °F											
	IBP-250	250-300	300-400	400-510	510-590	590-650	650-750	750-850	850-950	950-1050	1050+ residual	
Yield, vol %	-----	1.0	3.7	12.3	16.0	12.8	20.8	17.6	8.5	2.8	4.5	100
Cumulative yield, vol %	-----	1.0	4.7	17.0	33.0	45.8	66.6	84.2	92.7	95.5	100.0	100
Specific gravity	-----	0.814	0.821	0.848	0.876	0.885	0.911	0.920	0.939	0.980	1.059	0.904
Sulfur content, wt %	-----	0.430	0.714	0.555	0.670	0.561	0.531	0.400	0.503	0.893	1.32	0.64
Concentrated carbon content, wt %	-----	-----	-----	-----	-----	-----	0.01	0.11	1.43	6.29	27.2	-----
Nitrogen content, wt %	-----	-----	-----	0.458	0.640	1.327	1.598	1.532	1.605	1.778	1.98	1.30
Aniline point, °C	-----	-----	29	42	46	51	53	62	58	46	-----	-----

TABLE XI. - STABILIZERS FOR METHANOL-GASOLINE BLENDS AT 70° F

[From ref. 37.]

Blend composition	Stabilizer	Amount of stabilizer in blend, percent	Water added to haze point, percent
10 Percent methanol in 37 percent aromatic gasoline	None	--	0.17
	sec-Butanol	1	.22
	sec-Butanol	3	.35
	Ethanol	10	.80
	Methyl benzoate	10	.29
	Dimethylphthalate	10	.35
20 Percent methanol in 28 percent aromatic gasoline	None	--	0.24
	Isopropanol	5	.62
	n-Butanol	5	.79
	Isobutanol	5	.91
17 Percent methanol in 37 percent aromatic gasoline	None	--	0.3
	tert-Butanol	3	.5
	Methyl acetate	3	.5
	Dimethoxyethane	3	.6
	Tetramethylurea	3	.6

TABLE XII. - WATER SENSITIVITY OF

METHANOL-GASOLINE BLENDS

[From ref. 37.]

Blend in gasoline	Aromatics content, percent	Water added to haze point, vol %	Temperature, °F
10 Percent methanol			
Chevron U	19	0.025	37
		.10	70
Chevron S	37	.08	37
		.15	70
Texaco G	26	.13	Room
Texaco M	32	.16	Room
20 Percent methanol			
Chevron S	37	0.1	37
		.3	70
Texaco G	26	.23	Room
Texaco M	32	.26	Room
30 Percent methanol			
Chevron S	37	0.23	37
		.50	70
Texaco G	26	.35	Room
Texaco M	32	.38	Room

TABLE XIII. - POTENTIAL ELECTRIC AND HYDROGEN-FUELED

VEHICLES BASED ON EXISTING TECHNOLOGY

Fuel storage	Storage fuel weight, lb	Equipment weight, lb	Vehicle test weight, lb	Range, miles
Advanced lead-acid battery	1500	---	3975	52.9
Fe-Ti hydride	435	110	3010	[a]50
	669	167	3330	[b]52.9
	1736	436	4800	[c]200
Methanol reforming	69	282	2805	[d]50
	275	312	3055	[c]200
MCH-toluene	321	330	3125	[d]50
	965	400	3910	[c]200
Hydrogen liquid	33	220	2710	[c]200

[a]Nominal; equivalent to 5 gallons of gasoline plus a
one-third increase in thermal efficiency.
[b]Based on same run time over driving cycle plus 2.65 kg H_2/hr.
[c]Equivalent to 20 gallons of gasoline plus one-third
increase in thermal efficiency.
[d]Equivalent gasoline not stated.

TABLE XIV. - PRELIMINARY FUEL REQUIREMENTS FOR AUTOMOTIVE

GAS TURBINE AND STIRLING ENGINES

Property	Allowable range
Viscosity at ambient temperature, cS	<10
Boiling range, °C	≤ 400
Allowable hydrogen-carbon content	(a)
Aromatic content	(a)
Nitrogen content,[a] wt %	<0.08
Ash content, wt %	<0.01
Gum content, mg/milliliter	<7
Sulfur content,[c] wt %	0.5
Mercaptan content,[c] wt %	0.003
Vanadium content,[c] ppm by wt	0.5
Sodium and potassium content,[c] ppm by wt	0.5
Lead content,[c] ppm by wt	0.5

[a]To be determined.
[b]Depends on combustor type, vehicle fuel economy, and emissions regulations.
[c]For all-metal engines; content for ceramic components to be determined, but will be greatly increased.
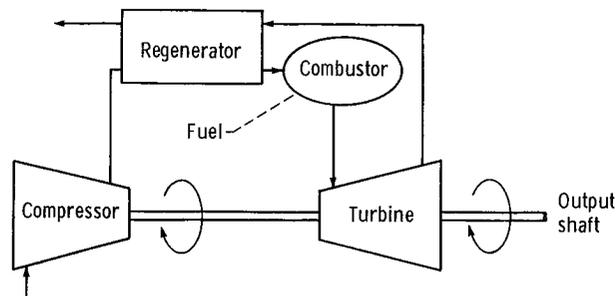
(a) Single-shaft configuration.
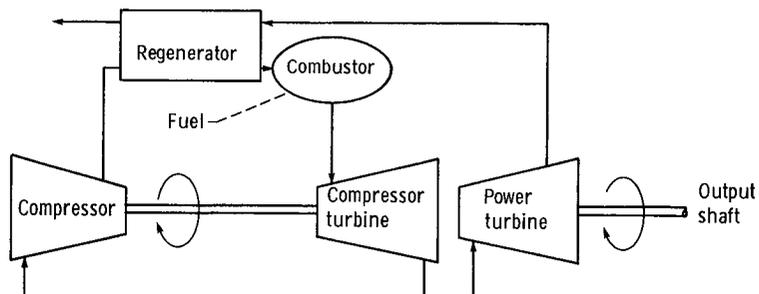
(b) Two-shaft configuration.

Figure 1. - Engine configurations for automotive gas turbines.
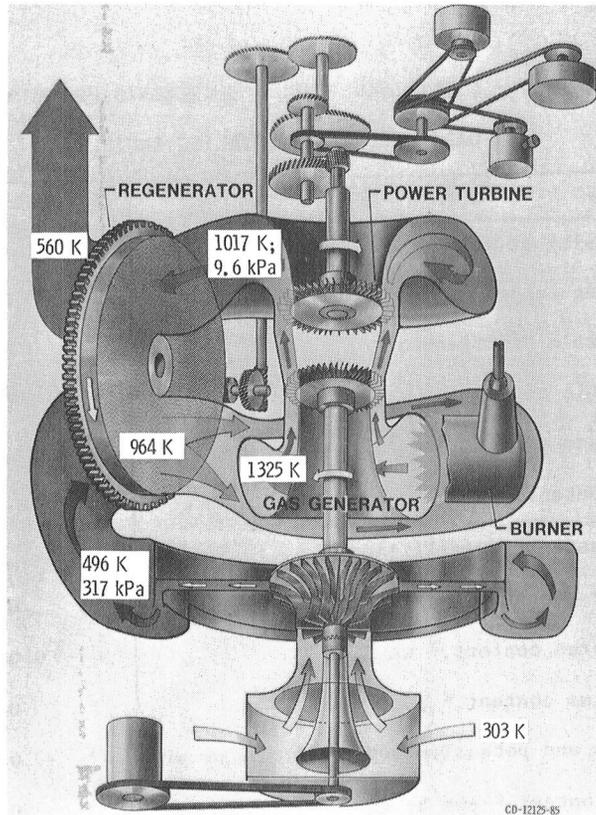
Figure 2. - Cutaway drawing of Chrysler upgraded engine.
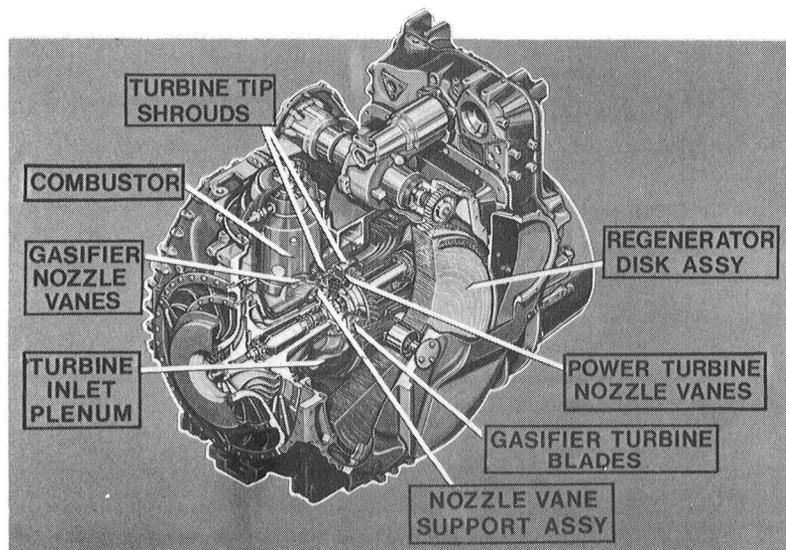
Figure 3. - Ceramic components used in Detroit Diesel Allison CATE program engine tests. (GT 404/505-4 engine; from ref. 3.)
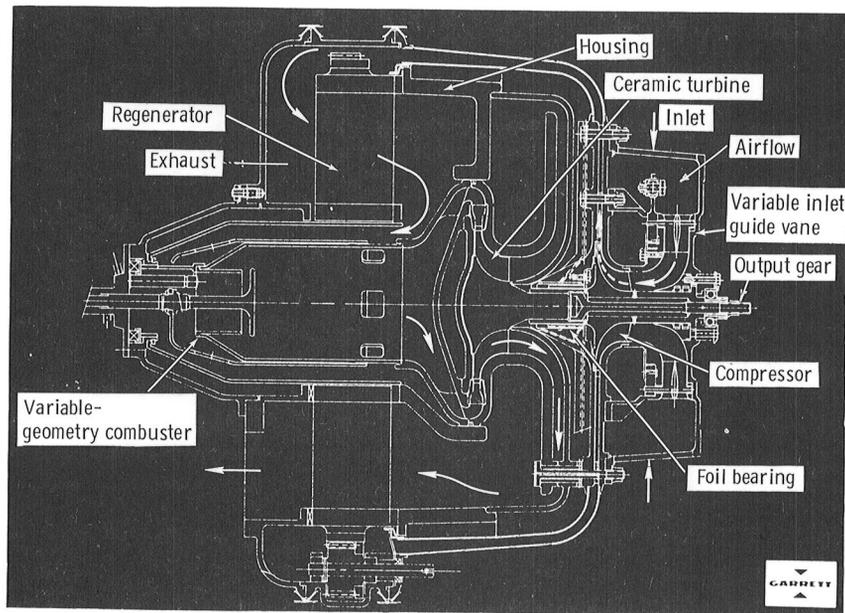
Figure 4. - Cutaway drawing of Ford-AiResearch automotive gas turbine. (From ref. 4.)
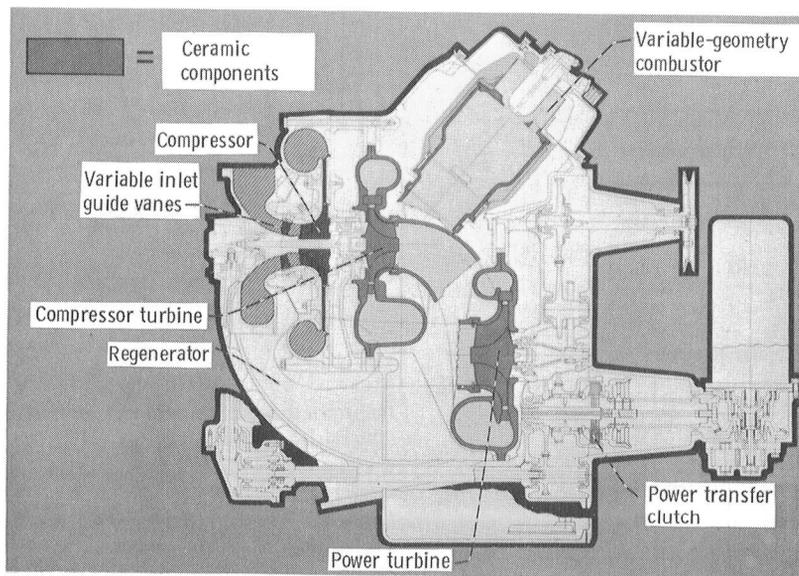
Figure 5. - Cutaway drawing of Detroit Diesel Allison automotive gas turbine. (From ref. 5.)
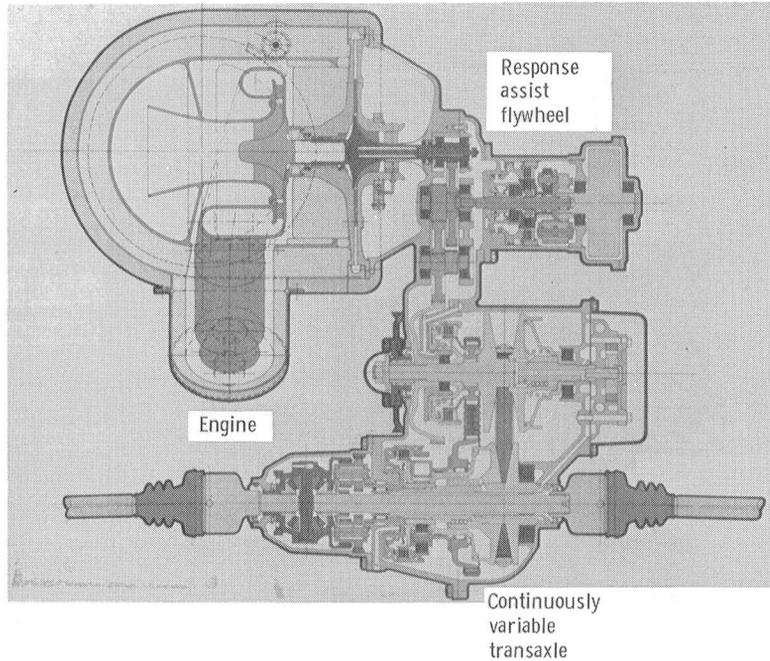
Figure 6. – Cutaway drawing of Chrysler automotive gas turbine.
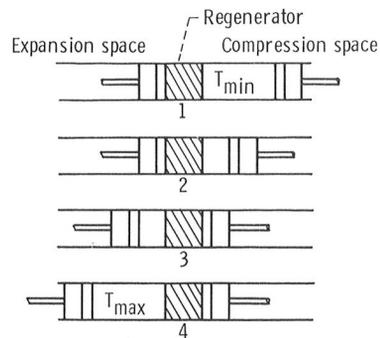
(a) Piston arrangement and terminal points of cycle.
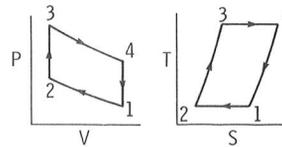
(c) Pressure-volume and temperature-entropy diagrams.
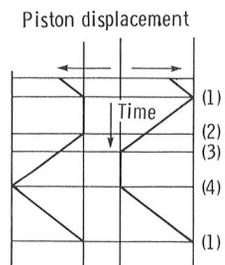
(b) Time-displacement diagram.

Process	Description
1-2	Isothermal compression; heat transfer from working fluid at T_{min} to external dump
2-3	Constant volume; heat transfer to working fluid from regenerative matrix
3-4	Isothermal expansion; heat transfer to working fluid at T_{max} from an external source
4-1	Constant volume; heat transfer from working fluid to regenerative matrix

Figure 7. – The Stirling cycle. (From ref. 7.)

SINGLE-ACTING STIRLING ENGINES

Piston and displacer in. the same cylinder

Crank-connecting-rod drive (Stirling)

Free piston (Beale)

Free displacer, crank-connected piston

Piston and displacer in separate cylinders

Parallel cylinders (Heinrici)

Cylinders at right angle (Robinsson)

Multiple compression spaces (Rainbow)

Multiple expansion spaces (Rainbow)

Single-acting two-piston engines

Parallel cylinders (Rider)

V-cylinders

Opposed pistons

DOUBLE-ACTING STIRLING ENGINES

Double-acting piston-displacer engines

Piston-displacer double-acting engine (Stirling)

Two-cylinder twin system (Finkelstein)

Stepped piston

Double-acting piston engines

Interconnecting adjacent cylinders (Rinia)
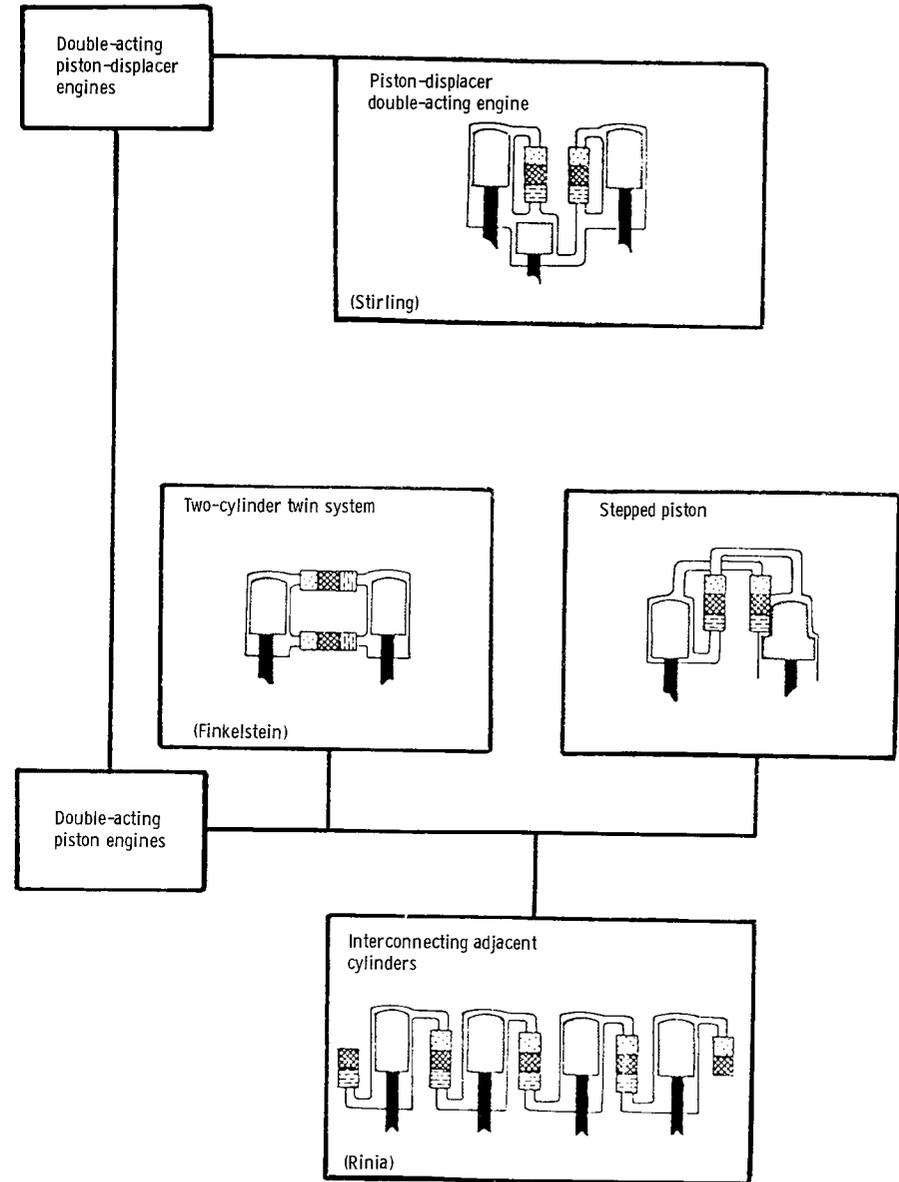
Figure 8. – Stirling engine cycle configurations. (From ref. 8.)
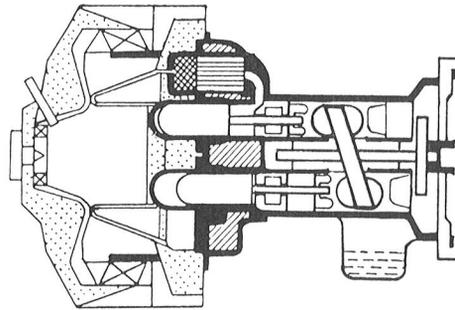
(a) Swashplate drive.
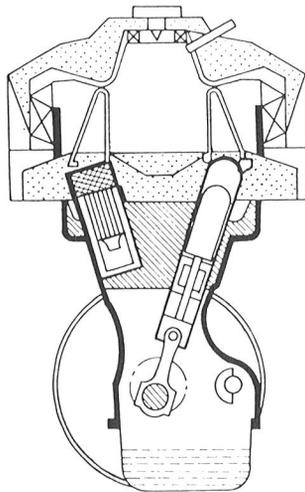
(b) V-drive.
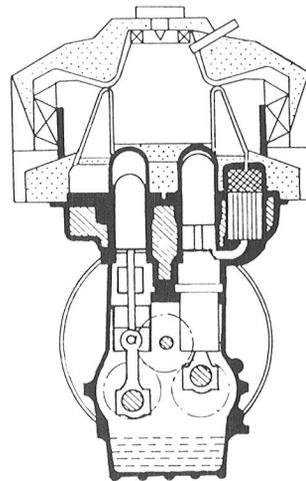
(c) U-drive.

Figure 9. - Stirling engine mechanical arrangements.
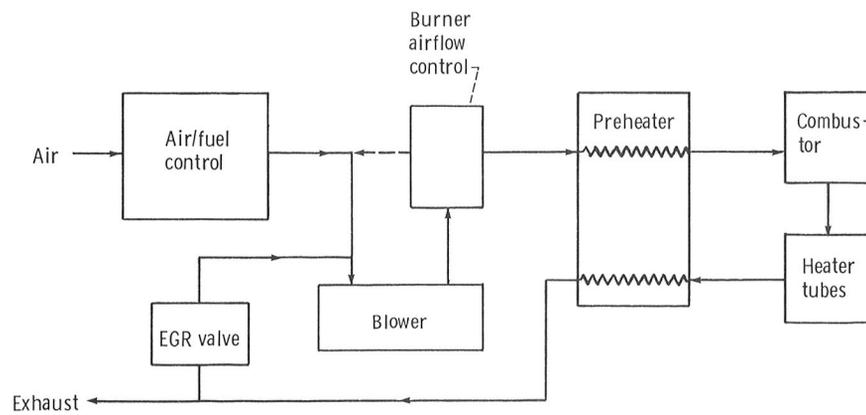
Figure 10. - Schematic of exhaust gas recirculation system.
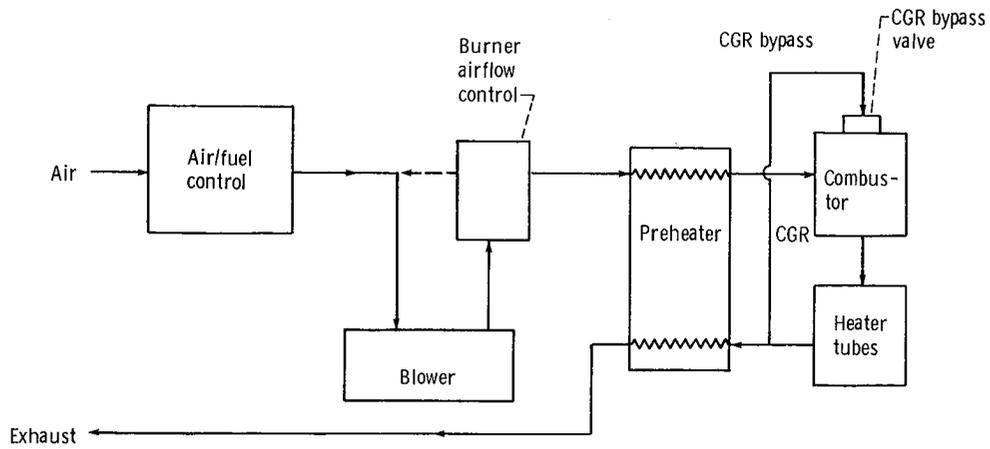
Figure 11. – Schematic of combustion gas recirculation system.

Figure 12. – Liquid hydrocarbons
atomic H/C ratio for different struc-
tures containing 10 carbon atoms.
(From ref. 29.)
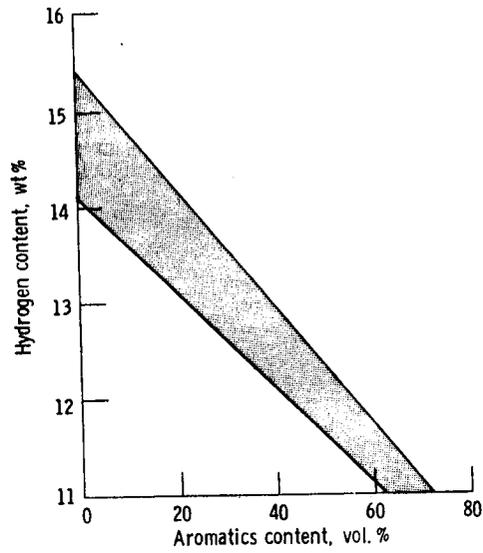
Figure 13. – Variation of hydrogen content with aromatics content. (From ref. 19.)
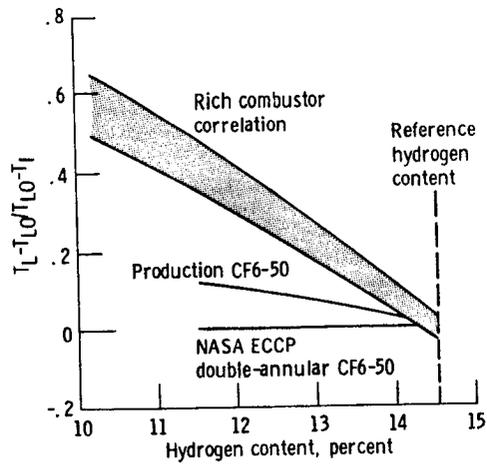
Figure 14. – Variation in maximum combustor liner temperatures with hydrogen content of fuel, where T_L is maximum combustor liner temperature, T_{LO} is maximum combustor liner temperature for a fuel with reference hydrogen content (14.5 percent), and T_I is combustor inlet temperature. (From ref. 16.)
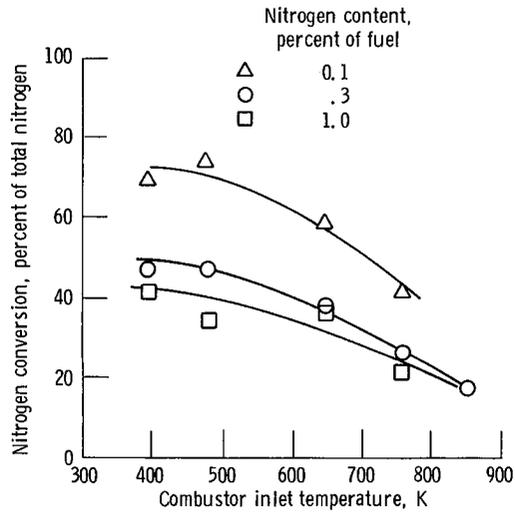
Figure 15. - Fuel-bound nitrogen conversion to NO_x in an aircraft gas turbine combustor. (From ref. 18.)
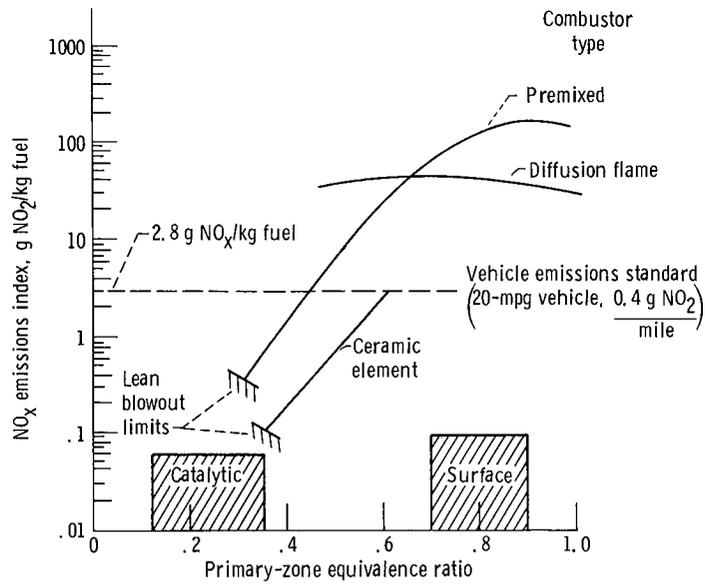
Figure 16. - Variation of NO_x emissions index with combustor type. Combustor inlet temperature, 978 K (1300° F); petroleum distillate fuel. (From ref. 23.)
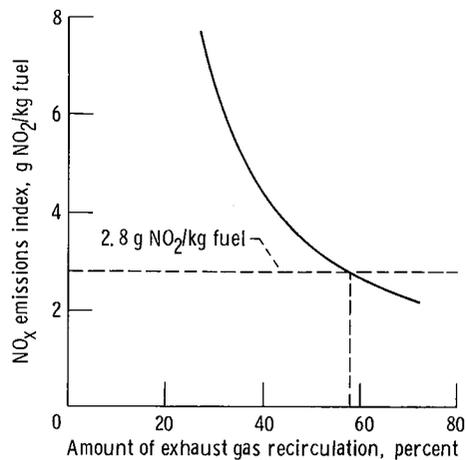
Figure 17. – Variation of NO_x emissions index
with amount of exhaust gas recirculation.
P-40 no. 1 acceptance test; equivalence ratio,
~0.8; fuel flow, 0.7 to 3.8 g/sec.
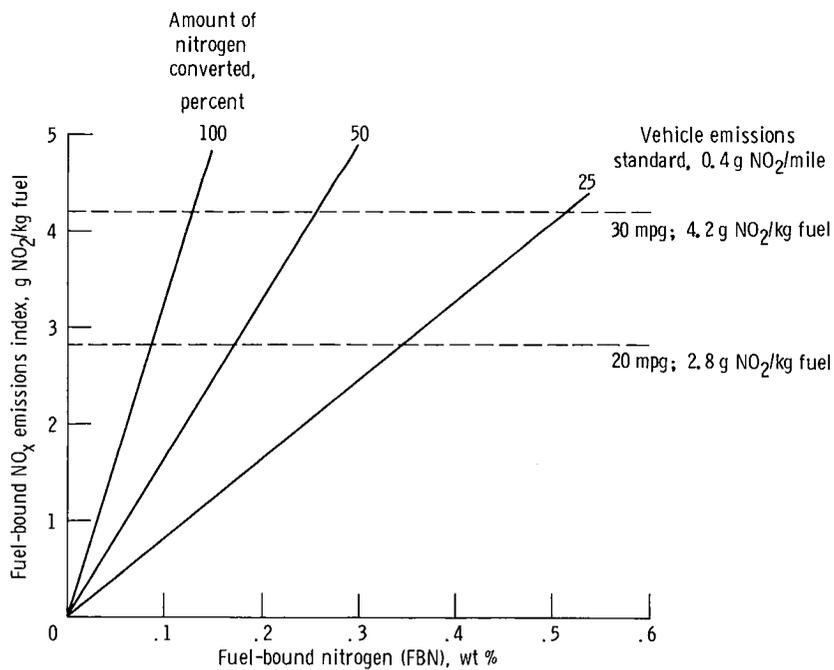
Figure 18. – Influence of fuel-bound nitrogen conversion rates on NO_x emissions (no thermal NO_x). Emissions index, 32.85 x FBN x conversion.
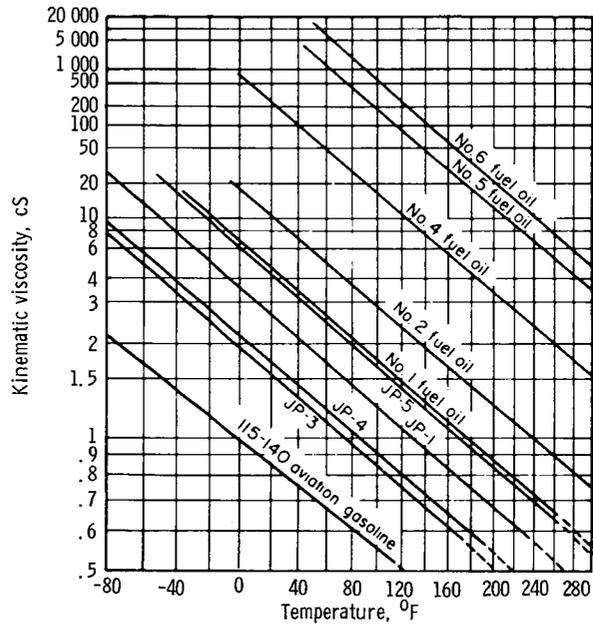
Figure 19. – Relation of viscosity to temperature for typical fuels. (From ref. 15.)

Figure 20. – Boiling range of various petroleum products. (From ref. 19.)

Figure 21. – Typical fuel blend freezing points. (From ref. 19.)
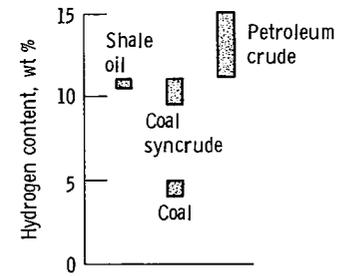
Figure 22. – Hydrogen content of alternative sources of jet fuel. (From ref. 19.)
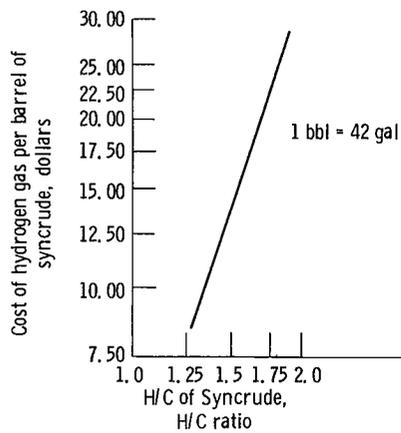
Figure 23. - Estimate of cost of hydrogen required to achieve a specific syncrude H/C ratio - starting from coal H/C of 0.75. Hydrogen gas cost (1980), $2/1000 ft^3; coal cost (1982), $20/ton.
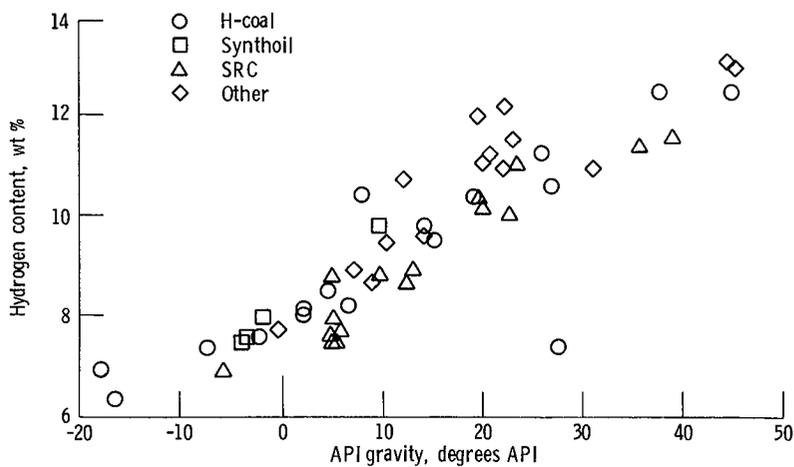

Figure 24. - Variation of hydrogen content of coal-derived fuels with API gravity. (From ref. 38.)
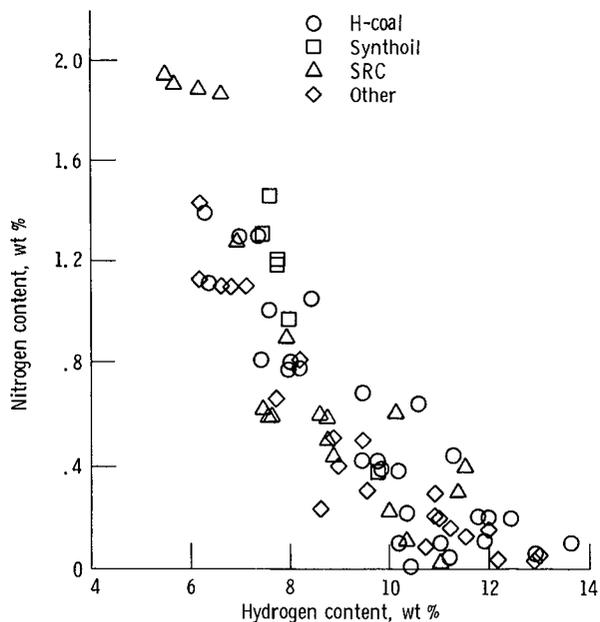

Figure 25. - Relation of fuel-bound nitrogen and hydrogen contents for coal-derived fuels. (From ref. 38.)
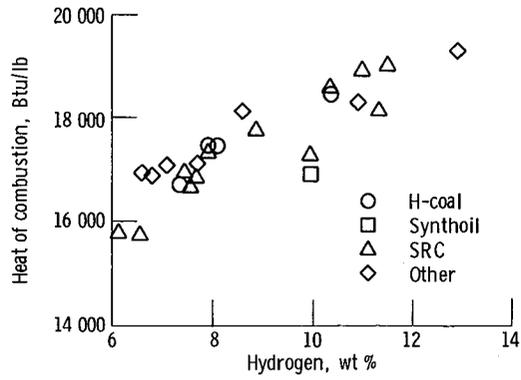
Figure 26. – Variation of heat of combustion of
coal-derived fuels for varying hydrogen content.
(From ref. 27.)
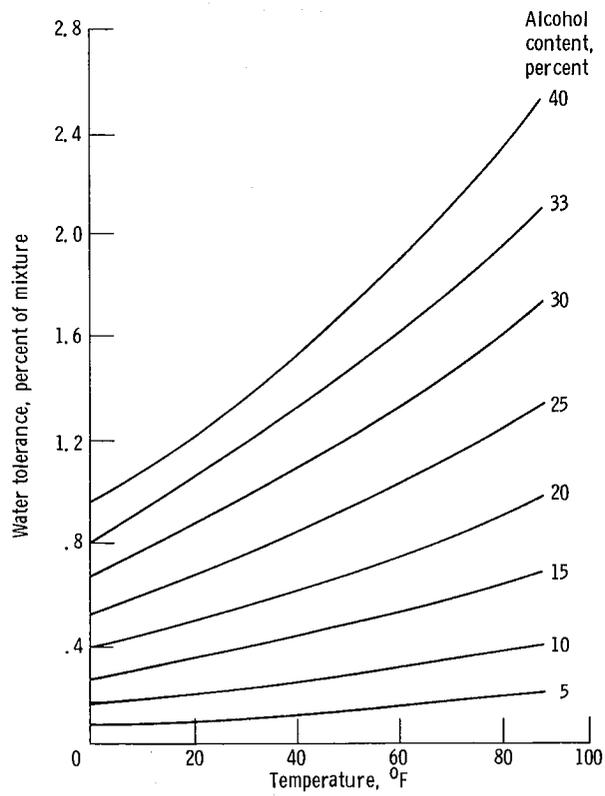
Figure 27. – Water tolerance of ethanol-gasoline blends. (From
ref. 37.)

1. Report No. NASA TM-81754	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle COMPATIBILITY OF ALTERNATIVE FUELS WITH ADVANCED AUTOMOTIVE GAS TURBINE AND STIRLING ENGINES - A LITERATURE SURVEY		5. Report Date May 1981
		6. Performing Organization Code 778-32-01
7. Author(s) James Cairelli and David Horvath		8. Performing Organization Report No. E-792
		10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		
		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address U.S. Department of Energy Office of Transportation Programs Washington, D.C. 20545		
		14. Sponsoring Agency Code Report No. DOE/NASA/51040-24

15. Supplementary Notes
Final report. Prepared under Interagency Agreement DE-AI01-77CS51040.

16. Abstract
The application of alternative fuels in advanced automotive gas turbine and Stirling engines is discussed on the basis of a literature survey. These alternative engines are briefly described, and the aspects that will influence fuel selection are identified. Fuel properties and combustion properties are discussed, with consideration given to advanced materials and components. Alternative fuels from petroleum, coal, oil shale, alcohol, and hydrogen are discussed, and some background is given about the origin and production of these fuels. Fuel requirements for automotive gas turbine and Stirling engines are developed, and the need for certain research efforts is discussed. Future research efforts planned at Lewis are described.

17. Key Words (Suggested by Author(s)) Alternative fuels; Petroleum; Oil shale; Coal; Alcohol; Hydrogen; Gas turbine; Stirling engine; Fuel properties; Combustion properties	18. Distribution Statement Unclassified - unlimited STAR Category 44 DOE Category UC-96	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price*

* For sale by the National Technical Information Service, Springfield, Virginia 22161