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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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on

Future Fuels for Aviation

by

I.I.Pinkel

NORTH ATLANTIC TREATY ORGANIZATION

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Advisory Report No.93

FUTURE FUELS FOR AVIATION

by

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Prepared for the Propulsion and Energetics Panel of AGARD.

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FUTURE FUELS FOR AVIATION

1. INTRODUCTION

The subject of future aircraft fuels involves a consideration of future fuel availability and price and the factors that influence them. These factors include:

(1) Future world petroleum and syncrude production.
(2) Changing patterns of oil product use.
(3) Changing characteristics of available hydrocarbons from all sources.
(4) Ability of aviation gas turbines to accommodate fuels of wide specification.
(5) Aviation fuel economies.
(6) Alternate fuels for aviation.

This report is a preliminary survey conducted for AGARD on the future fuel outlook for aviation fuels expressed by various segments of the aviation community of almost all of the NATO countries. The information for this report was obtained during meetings held under AGARD auspices in the United States, United Kingdom, Norway, Denmark, the Netherlands, Belgium, France, Germany, Italy and Canada. While an attempt was made to contact all segments of the aviation community in each of these countries, practical considerations of time, cost, and availability of key people limited such contact. The meeting list and the affiliation of the attendees, Appendix A, shows the breadth of representation of the aviation community that was achieved.

A rational treatment of the prospects for aviation fuel must be couched in the total energy outlook. For this reason, this report discusses the plans the NATO countries have for increasing the fuels derived from all sources (petroleum, natural gas, coal, tar sands, and shale oil) and the substitutions that are planned to relieve the demand for petroleum products by shifting some of this demand to other energy sources. Such shifting patterns of use offer an opportunity to aviation to insure a continuing supply of hydrocarbon fuel at a price it can afford for a greater number of years than would otherwise be the case. However, the aviation industry may be required to promote special R & D in the general fuels area and to make accommodations in its own field to exploit this opportunity. The nature of the research and development to accomplish this is the subject of part of this report. Some of this R & D is already underway or planned. All of it would benefit from AGARD encouragement.

Estimates of the variation of aviation fuel availability with time are difficult to make in view of the uncertainties regarding the success of petroleum prospecting and secondary petroleum recovery techniques, and the changing policies of the oil exporting countries. Likewise, the timing of the development of the syncrude industry for recovering hydrocarbon fuels from tar sands, oil shale and coal, is clouded by technical, political, and economic uncertainties that will be discussed.

Liquid hydrogen as an aviation fuel remains a highly controversial matter. The points of view expressed during this survey on liquid hydrogen are reviewed.

The private, university, and government research and development capability of the combined NATO countries is impressive and should be adequate for the R & D problems on aviation fuels in coordinated programs. Coordinated programs on special aspects of the aviation fuel problem and a fresh look at present fuel specifications and fuel handling practices is suggested by this review. These suggestions are developed from the point of view that shortages of aviation fuel of specification quality will appear in the near term in local areas for short periods of time, and in the long term, worldwide, as high grade petroleum sources dwindle. Near term local shortages will occur with increasing frequency as growing demand for petroleum products outstrips supply, petroleum is used as an instrument of policy, and war interrupts shipment. Also, limited fuel budgets, particularly for military fuels, imposes a shortage that relates to price. Fuel economies in airplane operations are a primary concern, therefore.

Quantitative forecasts of future supply and demand of hydrocarbons are the subject of other studies. In this report a growing shortage is assumed. Approximate estimates of the rate at which the shortage is expected to grow is given where appropriate to illustrate the order of magnitude of the time remaining in which solutions to the aviation fuel supply problem are required.

A survey such as this one, which draws information from many individuals, deals with matters of opinion as well as matters of fact. These are difficult to separate in some instances. While every attempt is made to present a balanced view of each issue, some of the remarks made in this report may be challenged by those who hold a differing opinion.

2. HYDROCARBON AVIATION FUEL SUPPLY OUTLOOK

While the military aviation fuel is the principal concern of this review, the fate of military fuels is tied to commercial aviation fuels, so both are considered together. Their availability and price are linked to the total supply of energy. For this reason, the total energy picture is displayed along with the discussion of aviation fuel.

2.1 The Prospects for Petroleum and Syncrude from NATO Countries

A. *Western Europe*

All the countries of Western Europe will continue to be wholly dependent on petroleum imports for liquid hydrocarbons with the exception of Norway and England who are served by the developing North Sea petroleum field. Norway will have enough petroleum to serve its modest needs and to export an amount which is small in terms of Western Europe's requirements. At the programmed rate of exploitation of the present North Sea field and a promising area further north which is held in reserve, Norway expects to be self-sufficient for the next 30 to 50 years. Denmark's share of the North Sea oil can meet only 5 to 10 percent of its domestic requirements.

The United Kingdom's North Sea field is expected to reach peak production by 1980 and supply all of the UK needs, with the possibility of some export, until 1990 when the yield from this field will decline. After 1990 the UK will have to supplement its petroleum supplies with imports. Only a modest substitution of coal for petroleum products for power production can be expected since the English coal mines are becoming too deep to be profitable and the remaining supply at present use rates is variously estimated to last for 30 to 100 years.

B. *Canada*

Canada's self-sufficiency in petroleum will last until about 1982 when demand will exceed supply of domestic petroleum. A policy of declining exports is now in effect which will end petroleum exports by 1980, approximately. Canadian petroleum production has peaked, and will begin to decline slowly in the next three years as the flow from present wells tapers off.

Canada has a proven reserve of about 6.2×10^9 barrels and a present domestic requirement of about 0.55×10^9 barrels per year. Of the 6.2 billion barrels, two billion barrels are held as emergency reserve. Present proven reserves would last 8 years.

There has been no major oil find in Canada since 1966. Most of the promising geological formations on land have been explored, and now prospecting has shifted to the waters and islands above the Arctic Circle, the Hudson Bay and Labrador waters. While the geology of these areas is promising, the results so far have been disappointing. Because the Arctic area is remote and icebound most of the year, petroleum must be transported by long expensive pipelines. Discoveries of major oil deposits only would justify such pipelines, and this has not happened so far. Large natural gas fields have been obtained, but the economics of pipeline transportation is also marginal now.

Prospecting off the coast of Labrador is restricted to about one month of the year when there is no threat from icebergs. Drilling rigs used in North Sea explorations are towed across the Atlantic for this one month of operation. There is no major oil find yet, but prospecting will continue. Even if oil is located in these waters, means for protecting the wells, pipelines, or tanker loading facilities from iceberg damage will require a major advance in ocean engineering technology. The expense of drilling in deep stormy seas off the coast of Labrador is a major deterrent to the rapid exploration of this promising area. Drilling a single well in deep ocean waters now costs about $2,000,000.00, exclusive of the cost of the drilling platform.

Hudson Bay prospecting is also done under difficult conditions and will proceed slowly.

Canada has two large hydrocarbon deposits which require major development in technology and enormous investments to exploit. One is the Athabasca Tar Sands in Alberta with a total reserve of 500 billion barrels, and the other is the huge deposit of heavy petroleum crude which is too viscous to flow to the surface through deep wells.

Fortunately, about 10–15 percent of the tar sands deposits lies within one hundred feet of the surface and can be mined in open pits. A potential of 50 billion (50×10^9) barrels is available from this open pit mining. The tar (bitumen) is separated from the sand by a hot water wash and removed by flotation. Distillation of the bitumen in a coker yields products similar to those derived from petroleum. A large coke residue results, some of which is burned to provide heat and energy for processing the tar sands. About 20% of the finished product is consumed in mining and processing the tar sands. Hydrogenation of the bitumen before distillation would increase the yield of liquid products and reduce the coke. Modest hydrogenation to remove sulfur, nitrogen and metals is done now. Hydrogen is produced from local natural gas. A single company, Great Canadian Tar Sands, is operating profitably now with a plant capacity of 65,000 barrels/day. The products, naphtha, gas oil and heavy oil are transported from Alberta by pipeline. The high cost of facilities and mining has discouraged rapid development of this resource. Present cost is estimated at 2 billion dollars for a plant capacity of 125,000 barrels/day. A second company known as Syncrude, which is a consortium of Canadian and US oil companies, is developing such a plant with financial support from the Canadian government.

Projection of Canada's fuel supply beyond 1985 shows a heavy reliance on tar-sand derived fuel. Present plans call for opening a 125,000 barrel/day plant every two years. By 1985 in-situ methods for separating the bitumen from the sand are expected to be in operation to exploit the 85%–90% of the tar sand deposit which is too deep for open pit mining. Start of this ambitious development of the tar sands awaits clarification of the government royalty and tax policies and success with in-situ recovery techniques.

Although the heavy, viscous petroleum deposits are estimated at several thousand billion barrels, only a small percentage can ever be brought to the surface profitably. A large expenditure of energy is required to warm the heavy crude in-situ to reduce its viscosity so that it will flow to wells and be pumped to the surface. Considerable development will be required to create a satisfactory process. There is a reasonable chance that the exploitation of this resource will never be profitable. A similar situation exists in Venezuela in the Orinoco field. Some development of in-situ recovery methods are under way, but a major technical breakthrough is required for success.

While Canada has coal in the west which it can hydrogenate to produce liquid fuels, it prefers to emphasize tar sand and heavy crude programs now. Canadian coal is not as plentiful as US coal; a large syncrude industry based on coal would be more expensive than one based on tar sands. Canada would have to mine 400,000 tons of coal per day (more than its present capability) to produce one million barrels/day of liquid fuel, which is a little more than half of its present requirements. Development of such an industry would require a major commitment of Canada's steel and energy resources. In any case, hydrogenated coal would not appear in significant amounts until after 1985. Since fuel from tar sands will constitute an important portion of the total Canadian fuel supply, the problem of its suitability for aviation use must be considered now. Canadian oil shale assays about ten gallons of oil per ton of shale, which is too low for profitable exploitation.

Canada does not believe it can be an energy supplier to the other NATO countries.

C. *United States*

Conservative estimates indicate that 150–200 billion barrels of oil are yet to be taken out of the ground in the United States. US consumption is now (1975) about five billion barrels per year and is growing. This unproven reserve represents a 20 to 25 year supply. US domestic production falls far short of demand today; the gap between domestic supply and demand will grow until the development of syncrude from shale and coal becomes substantial. According to present estimates US oil demand will rise from approximately 18 million barrels/day in 1975 to 29 million barrels/day in 1985. About one-half of US oil will be imported by then.

US oil shale is estimated to contain 1800 billion barrels of crude. Estimates vary regarding the portion of this deposit that can be exploited profitably since the largest portion of the oil is contained in shale of low oil content that cannot be recovered profitably by present techniques (1975). One of the richest areas is the Mahogany Zone in the Piceance Basin of Colorado, which occupies an area of 30 by 35 miles. A conservative estimate places the reserve in the profitable shale deposits at 130 billion barrels, and an ultimate recovery of 54 billion barrels from these deposits. Much of this recovery loss is due to the mining technique that requires 40% of the shale to remain in the mine as pillars to support the roof of deep mines (1200 feet). Other losses include the energy expended in mining, transporting, retorting of the shale and disposing of the spent shale.

In-situ methods for recovering the crude from the shale could make a large portion of the remaining shale deposit attractive for exploitation. These methods burn a portion of the crude in place to warm the remainder so that it will flow as liquid to a collection well, or be raised to the surface as vapor. Although many schemes are being studied, none appear close to success. Some doubt that an adequate in-situ method will ever develop.

Present estimates place the production of shale oil at 500,000 barrels per day by 1985 and about one million barrels per day by 1990. Further development depends on the solution to environment problems and the assurance of a price for the crude that makes the venture profitable. Cost per barrel of crude is estimated at 12 to 18 dollars per barrel by 1980, depending on depletion allowances, royalties and taxes, and the ultimate cost of facilities. While rising cost of petroleum increases the economic attraction of oil shale, the cost of facilities also increases with petroleum costs and offsets some of this economic advantage.

By any count, there is far less recoverable shale oil than recoverable coal. Coal is the ultimate fossil fuel.

There is a wide difference of opinion regarding the prospects for major recoverable oil deposits in the continental shelves of North America and Europe. Some petroleum geologists feel that the narrow sea that once separated the coast lines of Europe and North America was favorable to the development of rich petroleum deposits. The North Sea oil fields, whose recoverable reserves are estimated at 40 billion barrels, are offered as evidence of this. However, the little prospecting that has been done so far in the Atlantic Ocean has been disappointing.

D. *The World*

The consensus of recent estimates place the worldwide recoverable oil reserve at 1600–2000 billion barrels, a major portion of which is in the Middle East and the USSR. China is expected to have a substantial supply which is considerably less than Russia's. World oil consumption is 20 billion barrels per year in 1975 and is rising rapidly to an expected peak of about 27 billion barrels per year in 1985. After this time, world petroleum production is expected to decline. Declining reserves and the rising cost of exploration, development, and transportation of oil from remote areas of the world will inevitably raise the cost of oil products substantially.

It now costs about one million Danish Krone (about $200,000.00) to create a capability for producing 1 cubic meter (about 7 barrels) of finished product per day. Much of this cost is in prospecting. Large prospecting costs encourage the present trend toward oil company consortiums to finance and spread the risk of this exploration. Competition for the dwindling supply will accelerate rising prices. The pressure for removing government price controls to stimulate prospecting and investment will accelerate the price rise. At some point the price rise will reflect the fact that petroleum products have become too valuable to burn.

Calculations on the number of years petroleum fuels will be available for world aviation based on the ratio between total reserves and maximum annual use rate might be too optimistic. Many countries which are present petroleum exporters will probably follow Canada's example and stop exports when their remaining petroleum reserves are required for domestic use. An overestimate of the time available to develop alternate fuel sources and to accommodate aircraft engines to the available fuels may create a painful fuel-short era.

Worldwide natural gas reserves are estimated to be half that of petroleum on a heating value basis. In areas where natural gas is plentiful it will help to extend the years over which petroleum fuels are available by substituting natural gas for petroleum-derived fuels. Natural gas prices will rise rapidly as it depletes toward the end of this century. Natural gas is not considered a basis for a syncrude industry since it will disappear with petroleum.

2.2 Present Patterns of Fuel Supply and Demand

A. *General*

The NATO countries of Europe practice straight-run distillation of petroleum; a good market exists for all finished products with present use patterns. In contrast to Europe, the US practices much reforming and hydrocracking to provide 40–45 percent of the petroleum barrel for automotive gasoline. This capability gives US refineries considerable flexibility in refinery product distribution.

While the distribution of petroleum product use in the Western European NATO countries differs in detail, the following distribution is characteristic:

(1) Home and industrial heat – 40–50%
(2) Electrical power plants – 20–25%
(3) Transportation (automotive, diesel, aviation) – 20–30%
(4) Petrochemicals – 5–15% (and growing rapidly)

Those countries that have sizable coal deposits such as the UK and West Germany supply a substantial portion of their power needs with coal, but this amounts to less than half. Poland is a modest coal source for some of the Western European countries. The US and South Africa represent the largest potential coal sources.

B. *Aviation*

Aviation kerosene accounts for from 1.5 to 4 percent of the petroleum barrel in European NATO countries and about 7 percent in the US. Potentially, about 10 to 12 percent of the barrel can be made into specification aviation kerosene by straight run distillation. European refiners see no problem in meeting a growing demand for aviation kerosene, therefore. US refiners could resort to hydrocracking of middle and heavy oils to meet a marked expansion of kerosene demand. Since there is a present market for all the kerosene, competition will probably raise the price if the aviation kerosene consumption is increased. The US uses about 12% of the petroleum barrel for all forms of aviation fuel (kerosene, JP-4, gasoline).

In Canada the demand distribution for petroleum products favors the use of JP-4 for commercial aviation at a substantial price advantage. Pressure from government regulatory agencies to convert to kerosene for greater fire safety might force a change in spite of the excellent fire safety record that has been demonstrated with JP-4 (Jet B).

Airline and military engineering and maintenance personnel in several countries express a preference for kerosene because fewer precautions are required for hangaring or servicing the airplane and in handling the fuel. The air forces of some countries favor kerosene because of its reduced fire vulnerability in combat. Others favor JP-4 for its better high altitude performance (altitude relight) and are willing to protect against combat fire with reticulated foam in the fuel tanks. Still other countries are willing to accept either fuel if NATO establishes a uniform aviation fuel. The US Air Force is considering a shift from JP-4 to kerosene. They are cooperating with the Navy and Army to develop JP-8 which is a Jet A-1 kerosene with anti-icing and corrosion inhibitor additives. The Navy plans to hold to JP-5, the higher flash point kerosene, for shipboard use. The relative price of JP-4 and kerosene will no doubt be a determining factor in the choice.

The air forces of several countries admit to curtailed flying schedules because of growing high fuel costs, but all countries insist that there is no reduction in pilot training and proficiency flying.

2.3 Changing Patterns of Fuel Supply and Demand

Most of the NATO countries expect a rising need for energy of all forms, but, except for Norway and the UK, they are planning to reduce the rate at which their dependence on petroleum is growing by a strong shift to coal, natural gas, and nuclear power. In spite of these shifts, most countries expect to need increasing amounts of imported petroleum.

A. *Natural Gas*

Fortunately, Western Europe has a substantial supply of natural gas, the largest sources being the Groeningen fields in The Netherlands and the several fields of the North Sea. Some natural gas comes from Russia. Soon liquified natural gas will be available by tanker from the Middle East and North Africa. Until recently fuel oil for home heating was cheaper than natural gas on a calorie basis. Now, more extensive use will be made of natural gas for home heating. However, in some countries such as Denmark, the cost of establishing a piped gas distribution system to homes outweighs the price advantage of natural gas; they will continue to use heating oil until cheap nuclear electric power is available. The natural gas supply is estimated to last for about thirty years at the present use rate. The heating value of the remaining world's supply of natural gas is estimated to be about one-half the heating value of the remaining petroleum reserves.

B. *Nuclear Power*

Public opposition to nuclear power plants in some European countries may slow its introduction while the governments campaign to overcome this opposition through education. The European countries will cooperate in the rework of spent fuel elements, but the disposal of radioactive wastes from such rework is an unsolved problem that may restrict the rate of development of the nuclear power industry. Some countries hope to produce 20% of their electricity with nuclear power plants by 1985.

C. *Coal*

Only a limited substitútion of domestic coal for liquid hydrocarbons can be expected in most of Europe since only a few countries have mines that can be operated profitably. Europe is considered to have extensive coal deposits at 1000 meters below the surface, but these are not considered to be profitable to work by present mining techniques. Much of Europe's coal will have to be imported from South Africa and the US. An extensive syncrude industry in Europe based on coal is not likely since conversion of the coal to liquid fuel is accomplished most profitably near the coal source.

In the US there is considerable emphasis on the substitution of coal for petroleum fuels in a reversal of the recent trend from coal to petroleum-derived liquid. Western US low sulfur coals are suited for industrial use without treatment. Solvent refining processes to eliminate sulfur and ash from coal are being developed. Solvent oils derived from the refining process, enriched by a modest hydrogenation, are used to dissolve the desirable coal constituents. Subsequent separation of the oil provides a clean burning, environmentally acceptable solid fuel.

In the US there is considerable emphasis on the substitution of coal for petroleum fuels and natural gas. Large deposits of Western low-sulfur coals are suited for industrial use as mined. About 90% of the Eastern coals require desulfurization to meet anti-pollution standards. Solvent extraction processes have been devised for dissolving the desired coal constituents, leaving a residue of sulfur, ash, etc. Subsequent separation of the solvent oil provides a clean-burning solid fuel. The solvent oils, enriched by a modest hydrogenation, are derived from the extraction process.

A second desulfurization process involves the removal of the sulfur from the coal by treatment of the powdered coal with aqueous alkali solutions at temperatures from 225°C–350°C and pressures from 350 to 2500 pounds per square inch. Sulfur is recovered as a byproduct and the alkali is recycled. Expensive hydrogen is not required. Estimated cost is 10–15 dollars per ton of coal desulfurized.

For power plants and boilers which cannot use solid coal, several low cost liquifaction processes are being studied. These processes aim at producing a cheap low sulfur heavy oil as its principal product so as to minimize the use of expensive hydrogen. High sulfur coals can be used, since most of the sulfur is removed as hydrogen sulfide. In this process the hydrogen to carbon ratio for coal, which is given by the simple formula $CH_{0.9}$, is raised to the value for the heavy oil product whose simple formula is $CH_{1.1}$.

A further economy in this hydrogenation process has been developed by the substitution of a mixture of CO and H_2 (Syngas) for pure H_2. Since Syngas is available directly from the gasification of coal or by-product char, this mixture is far cheaper per mol than hydrogen alone.

In the coal hydrogenation process the CO is beneficial in reducing the viscosity of the product oil, in providing hydrogen for the process by reacting with the water in the coal, and by removing oxygen in the coal which would normally consume expensive hydrogen. Lignites, which contain a high percentage of water are well adapted to this process. Oil yield is three barrels per ton of dry ash-free coal. Additional coal is required to produce the syngas. Ash removal to 0.02 percent is possible by centrifuge and filtration treatment of the oil. This low ash content might make the oil suitable for stationary locomotive and marine gas turbines which can use high freezing point fuels that are rich in aromatics.

A byproduct gas from this Syngas coal liquifaction process is a hydrogen rich gas which can be recycled with make-up gas or used for the synthesis of methane for pipelines, or methanol, or serve as a starting point for Fischer-Tropsch synthesis of higher hydrocarbons such as motor and jet fuel.

Large scale development of such processes are being expedited. Successful commercial exploitation would save enough natural gas and oil presently used for electric power and industrial boilers and gas turbines to relieve the current US shortage of natural gas and divert much petroleum fuel for other purposes. This will be the principal contribution of coal liquifaction to improving the supply of hydrocarbon fuels in the next 10–20 years.

Hydrogenation of coal to produce lighter hydrocarbons does not look attractive now largely because of the high cost of hydrogen and unproven commercial scale technology. Nevertheless, there is a strong research and development activity under private and public sponsorship. Two of the most prominent processes involve the catalytic hydrogenation of powdered coal-oil slurry. In one, an ebullated bed of catalyst circulates through the reactor with the coal. The catalyst is separated, reactivated as required, and recirculated through the reactor with fresh coal-oil slurry. In the other process, a fixed catalyst bed is supported in the reactor. The mixture of coal-oil slurry and hydrogen flows over the bed with high turbulence to promote good contact with the catalyst and to prevent the accumulation of deposits on the catalyst surface.

Both processes have been studied in small pilot plant scale facilities. Operation on a commercial scale involves technical uncertainties which can have a large effect on product cost. Since 4500 standard cubic feet of hydrogen are required to make one barrel of product, a source of cheap hydrogen is essential. This hydrogenated coal product can be refined into finished fuels by established refinery techniques.

Regarding the economics of hydrogenation, one major oil company has indicated that a 20–30 percent increase in the cost of petroleum (1974) would make it profitable for them to engage in commercial scale hydrogenation of coal, and possibly wood, to produce liquid fuels by processes that they have been perfecting. Production of gasolines from coal by conversion first to syngas (H_2 + CO) followed by a Fischer-Tropsch synthesis is an operation under government subsidy in South Africa. Cost of this process is too high and is not part of the current development effort in the US.

D. *Oil Shale*

Shale oil is close to petroleum chemically; much of the petroleum technology for converting it to finished fuels applies. The distribution of refined products from shale oil syncrude is similar to those obtained with petroleum. Shale oil is regarded as a better stock than coal for producing aviation turbine fuels which permit limited aromatic content. Also, the composition of shale oil is less variable than coal; its processing is therefore more predictable.

Several above-ground processes have been developed for separating oil from shale. All of them involve retorting the shale at 770° to 900°F to vaporize the kerogen (oil) out of the shale. Higher temperatures (1150°F) induce thermal decomposition of some of the inorganic shale constituents which absorb heat and reduce the thermal efficiency of the process. Also, higher temperatures increase the thermal cracking of the kerogen and more gas is produced than might be desired. The kerogen (oil) yield is correspondingly reduced.

It will be advantageous to pipeline the kerogen to existing refineries to reduce facility costs and to increase the blending options. Kerogen pour point usually lies between 75–100°F and it is unsuited for pipeline transmission to the refinery from the mine. Pour point lowering can be accomplished by:

(1) Hydrogenating the kerogen.
(2) Removing the asphaltenes that boil above 800–900°F.
(3) Thermally cracking the larger paraffin molecules (boiling range 300°F and above) which contribute to high pour point.

Removing the asphaltenes and cracking the paraffins is preferred over the hydrogen treatment that would require much water and a fairly complex processing operation close to the mine. The oil shale area is arid and water is scarce.

In-situ recovered shale oil has less asphaltenes and therefore has a lower freezing point. Heating is less severe underground, on the average, and some asphaltenes are left in the shale.

Kerogen (shale oil) is high in sulfur and oil-bound nitrogen. The fraction which boils in the kerosene range is high in aromatics (up to 35%) and has a high pour point. Hard hydrogenation is required to reduce the nitrogen by conversion to ammonia. Unless this is done the nitrogen poisons the catalysts used in further processing. Sulfur is removed and aromatics are reduced by this hydrogenation step to remove nitrogen.

The total refining treatment for shale syncrudes has not been established. Recent batches of jet fuel (JP-4 and kerosene) from shale syncrude required extensive treatment with clay to produce a clear product. A light straw color persisted in the clear jet fuel, giving rise to concern about the thermal stability of the fuel. Further hydrogenation can improve stability, but adds to the cost.

Because finished fuels from oil shale have not been proved in extensive service, its early commercial introduction will probably be as blends with petroleum products to reduce the risk in their use. This will also simplify the refining of shale syncrude since some of the deficiencies in the syncrude products might be compensated by the blending. Eventually, however, shale oil fuels will appear without benefit of blending with petroleum products as these become more scarce.

E. *Methanol*

The use of methanol with automotive gasoline requires further development of the engine. The lower vapor pressure of methanol compared with the more volatile fractions in gasoline makes for poorer cold-starting and warm-up performance of gasoline-methanol mixtures. The lower heating value of methanol requires the use of larger carburetor jets than would be the case for operation with gasoline alone. To obtain satisfactory drivability with gasoline-methanol mixtures it may be necessary to operate with straight gasoline during the start and warm-up periods. Straight gasoline would be carried in a separate tank and metered through its own set of carburetor jets. Under the fuel-lean engine operation imposed by pollution considerations there is evidence that a ten percent methanol addition to gasoline is the maximum practical even with this complex start and warm-up arrangement. Fuel maldistribution problems encountered with gasoline-methanol mixtures may require the use of fuel injection systems in place of the carburetor. Corrosion of non-ferrous engine metals with such fuel mixtures is an added problem.

Opinion is divided on the ultimate prospects for using gasoline-methanol blends. Some believe that blends up to thirty percent methanol will be practical and that the high anti-knock rating of such blends will allow the use of more efficient high compression engines. Others doubt that the engineering problems and economics of methanol will ever make it attractive as an automotive fuel.

The present free-world production of methanol would hardly be adequate to produce the 30% blend for the gasoline consumed in West Germany today. While much experimentation is in progress to produce methanol from byproduct materials, particularly from agriculture, at attractive prices, natural gas is the most convenient starting material now. Conversion to methanol is simple and the technology is available. Where natural gas can be readily marketed, its conversion to methanol is wasteful since part of its heating value is lost in its partial oxidation to methanol. However, there are natural gas deposits in inaccessible areas which are too small or poorly located to justify a pipeline or gas liquifaction facilities. Conversion to methanol at the gas well, with transportation by tanker appears to be an economic alternative. Some of the gas wells in the North Sea and the Canadian Arctic islands and waters, for example, may be candidate sources for methanol shipped by tanker. The rapidly rising cost of gasoline might stimulate the development of methanol production that could relieve the demand pressure on the gasoline supply somewhat. It would probably take at least ten years (until 1985) to reach a substantial level of methanol production.

If substitution of methanol for substantial amounts of gasoline should occur then light fractions of petroleum would be available in some parts of the world as stocks for aviation fuels to be used directly in a JP-4 (Jet B) type fuel, or reformed at some cost to kerosene. However, the rapidly growing petro-chemical industry might outbid the aviation industry for much of these light hydrocarbons.

2.4 Aviation Fuel Demand

It is projected that in the US, the largest consumer of aviation fuel, demand for aviation fuel will grow at a faster rate than the demand for gasoline. If this holds for a period of years then a major shift in product distribution of US refineries must occur. It might be to the advantage of aviation to shift its specifications for aviation fuels accordingly to avoid expensive product reforming. A parallel condition may develop in other NATO countries. Most airplane operators who are using kerosene would be reluctant to change to a more volatile fuel. However, a fuel cost advantage could bring this change and some operators would like to keep this option open.

On the basis of shifts in energy use which are in process, or planned, it appears that the middle distillate fuels (heating oil and diesel fuel) are most likely to become available as additional stock for producing aviation fuel in the near term (10–20 years). Growing competition for this fuel may come from the greater use of stationary and marine gas turbines, and a marked rise in the popularity of the automotive diesel engine. The further development of the automotive diesel engine is being emphasized in some countries.

If aviation holds to present specifications for Jet A fuels, then an additional cost per gallon of 5–10 cents might be required to upgrade the middle oil to kerosene by hydrocracking. Much of the cost is for the hydrogen, since it takes about 2000 standard cu. ft. of hydrogen to upgrade a barrel of middle oil to kerosene. This cost would be less if the hydrocracking is done where hydrogen is cheap, as for example in the Middle East, where hydrogen can be made inexpensively from abundant natural gas. Middle East plans for developing its own refining capacity may include hydrocracking capability that is not now available in Europe. Alternatives for using some of the middle oil as aviation fuel without hydrotreating are discussed in subsequent sections of this report.

2.5 Summary of Hydrocarbon Fuel Outlook

The following remarks summarize the present picture on hydrocarbon fuel availability for the future:

A. The world's supply of recoverable petroleum is about 1600–2000 billion barrels. Considering a world demand peak of 27 billion barrels per year, and the requirement for emergency reserves established by the oil producing countries, which are to be withheld from market, less than 50 year supply exists. This is the maximum time available to develop alternate sources of hydrocarbons on a scale commensurate with the total demand. The required investment will be enormous and some technical breakthroughs are required.

B. Natural gas supplies available to the NATO countries at present rates of consumption are expected to last for about 30 years.

C. Only coal, oil shale and tar sands will remain as sources of hydrocarbon fuel after petroleum products become too expensive to burn.

D. The substitution of coal, coal-derived heavy oils, and nuclear energy for home heating, industrial boilers, and electrical power production will release substantial amounts of middle oil (heating and diesel) for other uses in 10–20 years.

E. The substitution of methanol for part or all of automotive gasoline would make the lighter hydrocarbons more available, also.

F. Aviation should explore now the manner in which it can benefit from these opportunities to reduce the rate of rise of aviation fuel costs should these opportunities occur. Each opportunity might happen at a different time and require a quick change in aviation fuel specifications to exploit it.

G. Inexpensive hydrogen is key to flexibility in converting petroleum products or sources of syncrude to specification fuels at reasonable cost. Also, by hydrogenating syncrudes, coal, tars, char and distillate residues, a greater yield of more valuable hydrocarbons is realized from finite resources. A comprehensive research and development activity on energy should include a substantial effort on the production of low cost hydrogen from char, low grade coal, and the dissociation of water chemically and electrically. The promise of cheap hydrogen from laser-stimulated nuclear fusion by the middle or late 1980's would have an enormous beneficial effect on the total energy picture generally, and on the availability of hydrocarbons in particular.

3. AVIATION FUELS

Concern for price, availability and safety of aviation fuels has stimulated interest in reviewing fuel specifications. Some specifications were formulated during the early years of the aviation gas turbine and some question is raised regarding their relevance to present engines. Changing sources of petroleum crude and the introduction of syncrude in the future suggests the desirability of reexamining fuel specifications to avoid unnecessary refining steps and restrictions on these fuels which would raise cost and reduce availability. Difficulties experienced with some fuels in airplane systems has generated recommendations for additions to the specifications and the formulation of convenient tests for implementing these additions.

Local fuel shortages may require emergency use of non-specification fuel. Some guide lines are desirable to cover airplane operation with non-specification fuel.

In the near term (1985–1995) syncrude fuels will find their way into the aviation industry, perhaps in local markets, as blends with petroleum products, or unblended. In the long term (beyond 1995) syncrudes will probably be a prime source of aviation fuel. Because of the long lead time required to introduce changes in production engines and airframes (10–15 years) the accommodation required in these units for use with syncrudes needs to be known by 1982.

The cryogenic fuels, liquid hydrogen and liquified natural gas have their proponents. The use of these fuels require large changes in airplane design and operation and in the handling of the fuel.

Other alternate fuels such as metal powders, slurries of metal powders in jet fuel and metal hydrides are not considered here since their experimental use in aviation gas turbines has been disappointing and their cost is excessive. Only magnesium and magnesium slurry performed well, but its use is advantageous only under very special circumstances and does not constitute a meaningful contribution to the available fuel supply for aviation.

3.1 Fuel Specifications

The following fuel specification items were raised for reexamination in the course of this survey:

A. *Aromatics*

A review of the specifications for aromatics, presently at a maximum of 20% for kerosene, with a short-time allowance up to 25%, is timely for the following reasons:

(1) It is estimated that a 10–20% increase in aviation fuel supply would result if the distillation end point for kerosene (Jet A) is raised from 250° to 288°C. This distillation temperature increase would allow aromatics to rise to 30% for some crudes. Since fuel price is sensitive to small differences between supply and demand, this 10–20% increase in supply would be attractive. With recurring shortages of specification fuel more likely from now on, this added fuel availability is important.

(2) Some of the developing oil producing areas, Nigeria for example, provide crudes which are somewhat higher in aromatics than current crudes. Presently, blending with low aromatic stocks helps. When such low aromatic stocks are unavailable for blending, the available fuels will be above specification in aromatics.

(3) Aviation fuels from tar sands, oil shale and, particularly, coal tend to be rich in aromatics.

(4) While aromatics can be reduced by hydrogenation, such treatment increases fuel cost.

The present limit on aromatics is based on the difficulties with smoke and combustor over-heat from luminous flames produced by the aromatics in early aviation gas turbines. Much of these difficulties were due to the high fuel concentration maintained in the primary combustor zone to provide flame stability and good high altitude relight capability. Present engines operate with leaner primary combustor zones to reduce smoke emission and combustor liner cooling is more effective with present designs. For these reasons, the need to review the present limits on aromatics has been raised.

Air line operators feel that their fuel tank seals will tolerate aromatics up to 30% at least.

The matter of fuels with high aromatic content is reviewed further in a later section that deals with the relationship between aromatic content and engine combustor design.

B. *Freezing Point*

An increase in the distillation end point of kerosene to augment the supply usually brings with it a rise in freezing point. Aircraft operators, military and civil, will accept a rise in freezing point only if it can be demonstrated by flight test that this is safe in the area of the world in which they operate. There is considerable skepticism regarding the practicality of a freezing point approaching –40°C which might occur with some fuels containing 30% aromatics. The airlines consulted on this matter indicated that they would consider the use of fuel tank heating if the availability and price of the higher freezing point fuel were sufficiently advantageous. Presumably heat for the fuel tank can be drawn easily from the engine. Both military and civil aircraft operators are cautious about agreeing to such techniques without further study.

C. *Fuel Lubricity and other Physical Properties*

Fuel lubricity has been a troublesome problem in some parts of the world with some engines. At times a poor correlation exists between lubricity of a fuel batch measured at the refinery and that which appears in service. Several oil companies and a university research center are working separately on the problem, but the need for a coordinated program involving the engine manufacturers and oil companies has been expressed by one of the major oil companies. A principal goal of such a program would be a reasonably simple laboratory bench lubricity test that correlates with service.

Those concerned with fuel procurement for some military aviation establishments have expressed the need for engine designs which are less sensitive to the physical properties of the fuel, principally lubricity and viscosity. Fuel properties are important to the wear of the engine fuel pump and the operation of the fuel control. Changes in the pump materials have reduced their sensitivity to low fuel lubricity. The trend away from hydromechanical fuel controls and toward electronic controls remove their dependence on fuel properties. Several engine manufacturers have portions of electronic fuel systems in service now and hope to have fully electronic systems on production engines by 1980. However, the present engines will be in service for many years, so fuel lubricity will continue to be a requirement.

Fuel lubricity is usually lost when the fuel is hydrotreated to remove sulfur, arsenic, nitrogen, etc. and to reduce aromatics. Syncrudes, which are high in nitrogen, are likely to undergo heavier hydrogenation with a corresponding decline in lubricity. Some fuel additives, such as corrosion inhibitors, restore lubricity, but their use in quantities required to do this might raise water separation difficulties. If it is desirable to use corrosion inhibitors in this way, then it may prove necessary to add the inhibitor after the water separator as the fuel is loaded on the airplane. Compatibility with other additives would have to be established as well.

D. *Thermal Stability*

Most engine companies are concerned for the lower thermal stability of the highly aromatic fuels, especially at the elevated combustor inlet air temperatures of modern high pressure ratio engines, and those used for supersonic flight. Engine development programs include thermal stability studies. So far thermal stability of the higher aromatic fuels appears adequate in engine systems. Further study would be required in complete airplane fuel systems to measure the degradation of fuel/oil heat exchanger performance by fuel decomposition products.

Those fuels derived from syncrudes and petroleum from the African and Alaskan oil fields may have poorer stability than fuels from present sources. Costly hydrogenation can improve stability if sufficient hydrogen is available. A corresponding increase in the cost of aviation fuel in the locales served by these sources would result.

While there is considerable surveillance of probable thermal stability problems with fuels of higher aromatic content there were no recommendations expressed to change present practices or specifications.

E. *Sulfur*

Airplane operators would like to hold to present sulfur specifications if fuel specifications are broadened to improve availability. They are concerned for corrosion of the pump and fuel control parts, some of which are plated with metals that are corroded by sulfur. Engine manufacturers believe that the metals and coatings of turbine blades in new engines can tolerate higher fuel sulfur, but older engines in use are susceptible. Present sulfur specifications will probably remain.

F. *Vanadium*

Vanadium in fuel can be highly corrosive to turbine blades, particularly if it appears with the alkali metals, sodium or potassium. The alkali metals can be in the fuel or enter the engine with the air from ocean areas. Distillate fuels with maximum boiling points equivalent to kerosene contain no vanadium as distilled. However, vanadium may be introduced accidentally in subsequent handling in pipelines and vessels that were used for petroleum crude or residual products which can be relatively rich in vanadium. Aviation fuels are intended to be handled to avoid such contamination.

The middle distillate oils (heating and diesel) are not subject to such careful handling and vanadium contamination might occur. The use of these contaminated oils in turbine engines, alone or blended with kerosene to augment the supply, could cause early turbine blade failure by corrosion. One engine manufacturer states that its turbine blade coatings have a high tolerance for vanadium for short exposure times. However, if operation with vanadium contaminated fuels is prolonged, blade deterioration continues after operation with vanadium-free fuel is resumed.

If stocks of heating or diesel oil are commandeered for aviation use during emergencies, a simple field test for vanadium would be desirable.

There did not appear to be any sentiment in favor of changing the fuel specifications for vanadium on the part of the engine companies. Generally, they felt that their engines have achieved a tolerance for vanadium that is higher than present specifications require. The upper limit on tolerable vanadium concentration varied among engine companies from 0.2 to one part per million.

3.2 Alternate Aviation Fuels

A. *Syncrude Products*

Most of the aviation community regard syncrude products as the future aviation fuel after petroleum is gone. In Canada, tar sands will supply the crude, while in the US oil shale and then coal will be the syncrude source. Some of the engine companies believe that the current interest in qualifying syncrude products for aviation is premature since they believe that petroleum-derived fuels will be available for aviation for 20 to 50 years. Meanwhile, syncrudes should be developed as a replacement for petroleum products where requirements are less stringent in order to release the petroleum fuel for aviation.

Another segment of the aviation community believes that syncrude aviation fuels need to be studied now so that there is sufficient time to correct problems while petroleum-derived fuels are still available. They hold that there is no assurance that syncrude-derived fuels will be handled separately from petroleum fuels in refineries and fuel distribution facilities. Syncrude fuels will enter the aviation system in the late 1980's unless a premium is paid to maintain separation. US engine companies and government laboratories have been trying syncrude derived fuels in their engines and test stand combustors. Kerosene derived from shale oil is reported to perform as well as petroleum kerosene. A successful demonstration flight on syncrude JP-4 has been made, also.

Fully hydrogenated coal produces fuels with up to 50% aromatics which do not look attractive for aviation gas turbines without further treatment, but they are excellent automotive fuel. A balanced US syncrude industry would use shale oil for aviation fuels and coal hydrogenation for automotive fuels. Eventually, when petroleum and oil shale are depleted, aviation will need coal-derived fuels.

The most complete program for qualifying syncrude fuels for aviation is the cooperative program among the US Navy, Air Force and NASA on aviation fuels from oil shale and coal. The program has the following objectives and scope:

(1) *Objectives*

(a) Determine the probable properties of jet fuels derived from oil shale and coal.

(b) Evaluate the effect of these fuels on engine component performance and engine materials.

(c) Solve the problems that are revealed for utilizing syncrude fuels in present and future engines.

(d) Assess the desirability of syncrude fuels with relaxed specifications and determine the accommodations that must be made in engine and airframe for their use.

(2) *Scope (Program progress goals)*

(a) Identify properties of syncrude aviation fuels from oil shale and coal – 1976.

(b) Evaluate fuel performance in combustor; obtain data on combustor durability and exit gas emissions – 1977.

(c) Determine compatability of fuel with engine fuel system, and tank materials – 1978.

(d) Acquire sufficient quantities of the most promising candidate fuel for component and engine tests – 1979.

(e) Perform full scale engine and fuel system tests; engines to be military and civil aviation types – 1980.

Shale oil production is expected to reach 100,000 barrels per day by 1980 and 500,000 barrels per day by 1985. If this schedule is realized there should be ample jet fuel to run the full scale engine/fuel system programs scheduled for 1980.

Some recent studies on the combustor performance of kerosene produced from oil shale have been conducted in single combustor cans using the standard duplex fuel spray injectors. This kerosene was subjected to a modest hydrogenation to remove sulfur, and fuel-bound oxygen and nitrogen. This hydrogenation treatment also reduced the aromatic content of the kerosene so that it had the same hydrogen/carbon ratio as petroleum derived kerosene. However, the nitrogen content of the shale oil kerosene was 800–900 parts per million, while petroleum kerosene typically has 10–20 parts per million.

The combustor performance of the shale-oil kerosene was comparable to petroleum kerosene in every respect, except that the NOx produced by the shale-oil kerosene may be above acceptable pollution standards because of its nitrogen content. About 60% of the fuel-bound nitrogen normally converts to NOx during combustion. Further hydrogenation of the shale-oil kerosene will be required to reduce the nitrogen content. A side benefit will be an improvement in the thermal stability of the kerosene since the fuel itself will receive additional hydrogenation. It is clear that such hydrotreating increases the cost. USAF has sponsored a study to relate the cost of the finished fuel to the refining process. Work is proceeding on the basis that shale oil is a better syncrude source of jet fuel than hydrogenated coal and that oil shale is closer to commercialization.

B. *Liquid Hydrogen*

Liquid hydrogen is regarded by many as the logical successor to petroleum-derived aviation fuel and press for its early introduction. They argue that its higher cost compared with hydrocarbons on a heating value basis is more than offset by the fact that it has about three times the heating value per unit weight. For long range flight, the take-off weight is far less for the hydrogen fueled airplane because of the lighter fuel so that the fuel consumption, and therefore, the cost for the mission is less. Also, those interested in special airplanes that require the heat sink provided by liquid hydrogen are anxious for its general aviation use to justify logistic support for hydrogen. The hypersonic airplane and turbine engines which employ compressor air cooling with liquid hydrogen to permit high supersonic flight are two outstanding instances where liquid hydrogen is essential.

Liquid hydrogen opponents consider that the airplane accommodations to handle and carry large volumes of hydrogen safely would offset any advantage. Because of the low density and the low temperature (−425°F) of liquid hydrogen its tanks would be exceptionally large and well insulated. The large tanks would dictate the overall airplane design. Safety would be an ever-present anxiety. Support systems at airports for safe liquid hydrogen storage and airplane servicing would be complex, expensive, and require high salaried professional personnel. Military aviation is opposed to its use except perhaps for the long range logistic airplane. Providing liquid hydrogen for these airplanes in remote areas appears formidable and it would have limited utility, therefore. Aircraft engine manufacturers do not consider LH_2 as practical aviation fuel even though it performs well in their engines and they feel confident that they can provide suitable fuel controls. Many doubt that hydrogen can ever be provided at an attractive cost as an aviation fuel until cheap power is available by nuclear fusion. Storage of hydrogen on the airplane as metal hydride to avoid the need for large cryogenic tanks and to improve safety is impractical because of the excessive weight of the metal.

However, the airplane performance advantages of the successful application of liquid hydrogen cannot be denied, and many airplane design studies are in progress at airframe companies of the NATO countries. Many of these studies have a low priority, but the enthusiasm and optimism expressed by some of those so engaged indicates a deep commitment to the concept. Others, including some of the major international airlines, while preferring to use hydrocarbon fuels, support liquid hydrogen studies in the event that it proves to be technically feasible and hydrocarbon fuel availability becomes a problem. As part of the work in support of liquid hydrogen fuels, it has been proposed that a current, large airplane be modified for hydrogen use and flown as a transport to obtain information on the operating and service problems hydrogen airplanes would present.

Fundamental liquid hydrogen combustion studies have been carried out in many research establishments in the NATO countries. Except for concern that there may be a combustion stability problem for some ranges of combustor operation expressed by one research group, all agree that hydrogen performs well, particularly under very high altitude conditions where hydrocarbon fuel performance begins to suffer because of low combustor pressure.

The individual studies on liquid hydrogen for aircraft are relatively small, but the total effort is appreciable. This suggests that coordination of these separate programs is timely.

Many believe that hydrogen can serve aviation best by meeting surface equipment fuel needs and releasing the hydrocarbon fuel for aviation. This concept assumes the existence of an energy allocation program that protects the hydrocarbon supply for aviation and distributes the cost of the different forms of energy equitably amongst all users.

C. *Liquified Natural Gas*

Some interest has been expressed for using liquified natural gas (LNG) as an aviation fuel since it will soon be available from North Africa and the Middle East by tanker in commercial quantities. However, LNG is a cryogenic, low density liquid that would require well insulated tanks similar to those for liquid hydrogen. Airplanes for using this fuel (LNG) would be a totally new design and would involve most of the difficulties presented by liquid hydrogen without many of the benefits. For example, the heating value of LNG is less than half that of liquid hydrogen and its performance in engine combustors is not as satisfactory. Also, LNG will probably be available as long as petroleum is, and its cost will probably rise along with that of petroleum products.

Further, liquified natural gas, which is largely methane, can be synthesized from coal. However, the process usually involves making hydrogen from coal first, to be followed by a methanation step which reacts this hydrogen with carbon. The methanation cost is avoided if hydrogen is used as the aviation fuel. Also, cheap nuclear power might provide low cost hydrogen in the future and relieve aviation from its dependence on fossil fuel. If a cryogenic airplane is to be developed, the advantage lies with the hydrogen airplane.

4. AVIATION FUEL CHARACTERISTICS SUMMARY

The following points summarize the issues raised on aviation fuel characteristics during the course of this survey:—

4.1 Fuel Specifications

A. Present fuel specifications reviews should include consideration of feasible engine and airplane systems modifications to allow relaxation of specifications.

B. Since higher aromatics in aviation fuels would increase its availability, the tolerance of present engines for higher aromatics should be studied.

C. Higher aromatic content often means a rise in the freezing point of the fuel. Airplane operators will accept this increase in freezing point only after it is demonstrated to be safe. Some would agree to fuel tank heating schemes if a fuel cost advantage is clearly evident.

D. Inadequate fuel lubricity has been a problem for some engines. Oil companies would like to have a better bench test that correlates laboratory lubricity measurements with service experience. Fuels which are heavily hydrotreated for sweetening or improved by hydrocracking are likely to have low natural lubricity.

E. Fuel procurement services want engines which are less sensitive to the physical properties of the fuel, particularly lubricity and viscosity. Changes in engine fuel pump design and materials, and the trend toward electronic fuel controls are providing some of this engine tolerance to variations in the physical properties of the fuel.

F. Several important developing petroleum fields and the syncrudes are sources of higher aromatic fuels. Since thermal stability usually declines with increasing aromatic content, the suitability of these higher aromatic fuels for the higher heat stress imposed by modern engines is questioned. Hydrogenation of these fuels to reduce aromatics and improve thermal stability raises the cost.

G. Greater use of high sulfur crudes may be required as low sulfur stocks become less available for blending. Refining costs to reduce sulfur to specification values may raise the price of aviation fuel. Present sentiment favors maintaining present specifications on sulfur content.

4.2 Alternate Aviation Fuels

A. Most engine companies have experience with engine operation with tar sand and oil shale-derived fuels and with liquid hydrogen and methane.

B. While they have operated successfully with all of these fuels, with the possible exception of methane (representing liquified natural gas) they believe that these fuels can serve aviation best in non-aviation service to release a corresponding amount of petroleum fuel for aviation.

C. Some engine manufacturers believe studies of alternate fuels for aviation are premature since petroleum fuels will supply aviation for 20–50 years. Others think that solutions to the problem of adapting these fuels for aviation must be faced now in order to have sufficient time to solve them while petroleum fuels are available.

D. Cooperative programs are in progress in the US to qualify aviation fuels from oil shale. Program includes characterization of physical and chemical properties of the fuel, operation in engine combustors and full-scale military and civil engines, and finally, duration testing in complete fuel systems when sufficient fuel becomes available in 1980.

E. Opinion is divided on the utility of liquid hydrogen as an aviation fuel. While the air forces of most NATO countries see no future for liquid hydrogen for military aircraft, there is strong enough sentiment in its favor for many small, low priority studies. The total effort is sizeable and should be coordinated now amongst the participating NATO countries.

F. Liquified natural gas (LNG) is a cryogenic liquid which presents many of the airplane design and handling safety problems of liquid hydrogen while it provides few of the benefits. There is little interest in its use for aviation.

5. FUEL ECONOMY AND IMPROVED AVAILABILITY THROUGH ENGINE DESIGN

The normal course of engine development leads to better fuel economy through improved component efficiency, more efficient cycles and lower engine weight. Also, in recent years the engine manufacturers and related research establishments have considered the matter of operating gas turbine engines with a variety of non-aviation fuels for surface service. This experience relates to the present question of improving aircraft fuel availability by widening fuel specifications. Engine manufacturers recognize that engine problems can no longer be solved by more stringent fuel specifications and that the engine must accommodate the available fuel.

This section of the report considers the trends in engine design that relates to fuel economy and improved availability. Limitations to specific fuel consumption reduction and fuel specification broadening imposed by engine materials, engine complexity and problems related to pollution are discussed.

5.1 Engine Cycles

Better engine cycles can improve fuel economy through more efficient thermodynamics and better propulsive efficiency. Higher engine pressure ratios and turbine inlet gas temperature contribute to improved thermodynamic efficiency. Increases in bypass ratio raise propulsive efficiency. Growth in thermodynamic efficiency is limited mostly by the high temperature strength and corrosion/oxidation resistance of engine materials. Increases in bypass ratio are limited largely by engine weight, nacelle drag, and engine complexity.

A. *Thermodynamic Efficiency*

(1) *Pressure ratio*

State of the art engine pressure ratio for the major engine manufacturers is about 25. Goals for the next generation engines lie above 30. In the view of some, pressure ratios well into the 30–40 range will be limited by the strength of compressor materials in the upper stages which run hot due to the compression. Added material to compensate for loss of strength will raise engine weight and negate cycle efficiency gains. In the view of others, pressure ratios above 50 will be attainable ultimately.

(2) *Turbine inlet gas temperature*

Turbine inlet gas temperatures for the next generation of engines to match the rising pressure ratios will lie between 1500°–1600°K (2200°F–2400°F) for cruise. Although improvements in turbine blade materials are allowing an increase in blade metal temperature of about 20°F per year, improvements in turbine blade cooling are expected to be more effective in attaining higher turbine inlet air temperatures. In 15 years turbine inlet air temperatures of 2800°F for commercial engines and 3000°F for military engines may be possible based on the success of new blade coatings and directionally solidified entectic blade materials. These blade materials present a fabrication problem which is being studied along with their development.

There is considerable effort in turbine cooling since the problem grows more difficult as the cooling air temperature increases with rising engine pressure ratio. While there is considerable confidence that the effectiveness of the blade cooling design can be increased, there is a limit to the amount of air that can be diverted from the main engine stream for cooling. Methods for reducing the temperature of the cooling air by heat rejection to the bypass air flow have been suggested, but this approach is not being pressed. Instead, some engine manufacturers hope to develop a ceramic turbine blade that can operate without benefit of any cooling. A recent development in the application of ceramics to turbines has appeared in the form of a metal blade coating which has low thermal conductivity and, if successful, will reduce cooling air requirements materially.

(3) *Combustor performance*

The combustor is required to provide turbine inlet gas with a radial temperature profile which results in the least stress to the turbine blades, and to operate with a steady, low smoke, low luminosity flame that radiates little heat to the combustor wall. Until recently, the primary combustion zone operated fuel-rich to provide good high altitude relight capability and satisfactory blow-out limits. Now, the primary combustor zone has been leaned out to reduce smoke emissions. Adequate altitude relight and blow-out characteristics have been restored after considerable combustor development. Further leaning out of the primary combustor zone would require another development program on altitude relight and blow-out limits.

Present fuel specifications which limit aromatics to 20% are based on the appearance of highly luminous flames in the older spray injection combustors with fuel-rich primary combustion zones when aromatics exceed this value. Excessive heating of the combustor walls by radiation imposed the 20% limit on aromatics. Leaning out the combustion zone to reduce smoke in the modern combustor reduced the flame luminosity as well. Further reduction of luminosity is possible by avoiding the fuel-rich layer that surrounds each fuel droplet in the combustion zone. Prevaporization of the fuel with good premixing with air avoids these fuel-rich layers around the droplets and luminosity is minimized.

Unfortunately, total premixing is limited by the fact that the air temperature entering the combustor of high pressure engines exceeds the spontaneous ignition temperature of the fuel and premature ignition produces flames that burn through the combustor walls. Compromise solution to the problem is the modern air-atomized and partially premixed fuel injectors whose sensitivity to increasing aromatics is far less than the older combustors and which avoid the preignition problem. These combustors are undergoing continual development to allow higher aromatic fuel content and to reduce NOx. Although aromatics include a wide class of molecular arrangements of carbon and hydrogen, the combustor wall temperature variation with aromatics correlates well on the basis of the hydrogen-to-carbon ratio of the fuel.

Another approach to increasing the aromatic tolerance of combustors depends on achieving more effective combustor cooling and accepting the higher heat radiation from the aromatic fuels. More effective combustor cooling has been obtained with air jet impingement techniques that are used for turbine blade cooling. The cooling air requirements and the pressure drop are the same as for more conventional combustors, but the cooling arrangements are more complex, the combustor is heavier, and it is more expensive.

Ceramic combustors which present no cooling problem are being studied by most engine companies. None of them feel that they are close to a practical design.

Combustor development tends toward the use of multiple burning zones. A pilot zone serves for low power operation, and main zone operates for higher power. The combustor uses premixed fuel and air which avoids excessive flame temperatures and therefore reduces NOx emissions. Higher tolerance for aromatics is an additional benefit.

Interest in the study of the combustion and associated aerodynamics of jet engine combustors remains high in all countries. Sophisticated measurement and analytical techniques are being used to follow the flow velocities and turbulence levels in the combustor flow. Such high quality research should be useful in achieving combustor designs for highly aromatic fuels with low NOx emission.

Some engine companies stress the need to consider the compressor exit air mass flow and turbulence distribution in the development of the combustor. They believe that no amount of treatment of this flow with vanes or other aerodynamic devices can correct the maldistribution of the flow enough to provide an overall gain. The combustor is required to accommodate the problem. Detailed attention to the combustor flow characterizes the present effort.

Several novel approaches to combustor design are being proposed; some are under study. One of special interest is the catalytic combustor which generally takes the form of a honeycomb ceramic whose passages are aligned with the normal direction of the flow, and whose walls support the combustion catalyst. A totally premixed fuel/air charge enters the combustor, thus avoiding the high temperature, fuel-rich, primary combustion zone of more conventional designs. Excellent combustion efficiency is obtained with present catalysts operating at 2000°F and above. The advantages claimed for this approach are:

(i) Low radiation to the combustor walls because fuel-rich high temperature primary combustion zones are avoided. High tolerance to aromatics is indicated, therefore.

(ii) The thermal inertia of the ceramic honeycomb support provides excellent flame stability and blow-out limits.

(iii) Better control of the turbine inlet gas temperature profile since the air recirculation and swirl in the primary combustion zone required by conventional combustors is avoided. For the honeycomb, the flow is axial throughout.

(iv) The narrow zones of high NOx formation rate that are present in conventional combustors are not present in the catalysed combustor. Lower NOx and CO emissions are expected.

(v) Although the ceramic honeycomb produces a 40% flow area blockage, the combustor pressure losses are expected to be no more than those for conventional combustors which employ a high degree of recirculation swirl, and mixing with secondary air.

The outstanding problems with the catalytic combustor are:

(i) Catalyst life; and the further requirements on the fuel to avoid catalyst poisoning.

(ii) Improved performance at temperatures below 2000°F.

(iii) Durability.

Application of the catalytic combustor as a simplified flame holder for jet engine afterburner operation is also under investigation. The catalytic combustor avoids the flow losses associated with the highly turbulent zone in the wake of the conventional flame holders.

(4) *Recuperators*

Most of the engine companies are reviewing the possibilities of using recuperators. None have progressed far enough in the study to make a judgment regarding its value. Its incorporation into the engine presents many problems, chief among them being the design of adequate seals. At this time, there appears to be a general pessimism that the recuperator benefits in the cycle will not justify the added weight and complexity.

B. *Propulsive Efficiency*

(1) *Bypass ratio*

Estimates vary from 7 to 10 on the maximum practical bypass ratio for aviation gas turbines without a gear box between the turbine and fan. While the gear box will permit higher bypass ratios, its weight detracts from the advantages gained. Also, the larger nacelle of the higher bypass engine imposes a drag penalty, which together with gear box weight, places an upper limit on bypass ratio growth. The value of this upper limit decreases with increasing flight speed. If cruise speed is reduced in the interest of fuel economy, then bypass ratio can grow.

The greatest gain in fuel economy is made if the cruise speed is lowered to about Mach 0.75–0.80 and the fan cowling is removed. The result is a many-bladed turbo propeller engine which can have an exceptionally high bypass ratio. However, the noise and vibration problems of the turboprop airplane must be faced again with a higher order of difficulty associated with the increased flight speed.

C. *Fuel Economy Estimates*

Every engine manufacturer agrees that all the gains in engines, cycle, component efficiency and engine weight reduction achievable in the next 15 years will result in a fuel economy of no more than 10–15%. The turbopropeller engine for flight at Mach 0.75–0.80 has the potential for fuel economies from 15–30% as compared to a turbofan for the same airplane.

6. FUEL ECONOMIES THROUGH AIRPLANE DESIGN AND OPERATION

Practically every phase of airplane design and operation is being explored for approaches to fuel conservation. Since most of the world's commercial aviation fleet, about 4,770 airplanes, are new and will be in service for many years, the fuel conservation measures must include items that make economic sense for them. New aircraft allow a wider range of fuel-saving innovations. Under present economic conditions airlines require that retrofit costs for fuel economy be returned in 1–3 years in fuel savings.

Most of the NATO countries have programs for increasing the fuel efficiency of aircraft. The following list of fuel conservation items includes all that were revealed during the course of this survey. Several items on the list are part of present programs, others are being considered for future work, and a portion will probably be rejected after further study.

Shortly after the large rise in aviation fuel price, the following measures were taken to conserve fuel:-

(1) Fuel reserves were more carefully estimated to reduce take-off weight.

(2) Flight speeds were reduced to improve fuel economy.

(3) More optimum flight altitudes were chosen.

(4) Air traffic control was improved to avoid delays.

In the US these measures produced a 9% fuel saving.

For the longer term, the following fuel conservation programs are being considered:

A. *Wing Aerodynamics*

(1) Supercritical wing designs for Mach 0.8 airplanes to achieve better lift/drag ratio from higher wing aspect ratio and lower wing sweep. Also, thick critical wing might hold all of the fuel and part of the cargo. This would allow a lighter airplane structure.

(2) Winglets on wingtips shaped to provide thrust and lift from wing cross-flow.

(3) Improved aerodynamic cleanliness of external stores on military aircraft.

(4) Better propulsion system integration.

B. *Friction Drag Reduction*

(1) Laminar flow control by suction through porous surface.

(2) Flow separation control by air injection through slots.

(3) Compliant fuselage skins which flex in the fluctuating pressure field of the adjacent flow.

Much fundamental work is required to exploit this approach. Manufacturers are receptive to the idea of drag reduction. Airlines are concerned for reliability, maintenance, system weight, and vulnerability to icing and minor accidents. New air pumping systems and lightweight porous composites hold the promise for developing reliable systems with low weight penalties. A fuel saving of 20–40% is estimated for successful application of these drag reduction devices.

C. *Active Controls*

Active airplane controls reduce trim drag, allow a smaller tail, and provide gust and maneuver load alleviation. General acceptance requires successful demonstration. Reduction in airplane drag and weight is computed to provide a 5% fuel saving.

D. *Airplane Structures*

Lightweight airplane structures employing composite materials made from tapes reinforced with filaments of glass, boron, graphite or PRD-49 with matrix of epoxy, polyimide, or aluminum are being developed. A 25% reduction in airplane structural weight appears possible. This weight reduction would provide a fuel saving of 10–15%.

A strong research and manufacturing technology program is aimed at providing structures with good fatigue life, tolerance for lightning strikes and high temperature and chemical environments, damage resistance, and that are easily repaired.

Airlines and aircraft manufacturers are anxious for in-service testing of primary and secondary structures made from these lightweight composites. Such testing is part of the existing program.

E. *Engines*

Fuel economies up to 5% are believed attainable by improved versions of present engines. Such improvements would include:

(1) Mixing of core and duct air streams before discharging through a common nozzle.

(2) Reducing compressor and turbine blade tip leakage.

(3) Minimizing engine seal leakage with compliant seals that adjust to changes in clearance with varying operating conditions.

(4) Employing blade shapes with materials that erode less in service and maintain component efficiency.

(5) Developing the variable cycle engine for efficient operation at subsonic and supersonic flight speeds. Promising concepts have been devised with mechanical parts of reasonable design.

Research is under way on correcting the causes for engine fuel consumption increases in service. For some engines each overhaul restores only a portion of the performance lost between overhauls, and so fuel consumption grows with engine use. One airline reports abrupt increases in specific fuel consumption of 8% sometimes followed by a return to initial values. Reasons for some engine performance deterioration are known. Others remain to be found and corrected.

F. *Avionics*

(1) Avionics for improved management of the approach with delayed flap actuation, and for climb, cruise and descent guidance are estimated to provide a potential fuel saving of 2–7%.

(2) Restructuring of cockpit avionics and controls would allow fuel savings in terminal areas by reducing the time required to land and by increasing the airplane acceptance rate. The wake vortex problem would require solution before full advantage could be taken of the higher airplane acceptance rate. A 6–12% fuel saving appears likely.

Remarks: It is unlikely that this total program on fuel economy through airplane aerodynamics and operations will be undertaken at once. Cooperation among the NATO countries on the non-proprietary aspects of this program would speed the benefits to be gained.

7. FUEL ECONOMY THROUGH THE USE OF FLIGHT SIMULATORS AND PILOTLESS AIRCRAFT

7.1 Flight Simulators

Military and civilian airplane operators are unanimous in their desire to increase the use of flight simulators for pilot training. However, they both agree that there is very little fuel saving to be expected from additional simulator use since there is an irreducible amount of airplane flying required to maintain pilot proficiency.

7.2 Pilotless Aircraft (drones)

Fuel economy through greater use of pilotless aircraft is not likely. Pilotless aircraft are used mostly for special reconnaissance and cannot perform the range of missions required of piloted aircraft. No reduction in the inventory or use of piloted aircraft results from the introduction of drones.

8. FUEL STORAGE

Increased fuel storage is one solution to the threat of recurring shortages. NATO countries are required to have a ninety day supply of petroleum in storage. Those in Western Europe are linked by pipeline so that resources may be shared. If it should prove desirable to store aviation fuel for long periods, then an accepted uniform storage practice needs to be developed for the NATO countries to establish confidence in the shared fuels that are released from storage.

With regard to the storage of aviation fuel, most military establishments insist on a maximum storage time of a few weeks to avoid troublesome concentrations of gum formed by slow oxidation. In one country aviation fuel is stored for six months without difficulty. An exchange of information on fuel storage equipment and practice would be useful if a review of fuel storage requirements by the NATO countries indicates that long term storage capability is desirable.

9. FUEL ECONOMY AND AVAILABILITY SUMMARY

(1) Fuel economy can be expected to improve through the normal increase in cycle efficiency that comes with each new engine generation.

(2) Pressure ratio in the next generation of engines is expected to rise above 30. Some manufacturers hold that this represents an upper limit, since the materials of the higher compressor stages become too weak at the elevated temperatures beyond this pressure ratio. Others ultimately hope to achieve a pressure ratio approaching 50.

(3) Turbine inlet temperatures will rise as well because of improved turbine cooling, and higher temperature capability of turbine materials and coatings. A fifteen year goal (1990) for one manufacturer is 2800°F turbine inlet temperature for commercial engines, and 3000°F temperature for military engines.

(4) Recuperators are being restudied for the contribution they can make to the cycle efficiency in a practical engine. So far the problem of using recuperators to advantage appears formidable.

(5) Propulsive efficiency will improve with higher bypass ratio. Opinion differs on the upper limit of bypass ratio when increased weight and nacelle drag cancel the improvement in propulsive efficiency.

(6) There is general agreement that the specific fuel consumption reduction from all engine improvements in the next 15 years will be 10–15%.

(7) The newer combustors operate with leaner fuel/air ratios in their primary zones to reduce engine smoke emissions. This leaner operation has raised the combustor tolerance for aromatics. Departure from fuel spray injection to air atomizing and prevaporizing or partial prevaporizing fuel injection has raised this tolerance still more. Now there is sentiment for a study of the tolerance of present combustors for aromatics to see if the present limit of 20% can be raised to improve fuel availability.

(8) Higher tolerance to aromatics will also come from improved combustor cooling. Ceramic combustors, which would have the best tolerance to aromatics because of their high temperature capability, are being developed in most engine companies, but none are close to a practical design.

(9) Combustor development is moving toward multiple zone burning which employs a pilot flame zone for low power operation and a main combustion zone for high power operation. The combustor operates with pre-mixed fuel and air which reduces flame radiation and lowers NOx emissions.

(10) Catalytic combustors and methods for artificially augmenting the combustion process are being studied now. Because these combustors will allow total prevaporization and premixing of fuel and air, they hold the promise for higher tolerance for aromatics. However, the problem of avoiding preignition of the fuel/air mixture remains to be solved.

(11) Fuel economies through improved aerodynamics, drag reduction, instrumentation and controls, lightweight structures are being reviewed. The following features are considered:

(a) Supercritical wing for Mach 0.8 flight.
(b) Winglets for added lift and thrust.
(c) Laminar flow and flow separation control.
(d) Active controls to reduce trim drag and weight associated with the airplane tail.
(e) Lightweight airplane parts from composite, fiber reinforced materials.
(f) Better control over air leakage at blade tips and engine seals.
(g) Compressor blade designs with improved resistance to performance degradation through erosion.
(h) Improved propulsion efficiency by combining bypass and core engine flow in same exhaust nozzle.
(i) Avionics for airplane guidance for fuel economy on terminal approach and departure.

(12) Further use of flight simulators and pilotless aircraft are not expected to provide meaningful fuel savings.

(13) Improved fuel storage practices might help to relieve periodic fuel shortages.

10. RECOMMENDATIONS

Introduction

The recommendations presented here for accommodating to the changing availability and price of aviation fuel are based on the following considerations:

(1) Even though the world's production of petroleum will grow over the next ten years, the gap between supply and demand will increase continuously with time, except for short periods of industrial recession.

(2) Aviation, both military and civil, must compete for petroleum fuels against other users who are in position to pay more. There is no assurance that aviation will always have a protected position on availability/price.

(3) Changing patterns of liquid fuel demand will provide aviation with opportunities for obtaining favorable prices if its fuel specifications can be flexible.

(4) Tolerance for flexible fuel specifications might require changes in airplane fuel systems and engines.

(5) Some fuel specifications might be too restrictive now because systems and engines have changed since they were established. Others might require review to assure their adequacy for the higher heat stress imposed by future engines.

(6) Fuels for the future must be matched to the next generation of engines. Some aspects of our fuel specifications require review now to anticipate changing requirements imposed by the engine. Likewise, engines for the future must recognize the limitations imposed by the available fuel.

(7) Local shortages of specification aviation fuel will become more frequent with time unless storage facilities are increased and the ability to store fuels successfully for long periods of time is demonstrated.

(8) Because local shortages of specification aviation fuel can be expected to occur with increasing frequency, an emergency fuel specification should be established which also defines the rules under which aircraft can fly with fuels not specialized for aviation use.

(9) While gains in fuel economy from engine development alone may be discouraging, the economy achieved by adding the contributions of improved airplane aerodynamics and flight management make the total effort worthwhile.

(10) Syncrudes will not be an important general source of fuel for the next twenty years, but will appear in local markets in meaningful amounts in about 10 years.

(11) Liquid hydrogen as an aircraft fuel cannot be ignored. There is sufficient interest in this fuel in several important quarters to justify R & D now.

(12) The effect of a change in fuel specifications or engine design can perturb the whole aviation system which is considered to include oil companies, airplane and engine manufacturers, military and civil aircraft operators, and research and development institutions that serve aviation.

Proposed Program

Much work is in progress or under consideration on aviation fuel economies and improved fuel availability that will proceed without AGARD encouragement and therefore need not be part of these recommendations. This work was reviewed briefly in earlier sections of this report. The following recommendations for AGARD's attention deal with those issues which are not treated adequately now and which could benefit from AGARD support. In several instances these recommendations are anticipated in earlier discussions, but are given explicit statement here. The relevant subjects are:

10.1 Improved Availability/Price,
10.2 Reduced Fuel Consumption,
10.3 Fuel Storage,
10.4 Non-Conventional Fuels,
10.5 Protecting Aviation's Share of Hydrocarbon Fuels.

10.1 Improved Availability/Price

Since the fuel available for military aviation is usually limited by the fuel budget, the fuel price determines whether or not the supply is adequate. Unnecessarily restrictive fuel specifications may limit the sources of candidate crudes for aviation fuel and raise refining costs. Also, emergency aircraft operation on non-specification fuel might become more common with increasing frequency of local shortages of specification fuel. Three areas that treat with these matters are recommended for PEP attention:

A. Fuel Specification Relaxation and Modernization,
B. Emergency Fuel Specifications,
C. Qualifying Fuels Derived from Syncrude for Aviation Use.

A. *Fuel Specification Relaxation and Modernization*

Since the cost of the fuel consumed throughout the life of an engine has become many times the engine cost, it is appropriate to reexamine the sensitive features of the engine that dictated fuel specifications to see which of these specifications might be relaxed to improve availability/price. Some of these specifications relate to the early aviation turbine engines and might not be appropriate now. Others might be relaxed by acceptable modifications to present and future engines. The following programs are suggested:

(1) *Aviation fuels of higher aromatic content*

It has been recommended in the course of this survey that the Propulsion and Energetics Panel of AGARD co-ordinate a study of modern engine tolerance for aromatics. The study would be conducted by the engine manufacturers on a series of reference fuels of increasing aromatic content. Details of the program would be established by consultations with all participants under PEP sponsorship. Since a change in aromatic content of a specification fuel can be widely accepted only if it serves all engines, the study must include all engine types in current use with present combustors or improved combustors which can be easily retrofitted to present engines at reasonable cost.

(2) *Prevaporizing combustor development*

Because the prevaporizing combustor handles highly aromatic fuels best, its development should be encouraged. A serious limitation to this combustor is its tendency to preignition in engines in which the air temperature leaving the compressor is above the spontaneous ignition temperature of the fuel.

Experimental exploration of methods for extending the upper limit of engine pressure ratio for prevaporizing combustors of refined aerodynamic design would be a useful contribution to the effort on improving fuel availability. This advantage will increase in importance when the highly aromatic coal-derived fuels become an important source of liquid fuel. Flame stability and high altitude ignition studies should accompany this effort.

(3) *Novel combustors*

New techniques for achieving flame stability and satisfactory blowout performance might provide combustors with greater tolerance for a broad range of fuels. The fuel availability/price situation justifies a bold approach to new designs which may involve greater complexity, size and weight. Present powerful research tools for combustor studies should be invaluable for this work.

Proposed program: Accelerate the development of novel combustors and associated ignition systems in a cooperative program of combustion fundamentals among the NATO country laboratories. A sample set of novel combustors includes:

(a) Catalytic combustors. Some of the principal problems are:

(i) Catalyst life; effect of fuel constituents and additives.
(ii) Low temperature combustor inefficiency.
(iii) Fuel mixture preignition avoidance.
(iv) Size and weight.

(b) Augmented combustion

(i) Hydrogen augmentation. Inject a small amount of hydrogen as a separate stream to mix with the combustor fuel. Hydrogen has a beneficial effect on the combustion process and may allow stable operation with lean fuel/air mixtures over wider limits of engine operation than is possible now. Also, because hydrogen ignites readily in lean concentrations, the ignitor may lie close to the hydrogen injector to provide the starting flame. Methods for converting hydrocarbons to hydrogen on portable devices have been devised for fuel cells. These might be adapted for converting a small portion of the engine fuel flow to hydrogen.

(ii) Radiation stimulated combustion and ignition. Lasers and other powerful radiation sources of related wave lengths for promoting combustion and/or ignition might prove advantageous. A laboratory evaluation of such devices might provide a fresh approach to combustor design.

(4) *Fuel system seals for highly aromatic fuels*

Aircraft fuel systems can tolerate aromatics up to 30% without seal leak problems. If it proves desirable to increase aromatics above 30% then a tank seal development program might be required to support this work.

(5) *Higher freezing point fuels*

It is estimated that a rise in freezing point of fuels from −58°C to −40°C would increase the available Jet A fuel supply by about 20%. During the fuel shortage of the winter of 1973/74, a ten degree rise in freezing point was accepted with some anxiety as an emergency measure for domestic flights. While airplane operators, civil or military, are generally willing to accept a rise in the freezing point of the fuel, they did insist on flight demonstration that such a rise is safe for their operation. Little would be gained by a rise in fuel freezing point if the airplanes are forced to fly at lower, warmer altitudes where they are penalized by higher fuel consumption. Also, a rise in freezing point means the introduction of higher boiling fractions of petroleum. For some sources of crude these fractions are high in aromatics, and may carry a higher vanadium content than present specifications allow.

Proposed program: Information already exists which shows that airplane operation is unsatisfactory in colder parts of the world with high freezing point fuels in integral tanks. Also, calculations show that the advantage conferred by preheating the fuel loaded into an airplane is largely lost toward the end of a long flight. For aircraft which are not fuel-volume limited, a study of the optimum use of a combination of tank insulation, fuel preheat, and a modest amount of tank heating might show how this approach to the use of higher freezing point fuels can be made attractive.

Mapping the areas of the world and the flight routes which would allow fuels of higher freezing point in unmodified aircraft might be useful in developing a fuel distribution strategy for optimizing the availability/price. The added complexity of having several qualified fuels in the world-wide aviation system would be one of the principal penalties for using this approach.

(6) *Fuel lubricity*

Present laboratory tests for lubricity used by oil companies to meet specification requirements sometimes do not correlate well with use in engines. Since a greater degree of hydrocarbon conversion and processing can be expected in the future which might reduce their natural lubricity, it would be well to establish a meaningful laboratory lubricity test to guide the oil industry.

Proposed program: The development of a revised convenient bench lubricity test should be a cooperative program involving the oil companies and engine manufacturers. PEP may wish to introduce existing aviation industry organizations, such as the Coordinating Research Council, to the need for this work. It is suggested that this study include a review of the fuel control and pump materials that operate well with fuels of low lubricity.

(7) *Engine fuel controls*

The present hydromechanical fuel control is sensitive to the physical properties of the fuel (viscosity, lubricity, etc.). Some of these properties are difficult to control since they may change with fuel moisture content, fuel additives, and long term storage. The fuel supply problem would be eased if concern for this fuel issue could be ended.

Proposed program: Accelerate the development of electronic fuel controls whose performance is insensitive to the physical properties of fuel. Since relaxation of these fuel property requirements can be allowed only when practically all of the engines are so equipped, the accelerated program should begin soon. Electronic controls would allow easy adjustment to a variety of fuels by conveniently placed dials. Hydromechanical controls require cumbersome manipulation for such adjustment.

B. *Emergency Fuel Specifications*

Local shortages of specification aviation fuel might force aircraft to operate on other available fuels. These fuels might be automotive gasoline (unleaded) and diesel (heating) oil which are blended to make emergency fuel.

Proposed program: Criteria for formulating emergency fuels should be prepared ahead of the need. Such a study would include at least the following factors:

(1) Blending proportions.
(2) Fuel additives.
(3) Filtration and water separation requirements.
(4) Engine and airplane systems adjustments and calibration for using emergency fuel.
(5) Restrictions on engine power.
(6) Maximum rate of climb as a function of fuel temperature; to include consideration of the feasibility of prechilling volatile fuels to avoid boil-off losses during climb.
(7) Engine and airplane inspection, maintenance, and overhaul instructions when operating on emergency fuel.
(8) Fuel storage requirements.

Development of such emergency fuel specifications is a major task. It should be a cooperative effort involving representatives of the fuel, engine and airframe industry, and the military and civil airplane operators.

C. *Syncrude*

It appears that the program for evaluating syncrude fuels is well established and adequately funded under USAF, Navy, Army and NASA sponsorship. However, the syncrude fuel to be provided for these studies is obtained by a simple refining process which may differ enough from that which will be used commercially to require confirmation of the results of the present program. The difference in these processes may include a far greater degree of hydrogenation over specialized catalyst to optimize the yield for best economic return for the commercial process. While hydrogenation generally improves the quality of the fuel for aviation use, the presence of minor constituents in the fuel may prove troublesome. Some fuel experts think that there is no problem with these minor constituents. Others hold that the matter needs to be checked by the operation of complete fuel and engine systems. The present study of syncrude aviation fuels includes this check as one of its goals.

(1) *Oil shale*

There does not appear to be an active role for PEP in the promotion of aviation fuel from oil shale at this time. When the 100,000 barrel/day production of shale oil scheduled for 1980 materializes, PEP may wish to arrange a coordinated program to include European engine manufacturers in the full scale engine testing of the fuel. Meanwhile, PEP may wish to establish contact with the NASA panel on aviation fuels to be kept informed of progress.

(2) *Coal hydrogenation*

Fuels synthesized from coal are expected to lie mostly in the gasoline range. Conversion to kerosene would increase the fuel cost. If concern for ecological damage thwarts the exploitation of oil shale, then coal will be the basic source of syncrude. If this proves to be the case, then PEP may wish to promote research on commercial coal hydrogenation processes and related catalyst development that results in adequate yields of kerosene without further processing.

(3) *Tar sands*

Fuels from tar sands will constitute an important proportion of the total fuel available in Canada in ten to fifteen years. Exploitation of this resource is a reality and present plans call for accelerating production. Since tar sand fuels are not emphasized in the US programs, PEP may wish to promote an aviation fuel qualification program for these fuels. Such a program should recognize that future processing of tar sands crude may involve heavy hydrogenation of the raw bitumen to increase the total yield of usable fuels and reduce the char residue. Aviation fuels resulting from such processing may be different from that which is available now. Present processing uses a low degree of hydrogenation of the products obtained from the bitumen coker.

D. *Fuel Sources Survey*

For some NATO countries the sources of crude for all or part of the country will change in the next ten years. For example, the eastern provinces of Canada will be served by pipeline from the oil producing areas of Western Canada and they will rely less on Venezuelan and Middle East oil. Oil from Western Canada will have an increasing amount of tar sand syncrude. Western US will be served by Alaskan oil in a few years. Syncrudes from oil shale may appear in local US markets in important amounts in about ten years. The North Sea and Africa will be new sources of fuel for Western Europe. Present patterns of fuel stock blending will change as old sources are depleted and new sources take over.

It is important to know at the earliest date how these shifts in crude sources will influence the price of specification aviation fuel in the affected areas. Some of the new sources are high in aromatics, have high pour point, and are sulfur-rich. With the growing scarcity of low aromatic, low sulfur blending stock, costly hydrogenation may be required to produce specification aviation fuel. Hydrogen demand may exceed local supply so that a local scarcity of aviation fuel will exist unless adequate hydrogen production capability is created. This will be expensive hydrogen whose cost will increase with delay as facility construction costs rise with time.

This information should be obtained as soon as posible so that the petroleum industry can forecast facility needs, fuel costs and availability. The engine, air frame and operators can adjust to changing fuel specifications if these are required to assure adequate fuel at reasonable cost everywhere.

Proposed Program: A survey should be started soon to develop the following information that will influence the availability and cost of aviation fuel in the various zones of NATO:

(1) The properties of the crude oils that will serve each zone.

(2) The probable increase in cost of producing aviation fuel to present specification.

(3) Adequacy of facilities for refining these new crudes to produce aviation fuel.

(4) Reduction in fuel cost and improvement in availability if fuel specifications are changed.

(5) Changes to engine, airplane, airplane maintenance equipment and service requirements to accommodate specification changes; to include retrofit costs to existing aircraft to make them compatible with specification changes.

(6) Changes in airplane, service equipment and fuel handling techniques to maintain operational safety.

10.2 Reduced Fuel Consumption

Since aviation uses only a small percentage of the fuel produced in NATO countries, economies in aviation fuel consumption can have little effect on the total fuel supply. However, because military and civil aviation operate with limited fuel budgets, fuel economy can make the difference between adequate and dangerously inadequate levels of operation. Substantial fuel economies can be realized by a pattern of improvements in engines, aerodyanmics, and airplane operations.

A. *Engine Cycle*

Higher cycle pressure ratio will probably be accomplished by increasing the work per stage of the compressor and turbine to minimize engine weight. More work per compressor stage is accomplished by raising the blade loading or tip speed, or both. Higher blade loading requires refined blade shape, while higher tip speeds will result in slimmer blade profiles that are more vulnerable to foreign object damage and erosion. The total performance of the engine becomes more sensitive to departures from optimum blade configuration, and specific fuel consumption increases with engine use between overhauls. Also, engine seals, and fuels and lubricants suited to higher engine temperatures require development attention now.

Proposed program:

(1) *Compressor stage deterioration*

Require each engine manufacturer to determine from experiment, computer program, or both, which stages of the compressor are most likely to cause serious flow mismatch between compressor stages if their performance deteriorates by virtue of blade damage. This information would help define when compressor blade replacement rather than refurbishment should be practiced.

A corrolary to this program would be a set of standards for acceptable rates of blade deterioration and a description of the blade geometries that conform to these standards. The relevant questions would be:

(1) Which features of the blade that are critical to performance are also vulnerable to foreign object damage by impact or erosion?

(b) What blade shapes would provide a reasonable engine operating time between overhaul with acceptable performance decline?

Such determination might be part of each engine development program. PEP could support such an effort as part of its present study of engine performance deterioration.

(2) *Engine seals*

Some of the gains in specific fuel consumption to be expected from higher engine pressure ratio may be lost through increased leakage by engine seals. While some engine manufacturers deny that this problem will become critical as engine pressure ratios rise above thirty, the matter deserves some attention from an independent survey. Face contact seals, which have the potential for lower leakage, may be required to replace the labyrinth seals presently in use. Seals for recuperators pose a difficult design problem and will probably be vital to the success of the application of recuperators. This inquiry, too, can be part of the PEP effort on engine performance deterioration.

(3) *High temperature cycles and fuel stability*

It may be timely to review the whole matter of the future availability of fuels of high thermal stability to see if an upper limit on engine cycle temperature is imposed by fuels of acceptable cost and availability. Such a review might include a study of the feasibility of alternative methods for providing some oil cooling to relieve the thermal stress on the fuel.

(4) *Lubricants for high temperature engines*

Lubricants that can serve the high temperature bearings of advanced engines deserve some attention. Most of the present synthetic lubricants have spontaneous ignition temperatures below bearing operating temperatures of future engines. A serious air leak through the seal around the bearing could ignite the lubricant. PEP may wish to see whether or not the present effort of high temperature lubricants is adequate.

B. *Airplane Aerodynamics and Structures*

Fuel economy is obviously possible through improved airplane aerodynamics and lightweight structures. Commercial aviation might be willing to optimize new airplane design for best fuel economy in view of the rising cost of fuel. Such optimization might involve greater airplane complexity to reduce drag, and the use of unconventional structures, particularly of non-metallic and metallic composite materials, to reduce weight. Military aviation is not likely to accept added complexity for purposes of fuel economy alone, but might consider such complexity if it improves airplane performance (range, payload, speed).

Proposed program: Research and development on improved airplane aerodynamics and structures are in progress in several NATO countries and one doubts that AGARD attention is required for the main course of the work. However, in view of the growing use of non-metallic composite structures, AGARD may wish to assure itself of the quality control of new or repaired structures, detection techniques for assessing structural deterioration with use, effects of lightning strikes on structural integrity, and the probability of fuel tank ignition by lightning. Also, AGARD may wish to assess the likelihood that lightning strikes might induce voltages and currents in circuits contained within non-metallic structures that can endanger delicate electronic components or introduce spurious signals in fly-by-wire airplane control systems.

C. *Airplane Flight Management*

Flight management schemes for reducing fuel consumption, particularly during approach and landing, are being studied by NASA and others. AGARD need not have an active role in this area except to promote the adoption of those procedures which are shown to be worthwhile.

Fuel savings are possible in the selection of the optimum plan for long range flight and by using rational methods for computing fuel reserves. Some airlines provide their own flight planning, while others contract for it. Computation of fuel reserves is often at the pilot's discretion and tend to be overestimated.

Proposed program: It may prove instructive to make a comparative study of the route planning methods used by airlines to establish which are superior. A related study would consider the fuel economy associated with changes in air traffic control practice which would allow aircraft to climb as they consume fuel.

Rational methods for computing fuel reserves would benefit all airplane operators since the extra fuel consumed in carrying unnecessary reserves reduces the general fuel supply and raises the cost. A review of airline practices and the development of rational procedures for computing fuel reserves based on such a review may provide meaningful economies.

10.3 Fuel Storage

Long term storage of aviation fuels is one approach to avoiding periodic shortages. Formation of gums by the slow oxidation of stored fuels and the loss of valuable additives limits storage time. The marked difference in successful storage time achieved by the NATO countries shows that there is some technology to share and to improve.

Proposed program: A fuel storage research and development program would contain the following parts as a minimum:

(1) Determination of useful fuel storage times to cover emergency periods.

(2) Evaluation of the role of the normal fuel additives (anti-corrosion, static, icing) in extending or limiting fuel storage time.

(3) Development of compatible additives for increasing storage time.

(4) Appraisal of the benefits to be gained by limiting air contact with fuel intended for long term storage.

(5) Fuel treatment during and following long term storage that overcomes undesirable changes in the fuel while in storage.

PEP may wish to promote an exchange of fuel storage practice and experience among the member countries. On the basis of such an exchange the need for further R & D can be determined.

10.4 Liquid Hydrogen

Of the several non-conventional fuels proposed for aviation, liquid hydrogen is the only one that remains with strong support. However, many think that liquid hydrogen will never be used for aviation because of the fuel system and safety problems it presents. They feel that aviation will always be served with hydrocarbons derived from syncrudes after petroleum is depleted. Yet the airplane performance advantages provided by liquid hydrogen cannot be denied, and support for its ultimate application to aviation is widespread.

Since most supporters of liquid hydrogen for aviation think that it will be ready for aviation after thirty years, the research and development on this subject generally has low priority. However, the combined effort in the NATO countries is significant. Much of the current work relates to combustor performance, airplane configuration studies, some systems design, and an assessment of logistic support problems for the hydrogen airplane.

A coordinated NATO program would avoid duplication of effort and assure more rapid progress. The problems that require solution for hydrogen to become a practical aviation fuel are many and difficult. They will require the best research and development effort applied over many years.

Proposed Program: It would be well to have an early decision on the potential of hydrogen for civil and military aviation to avoid long, fruitless programs on the subject. The ingredients of a program that would define the major problems and indicate the R & D required for their solution would include, at least, the following:

(1) Aircraft configurations for civil and military transports and long range strategic and logistic support aircraft. Hypersonic vehicles are considered a separate category of aircraft whose requirements for a liquid hydrogen fuel

would be too small to establish it as a general aviation fuel. Since airplane configuration has a large effect on many of the systems problems that would require solution, it would be well to subject candidate configurations to a detailed critical review early in the program. Such a review, conducted by a team qualified to make a total systems evaluation, would include:

(a) Airplane flying qualities with full and near empty fuel tanks.
(b) Crash and ditching safety.
(c) Flight fire control; vulnerability to lightning strike; flight icing.
(d) Passenger, freight, and stores handling; service, inspection and maintenance.
(e) Consequences of fuel leaks to vital airplane structure, controls, systems and the occupants.

(2) Fuel tank pressure control, without benefit of helium, under all phases of airplane operation, including emergency descent with near empty tanks.

(3) Engine combustor design, fuel controls, and liquid hydrogen positive displacement fuel pumps for long service.

(4) Fuel storage and aircraft fueling facilities; to include safe handling of hydrogen gas displaced from tanks being fueled.

(5) Fuel distribution methods, associated logistic support; and liquid hydrogen quality assurance at the airplane loading point.

(6) *Cost*

Flight programs with present aircraft modified to operate with liquid hydrogen, which are conducted to obtain experience with hydrogen operation, should simulate the features of a promising hydrogen airplane configuration. Unless this is done, the information obtained may have little relevance. Also, operation of the liquid hydrogen airplane in frigid parts of the world should be included to determine whether the water in the engine exhaust forms dense ice crystal fogs that obscure runways.

10.5 Protecting Aviation's Share of Hydrocarbon Fuels

There is no assurance that aviation's needs for hydrocarbon fuel will receive priority consideration as supplies dwindle. The political leverage of the non-aviation community is too great to be ignored when fuel allocation is at issue. A preview of the poor position aviation enjoys when fuel is allocated occurred during the winter of 1973/74 when a shortage existed. Airline schedules were curtailed even with fuel support from military stores.

If premium fuels (hydrocarbons) are to be reserved for premium use (aviation) then the needs of the non-aviation community will have to be met by other energy sources. The non-aviation community, which is not so highly organized for R & D as is the aviation industry, will be slow to solve some of the problems required to make the transition. In support of its own interest, the aviation community should lend reasonable support to the R & D required to serve potential competitors for hydrocarbon fuel with alternate energy sources. To do this, it must take an active interest in the total energy problem and arrange to be represented knowledgeably where policy on energy allocation and R & D is handled. Since the problem is international, AGARD could provide coordination, information and expert consultation.

Proposed program: A sample list of relevant subjects that were suggested in the meetings held during this study includes:

(1) Selection of alternate energy sources for the competitors for fuel stocks which can be converted to aviation fuels at reasonable cost.

(2) Preparation of plans for converting fuels made available by changing demand to aviation fuel at attractive costs. The following issues should be covered at least:

(a) Cost of modifying the available fuel through refining to an aircraft fuel that meets present specifications.

(b) Cost of modifying the airplane and supporting facilities to accept the available fuel with a minimum of modification.

(c) Aircraft modifications and fuel servicing and treatment techniques that maintain a high level of safety regardless of fuel volatility; to include such techniques as servicing the airplane with volatile fuel which is cooled to reduce its vapor pressure so as to avoid fuel loss from tank vents due to severe boiling during initial climb.

(d) Adequacy of present fuel additives.

(e) Compatibility of syncrude-derived fuels with petroleum fuels in blends. Can the low-aromatic portions of fuels derived from coal hydrogenation be added to shale oil and petroleum fuels to augment the supply of aviation fuel? What added treatment would be required to overcome incompatibilties?

(3) Promotion of the use of methanol for blending with gasoline for automobiles.

(4) Encourage the application of liquid methane and hydrogen as automotive fuels.

(5) Promote the development of methods for producing low-cost hydrogen for use directly as a fuel, and for hydrogenation and hydrocracking processes for increasing the yield of useful hydrocarbons from petroleum, coal, shale, and tar sands.

(6) Encourage the development of means for improved fossil fuel recovery.

(a) Much petroleum is too viscous to recover from oil wells by present methods. Enormous oil reserves would become available from successful development of new methods of encouraging the flow of viscous petroleum to wells. In-situ heating and pressurization of oil bearing strata must be highly effective to provide a return of oil high enough to justify the investment in energy and other resources.

(b) In-situ recovery of shale oil may prove to be the only environmentally acceptable method for exploiting this resource.

(c) There are extensive coal deposits in NATO countries which lie too deep for economical mining by present techniques. New mining methods or in-situ methods for converting the coal to liquid or gas that can be brought to the surface easily are desired.

10.6 Miscellaneous Issues

In the course of the interviews with the aviation community conducted under this contract with PEP, several issues were discussed that merit consideration in a comprehensive review of the aviation fuel problem. Some of the most relevant are offered for critical review.

(1) Consider the desirability of standby hydrocracking facilities for Western Europe optimized for converting heating (diesel) oil to aviation kerosene as a war emergency measure. Since the NATO countries are interconnected by pipeline, only a few of these facilities would be required.

(2) Review turbine blade life evaluation methods. Determine reasons for discrepancy between predicted and service life. Are competitive pressures among engine manufacturers leading to unrealistic engine ratings?

(3) Review the present effort on updating fuel specification:

(a) Judge the effect of proposed specification changes on fuel availability/price.

(b) Determine if the problem requiring the specification change can be handled better by modification of the engine/airplane fuel system.

(4) Promote the development of commercially attractive processes for upgrading tars and chars to useful fuels. A superabundance of these materials will be produced in some countries as the consumption of fossil fuel grows.

11. CONCLUDING REMARKS

The essential point revealed by discussions with the aviation community during this study was the need to remain flexible on the matter of future aviation fuels. While some expressed preference for a particular fuel, most were willing to consider alternatives.

The broad range of subjects included in the *Recommendations* section of this report reflects the fact that there is no clear direction for aviation to take now in providing aviation fuels and so it must be prepared to exploit whatever opportunities that develop.

In the face of diverse opinion from experts on the ultimate recoverable petroleum reserves, fuel specifications, the economics of oil recovery from shale, liquid hydrogen as an aviation fuel, the reality of the hydrogen economy and its promise of cheap hydrogen in the next thirty years, and the projected growth of military and civil aviation, the public and political sector are poorly directed to make their contribution to the energy problem generally, and the aviation fuel problem in particular. It would help if the aviation community could provide leadership in clarifying the situation so that constructive public action can be realized as soon as possible.

Implied in the estimate raised by several in this survey that petroleum-derived fuels can serve aviation for the next thirty to fifty years is the assumption that aviation's fuel needs will be protected. This will not happen automatically. The aviation community must be prepared to defend its claim on petroleum-derived fuels while others are put to the expense of using alternative energy sources. It must take an active part in the formulation of future energy allocation plans and be prepared with a reasonable program that shows how all others can have their energy needs satisfied.

To implement these suggestions two types of standing committees for safeguarding aviation's fuel interests are required:

(1) Committees which represent aviation's fuel needs to the relevant technical and political sectors of the NATO countries at a policy making level.

(2) Technical committees for constantly evaluating the changing fuel choices open to aviation and providing guidance on the research and development required to exploit opportunities that appear.

APPENDIX A

LIST OF MEETINGS

I. National Gas Turbine Establishment – Pyestock, Farnborough, England
October 29, 1974

Mr John James Macfarlane – Head, Combustion and Instrumentation Technology Department

Subjects discussed:
(1) Availability of aviation fuel in the UK.
(2) Combustion research and combustor design for handling fuels of broad specification.
(3) Prospects for reducing specific fuel consumption.

II. Ministry of Defence – St Giles Court, London
October 30, 1974

Mr Ray Holl – Assistant Director, Engines
Mr John Ogle – Section Leader

Subjects discussed:
(1) Desirable fuels for aviation.
(2) Fuel availability and cost.
(3) Engine development and fuel economy.

III. Shell Research Ltd, – Thornton (Chester), England
October 31, 1974

Mr Alan Lewis, Shell Research Ltd
Mr John G.Kirtley, Shell International Petroleum Co., London
Mr Ben Zietse, Shell International Petroleum, The Hague, Netherlands

Subjects discussed:
(1) Fuel availability and price.
(2) Fuel storage.
(3) Synthetic aviation fuels.

IV. Rolls-Royce – Derby, England
November 1, 1974

Mr A.E.Peat – Divisional Fuel Technologist, Derby Engine Division
Mr Harry Bennet – Head, Special Projects Group, Advanced Engine Studies Dept. (DED)
Mr Frank Smith – Senior Engineer, Advanced Engine Studies Dept., (DED)
Dr Brian Edwards – Deputy Head, Combustion Research, Development Group, (DED)

Subjects discussed:
(1) Engine developments which promise reduced fuel consumption.
(2) Aviation fuels.

V. Braathens Safe Airline, Stavenger, Norway
November 2/3, 1974

Mr Sigurd Wessel Tonnessen (Phone interview), Engineering Department
Mr Berger Larson – Engineering Department

Subjects discussed:
(1) Prospects for future aviation fuels from petroleum.
(2) Fuels specifications.
(3) Non-hydrocarbon fuels.

VI. SAS – Oslo (Koksa), Norway
November 4, 1974

Mr R.Finholdt – Manager, Flight Systems

Subjects discussed:
(1) Fuel specifications.
(2) Fuel economy in SAS operations.

VII. Norwegian Air Force – Air Material Command, Kjeller, Norway
November 5, 1974

Capt. Ivar Gjetnes, LFK/TF

Subjects discussed:
(1) Prospects for petroleum derived aviation fuels.
(2) Fuel specifications.
(3) Fuel economy in Air Force operations.
(4) Liquid H_2 as an aircraft fuel.

VIII. Danmark Tekniske Højskole Laboratoriet for Energiteknik, Lyngby, Denmark
November 6, 1974

Professor J.Chr.Knutzen
Professor E.Bjorn Qvale

Subjects discussed:
(1) Sources of petroleum derived fuels for Denmark.
(2) Future fuel prospects.

IX. Air Force Materiel Command, Materiel Division, FMK-Ty, Denmark
November 7, 1974

K.Skeel Christensen, Civil Engineer, Air Materiel Command
Prof. J.Chr.Knutzen, Technical University, Denmark

Subjects discussed:
(1) Fuel supply and fuel handling.
(2) Aviation fuel specifications.
(3) Fuel additives.

X. British Petroleum, Copenhagen, Denmark
November 8, 1974 (morning)

Helge Ljungdahl – British Petroleum (Civil Engineer)
Thorkild W.Mai – Dansk Shell (Chemical Engineer)
Torben Larsen – Air Force Superintendent, Shell
Prof. Knutzen – Danmark Tekniske Højskole
Dr Knutzen – British Petroleum

Subjects discussed:
(1) Sources of aviation fuel for Denmark.
(2) Relaxing fuel specifications.
(3) Prospects for reducing demand for petroleum fuels in Denmark.
(4) Development of alternate sources of hydrocarbons.

Ministry of Commerce, Energy Office, Copenhagen, Denmark
November 8, 1974 (afternoon)

Mr E.Moe – Ministry of Commerce
Prof. J.Chr.Knutzen – Danmark Tekniske Højskole

Subjects discussed:
(1) Fuel storage.
(2) Government control of energy production, utilization and allocation.
(3) Danish involvement in international programs on energy.

XI. National Aerospace Laboratory, NLR, Amsterdam, The Netherlands
November 11, 1974

Mr van Grouw – Fokker-VFW
Mr Huls – NIVR (Ministry of Transport)
Col. Wamsteker – Royal Netherlands Air Force
Col. Kreuning – Royal Netherlands Air Force
Lt Col. Wegner – Royal Netherlands Air Force
Mr Rede – KLM Airlines
Mr Vleghert – NLR (National Aerospace Laboratory)
Mr Jaarsma – NLR (National Aerospace Laboratory)

Subjects discussed:
- (1) Fuel economy through engine maintenance and modification, and aerodynamics.
- (2) Fuel economy through use of drones and flight simulators.
- (3) Fuel specifications.
- (4) Alternate aviation fuels.

XII. The Hague
November 12, 1974 a.m.

Defence Research Organization
Commodore (Ret) R.H.Kerkhoven (Royal Netherlands Navy) – Liaison of Defense Research Organization with Armed Services
Dr B.H.H.Brader, Secretary
Ir. C.W.deJong – Expert of the Technological Laboratory.

Ministry of Defence
Brig. Gen. H.Doup – Coordinator Research Projects
Jhr. i.r. R.J.D.Tulleken – Defence Fuel Executive Committee
Col. F.L.Jochems – Int. Service Oil Distribution Organization

Royal Netherlands Army
Major ir. A.Kamphuis
Ing. T.D.Bouma

Royal Netherlands Air Force
Col. P.J.Wamsteker
Lt Col. H.Krouning
Maj. A.L.Staalberg

AGARD
F.Jaarsma, Chairman Propulsion & Energetics Panel
A.H.Geudeker, National Coordinator

Subjects discussed:
- (1) Trends in military fuel requirements for The Netherlands.
- (2) Fuel storage.
- (3) Fuel supplies.

XIII. Delft University of Technology, The Netherlands
November 12, 1974 p.m.

Prof. ir W.H. van Eek, Delft University of Technology; Dept. of Mining Engineering
Ir. F.Jaarsma, National Aero-Space Laboratory (NRL)
Chairman Propulsion and Energetics Panel, AGARD
Ir. J.Knobbout, Central National Organization for Applied Scientific Research, (TNO) Apeldoora
Prof. ir H.Wittenberg, Delft University of Technology, Dept. of Aerospace Engineering, Member Propulsion and Energetics Panel, AGARD
Prof. ir C.W.J.van Koppen, University of Technology Eindhoven, Dept of Mechanical Engineering
Drs. J.B.Zabel, Central National Organization for Applied Scientific Research (TNO) The Hague
A.H.Geudeker, National AGARD Coordinator

Subjects discussed:
- (1) Netherlands present policy on energy.
- (2) Energy sources.
- (3) Fuel conservation

XIV. Free University of Belgium, Brussels, Belgium
November 14, 1974

Prof. A.Jaumotte, President, Free University of Brussels
Prof. E.J.A.Sibenaler, Professor, Free University of Brussels and Ecole Royal Militaire (ERMD)
Directeur du Laboratoire de Mécanique-Transport de l'ERM
Mr B.V.L.Leduc, Assistant at the Institute for Applied Mechanics, Free University of Brussels
Prof. Jacques Chauvin, Professor, University of Brussels, Liège, and von Kármán Institute – Head of von Kármán Institute Turbomachinery Lab., PEP Panel Member

Subjects discussed:
- (1) Engine development for improved fuel economy and longer life.
- (2) Turbine engine component aerodynamics.
- (3) Engine deterioration.

XV. Institut Français du Pétrole (IFP), Paris, France
November 19, 1974

Mr Sale – IFP
Mr Jean-Claude Guibet – Division of Application, Puteaux
Mr Jean-Pierre Frank – Division "Recherche Chimiques de Base", Puteaux
Col. Duffet – Director of Research and Testing, Ministry of Defense, DRME, Paris
Mr Marc Pianko – Chief Engineer, Motors Section, Ministry of Defense; STAc, Member PEP/AGARD

Subjects discussed:
(1) Prospects for continuing supply of aviation fuel from petroleum.
(2) Alternate fuels for aviation.

XVI. Compagnie Française de Raffinage (Total), Paris, France
November 20, 1974

Mr Jean Faché – Compagnie Francaise de Raffinage (Subsidiary of Compagnie Francaise de Pétrole)
Mr Bernard Metais – Compagnie Francaise de Pétrole, Quality Control, (Subsidiary of Air Total International)
Mr Jean Fatras – CFP, Refining Department, Product Quality
Mr Louis Tranié – CFR, Research Center, LeHavre, Gasoline Fuels Dept., Total Technique
Mr Marc Pianko – Chief Engineer, Motors Section, Ministry of Defense – Member PEP/AGARD

Subjects discussed:
(1) Aviation fuel availability in the future.
(2) Fuel specifications.
(3) Fuel storage.

XVII. SNECMA, Paris, France
November 21, 1974

Mr J.F.Chevalier – Research Director
Mr Jacques Carvel – Chief, Combustion Department
Mr A.Quillevere – Deputy Director, Research
Mr C.Menjoux – Preliminary Project Engineer

Subjects discussed:
(1) Combustor research.
(2) High temperature turbine materials research.
(3) Recuperators for fuel economy.

XVIII. ONERA, Paris, France
November 22, 1974 (morning)

Mr M.L.Barrère – Director Scientifique de l'Energetique (PEP Member)
Mr Poulignier – Director Scientifique Adjoint; Direction des Matériaux
Mr Duban – Adjoint Chief of Division Turbomachines, Direction de l'Energetique
Mr Duterque – Research Engineer, Direction de l'Energetique
Mr Verdier – Research Engineer, Direction de l'Energetique
Mr Lengelle – Research Engineer, Direction de l'Energetique
Mr Pianko – Head, Motors Section, Air Ministry – Member, PEP/AGARD

Subjects discussed:
(1) Compressor research.
(2) Turbine research.
(3) Combustor research.
(4) Special fuel economy program.

XIX. Summary Meeting of French Establishments
ONERA, Paris, France
November 22, 1974 (afternoon)

Mr Grossin – Society Bertin (private consulting company)
Mr Doyotte – Society Bertin
Mr Fatras – Compagnie Francaise de Pétrole, Director Raffinage Air Total International
Mr Metais, Compagnie Francaise de Pétrole
Mr Vasse, Compagnie Francaise de Raffinage, Centre de Recherche, Total
Mr Quillevere – SNECMA
Mr Duban – ONERA
Mr Duterque – ONERA

C.Rodriguez – (French Air Force Headquarters) EMAA/BPE
Col. Duffet – Air Ministry DRME/SPR/GF
Mr Verdie – Air Ministry STAc/M
Mr Pianko – Air Ministry STAc

Subjects discussed:
(1) NATO fuel specification.
(2) Research support required for broadening fuel specifications.
(3) Hydrogen as an aviation fuel.

XX. Deutsche Forschungs und Versuchsanstalt für Luft-und Raumfahrt E.F.–DFVLR, Cologne, Germany
November 25, 1974

Dr Winterfeld –DFVLR, Porz Wahn (Head of Institute for Airbreathing Engines)
Dr Kunchler – Research Scientist – T.H. (University), Aachen
Dr H.G.Klug – Project Engineer – MBB (Messerschmidt-Bolkow-Blohm), Hamburg
Dipl. Ing. R.John – VFW (Sect. Efr) Fokker, Bremen (Vereinigte Flugzeugwerke)
Dr Bandel – BMFT, Bonn (Project Official for Alternative Fuels, Ground Transportation – Federal Ministry of Research and Technology)
Dipl. Ing. Hassel – TUV – Rheinland (Technical Supervisory Board, Rheinland)
Dr Eder – Responsible Official for Fuels – BMVg, Bonn (Ministry of Defense Rü III/8)
Dr Dieberg – Head of Subdivision, Fuels/Lubricants – Ministry of Defense (BWB-Koblenz) Federal Agency for Armament Technology and Procurement

Subjects discussed:

A. Ministry of Defense
(1) Fuel availability research.
(2) Combustion research.
(3) Fuels properties.

B. Air Force
(1) Fuel preference.
(2) Fuel storage.

C. Ministry of Research and Technology
(1) Alternate fuels program for ground transportation.

D. Aircraft Manufacturers
Messerschmidt
(1) Fuel economy for present engines.
(2) Hydrogen as an aviation fuel.
VFW-Fokker-Bremen
(1) Fuel economy with new engines.
(2) Hydrogen as an aviation fuel.

E. DFVLR, Brunswick
(1) Hydrogen as an aviation fuel.

F. Technical University, Aachen
(1) Turbo jet/ram jet systems.

G. Institute for Air-Breathing Engines, DFVLR, Cologne
(1) Combustor modelling.
(2) Hydrogen combustion.

XXI. DFVLR, Munich, Germany
November 27, 1974

Dr Gemperlein – Head, Institute for Fuels and Lubricants, DFVLR, Munich
Dr E.Jantzen – Head, Lubricants Section, Institute for Fuels and Lubricants – DFVLR, Munich
Dr Kern – Head, Fuels Section, Institute for Fuels and Lubricants – DFVLR, Munich
Dipl-Ing. Spirkel – Research Scientist – DFVLR, Munich
Dipl-Ing. Zimmer – Project Engineer – Dornier, Friedrichshaven
Dipl-Ing. Kaufmann – Project Engineer – MBB/RCOL, Munich
Dr Ing. Ackermann – Deputy Head, Advanced Project Section (MTU – Motoren-Turbinen-Union) Munich
Dr Tech. Hagen – Head, Engine Performance Section, MTU, Munich

Subjects discussed:
(1) Petroleum use in West Germany
(2) Proposed R & D for best energy utilization.
(3) Hydrocarbon fuel storage technology.
(4) Lubricants for high temperature engines.

XXII. DFVLR, Stuttgart, Germany
November 28, 1974

Prof. Dr Knoernschild – Head (Retired) Institute for Energy Conversion, DFVLR
Prof. Dr Peschka – Head, Institute for Energy Conversion, DFVLR, Stuttgart
Dr rer.nat. Th.Just – Head, Institute for Reaction Kinetics, DFVLR, Stuttgart
Prof. Dr Buhler – Head, Institute for Aerospace Propulsion, Technical University, Stuttgart
Dipl. Ing. P.Kramer – Research Scientist, Institute for Aerospace Propulsion, Technical University, Stuttgart

Subjects discussed:
(1) Range of DFVLR, Stuttgart, interest in energy research.
(2) Drone engines.
(3) Liquid hydrogen aircraft systems.

XXIII. National Propulsion Center, Machines (CNPM) – Politecnico, Milan, Italy
December 4, 1974

Prof. Corrado Casci – CNPM
Dr Ing. Roberto Corlevaro – CNPM
Dr Aldo Coghe – CNPM
Dr Pasini Suvano – CNPM
Dr Ghizzi Umberto – CNPM
Dr Luigi de Julio – Alfa Romeo
Dr Vittorio Bruno – Alfa Romeo
Dr Guiseppi Caliri – Fiat – Aviation Division

Subjects discussed:
(1) Aircraft engines.
(2) Combustor research.

XXIV. National Research Council, Ottawa, Canada
January 20, 1975

Dr R.B.Whyte, Head, Fuels and Lubricants Section
Dr Thomas Ledwell, Fuels and Lubricants Section

Subjects discussed:
(1) Trends in Canada's fuel use.
(2) Aviation fuels for Canada.
(3) Diesel fuel experience in stationary gas turbines.

XXV. Department of Energy, Mines and Resources, Bells Corner, Ottawa, Canada
January 20, 1975 (afternoon)

Dr Douglas S.Montgomery, Head of Energy Research Program, Canadian Center for Mining and Energy Technology

Subjects discussed:
(1) Present Canadian petroleum reserves.
(2) Aviation fuels from syncrudes.
(3) Problems with present petroleum prospecting.

XXVI. Department of Energy, Mines & Resources, 580 Booth Street, Ottawa, Canada
January 22, 1975

Dr W.G.Mathews

Subjects discussed:
(1) Availability of aviation fuel in Canada.
(2) Future fuel sources.

XXVII. Shell, Toronto, Canada
January 22, 1975

Mr David Salter, Director, Products Application
Mr John McClurg – Corporate Planning

Subjects discussed:
(1) Demand forecast for petroleum products.

XXVIII. Sun Oil Company, Ltd, Canada
January 22, 1975 (afternoon)

Mr Jack Peake, Coordinator of Environmental Conservation, Sun Oil Company of Canada, Ltd

Subjects discussed:
(1) Tar sands development.
(2) Government royalty and taxing policies.
(3) Characteristics of tar sands products.

XXIX. General Electric Company, Evendale, Cincinnati, Ohio 45200, United States
April 30, 1975

Morris Zipkin, Manager, Advanced Engineering & Technology
A.L.Meyer, Manager, Combustion Program
D.W.Bahr, Manager, Advanced Combustion and Emissions Control Technology
R.Payzer, Manager, Evendale Preliminary Design
M.Shayeson, Fuels Cons.
A.Schexnayder, Manager, Component Technology Programs

Subjects discussed:
(1) Broadening fuel specifications to improve availability/price.
(2) Performance tests of kerosene derived from oil shale.
(3) Fuel lubricity.
(4) Hydrogen as an aircraft fuel.
(5) Limits to engine pressure ratio and cycle temperature.

XXX. National Aeronautics and Space Administration (NASA), Washington, D.C. 20595
May 1, 1975

Mr James J.Kramer, Director, Aircraft Fuel Conservation Task Force and Aerodynamics and Vehicles Systems Division

Subject discussed:
(1) Preliminary program on aircraft fuel conservation technology.

XXXI. Pratt and Whitney, United Technologies Corporation, East Hartford, Conn. 06108
May 7, 1975

William Sens, Manager, Advanced Gas Turbine Projects (P & W)
A.R.Marsh, Manager, Fuels & Lubricants Dept. (P & W)
Donald White, Manager, NASA, Programs, Engineering Dept. (P & W)
Joseph Chew, Manager, Cleveland, Ohio Office (P & W)
Milton Beheim, Chief, Wind Tunnel and Flight Division (NASA)

Subjects discussed:
(1) Trends in engine design which affect fuel economy.
(2) Combustor performance with fuels of high aromatic content.
(3) Engine problems with non-specification fuels.
(4) Deterioration of engine fuel economy.
(5) Engine life.

XXXII. EXXON Research and Engineering Company, Cambridge, Mass.
May 8, 1975

Dr John Longwell, Senior Scientific Advisor, Corporate and Government Research

Subjects discussed:
(1) Demand for aviation fuel.
(2) Petroleum reserves.
(3) Prospects for fuel derived from syncrude.
(4) Upgrading heavy oil to aviation fuel.
(5) Long term fuel storage.
(6) Fuel advisory group for aviation.

XXXIII. R.Dixon Speas Associates, Manhasset, Long Island, New York
May 9, 1975

Mr R.Dixon Speas

Subjects discussed:
(1) Fuel economy through flight routing.
(2) Fuel economy through fuel handling audit.
(3) Fuel economy through rational computation of fuel reserves.

XXXIV. US Energy Research and Development Administration, Pittsburgh Energy Research Center, Pittsburgh, Pa.
June 3, 1975

Dr Irving Wender, Director
Dr Bernard D.Blaustein, Supervisory Research Chemist
Dr Herbert Appell, Research Chemist
Dr Brad Bockrath, Research Chemist
Dr Y.C.Fu, Research Chemist
Dr Sayeed Akhtar, Project Leader, Synthoil
Dr Fred Steffgin, Research Supervisor, Chemistry

Subjects discussed:
(1) Laboratory scale batch and continuous flow coal liquifaction processes under study by the Pittsburgh Energy Research Center.
(2) Plans for pilot plant scale coal liquifaction facilities for developing basis for commercial exploitation of promising processes.

*****

NASA, Lewis Research Center, Cleveland, Ohio
October 21, 1974 – June 30, 1975

Conferences were held with the following members of the NASA, Lewis Research Center staff over this period:

XXXV. Salvatore J.Grissafe, Head, Surface Protection Branch

Subjects discussed:
(1) Corrosion of turbine engines.
(2) Turbine blade coatings.

XXXVI. John C.Freche, Associate Chief, Materials and Structures Division

Subjects discussed:
(1) Advanced turbine blade materials.
(2) Filament reinforced turbine blades.
(3) Powder metallurgy progress.

XXXVII. Richard J.Weber, Head, Mission Analysis Branch

Subjects discussed:
(1) Turbine engine design trends.
(2) Engine fuel economy.

XXXVIII. Jack B.Esgar – Chief, Air Breathing Engine Division
Jack S.Grobman – Advanced Technology Section, Air Breathing Engine Division
Thaine W.Reynolds – Combustion and Pollution Branch, Air Breathing Engine Division
Richard A.Rudey – Head, Combustion and Pollution Branch

Subjects discussed:
(1) NASA, Air Force and Navy programs for qualifying syncrude fuels for aviation.
(2) Combustor test results with syncrude fuels; pollution measurements.
(3) Combustor tests with fuels of high aromatic content.

******

XXXIX. Wright-Patterson Air Force Base, Dayton, Ohio
July 3, 1975

Mr Herbert R.Lander – Acting Technical Area Manager, Fuels Development
Dr William S.Blozowski – Chief, Exhaust Emissions Technology Branch, Fuels and Lubricants Division
(Primary contacts absent from meeting):
Mr Arthur V.Churchill – Chief, Fuels Branch, Fuels and Lubricants Division
Mr Robert D.Sherril – Assistant Chief, Fuels and Lubricants Division

Subjects discussed:
(1) Aviation fuels from shale oil.
(2) Combustor performance with alternate aircraft fuels.
(3) Novel combustors and ignitors.
(4) Exhaust emissions.

XL. Paraho Oil Shale Demonstration, Anvil Points, Rifle, Colorado
August 9, 1975

Telephone contact: Mr Harry Pforzheimer, Program Director
300 Enterprise Bldg.
Third and Main Street
Grand Junction, Colorado 81501

Visited: Mr Harry Pforzheimer III
Paraho Demonstration Plant
Anvil Points, Rifle, Colorado

Subjects discussed:
(1) Mining methods of the Mahogany Zone, Colorado River Valley portion.
(2) Oil shale retorting for oil (kerogen) recovery.
(3) Refined oil shale products.

(Witnessed shale mine operation and shale handling.)

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Procurement	Research projects	

15. Abstract

This report summarizes the survey of NATO nations made by Mr Pinkel on behalf of the Propulsion and Energetics Panel of AGARD. It presents a consolidation of the data gathered in almost all NATO nations through a series of interviews and correspondence. It addresses the fuel supply outlook within the NATO nations for hydrocarbon fuels as well as alternate fuels. Also discussed are possible specification changes for fuels and changes in design and operation. Included are numerous recommendations for future programs in the fuels area.

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