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High Speed Commercial Transport Fuels Considerations and Research Needs

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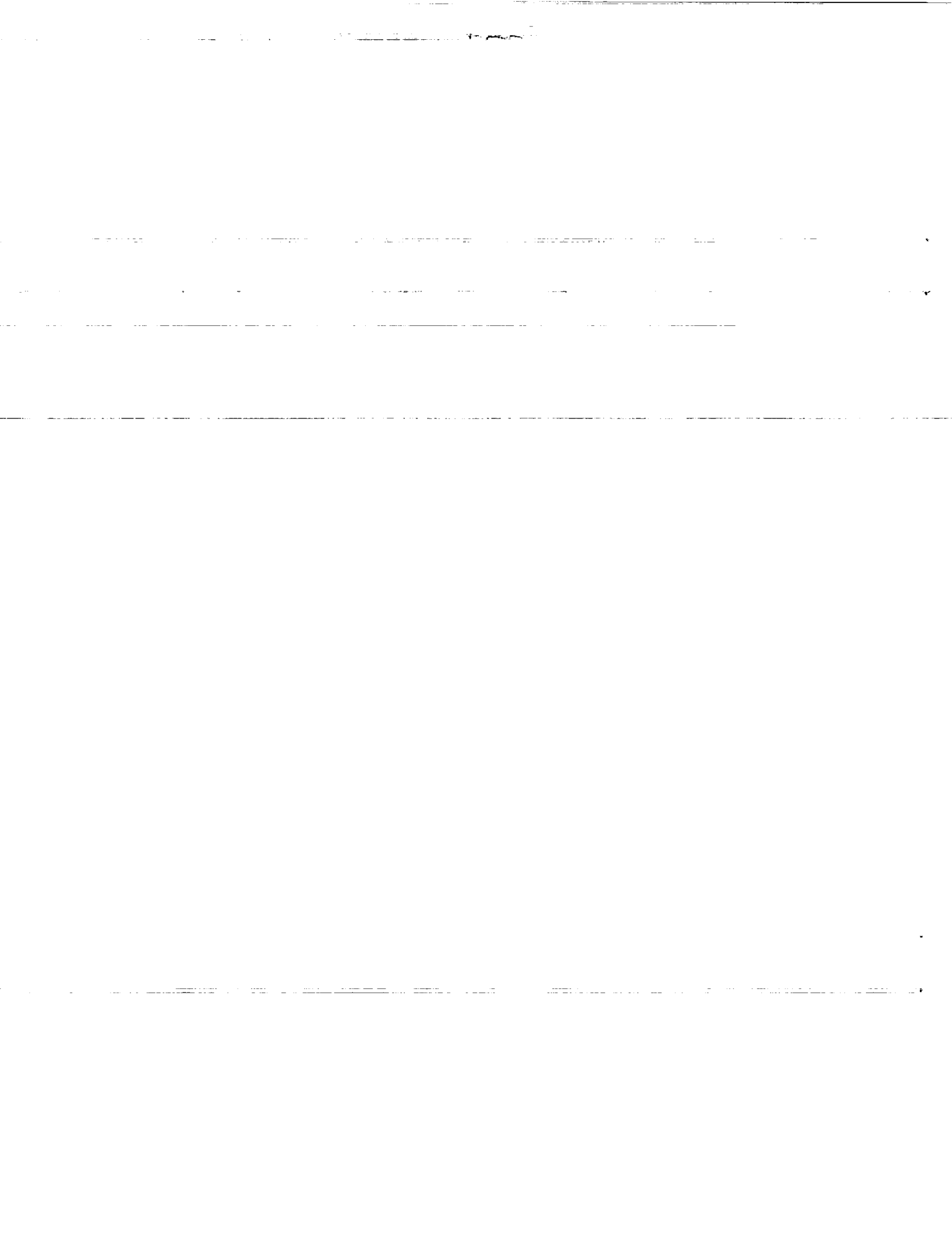
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HIGH SPEED COMMERCIAL TRANSPORT FUELS CONSIDERATIONS AND RESEARCH NEEDS

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FUELS WORKSHOP

The National Aeronautics and Space Administration Agency (NASA) is advocating a new initiative in commercial aeronautics that has the goal of reducing long-range flight times by as much as 75%. The HSCT Program is focused on establishing the technical feasibility, economic practicality, and environmental acceptability of an advanced high-speed commercial transport for potential implementation early in the next century.

As part of the ongoing HSCT studies, issues regarding fuel impacts received much initial concern. Fuel capabilities and economics are very important in determining viable flight speeds. In addition, operation at supersonic speeds provide different and far greater potential difficulties regarding the fuels than is encountered during subsonic flight, due to the high temperature environments. HSCT fuels will not only be required to provide the energy necessary for flight, but will also be subject to aerodynamic heating and, will be required to serve as the primary heat sink for cooling the engine and airframe. To define fuel problems for high speed flight, a fuels workshop was conducted at the NASA Lewis Research Center (LeRC) during October 14-15, 1987. The purpose of the workshop was to gather experts on aviation fuels, airframe fuel systems, airport infrastructure and combustion systems to discuss high speed fuel alternatives, fuel supply scenarios increased thermal stability approaches and measurements, safety considerations, and to provide directional guidance for future R and D efforts. Participants included representatives of nine government agencies and sixty-two corporations.

The major conclusions from the workshop include the following:

1. Both Thermally Stable Jet Fuels (TSJF) and Liquid Methane (LCH₄) should continue to be studied as viable candidates for supersonic commercial transports. Endothermic fuels are viable for military missions but due to their high cost and the preliminary stage of development regarding their usage, are not current candidates for commercial aircraft. TSJF fuel technologies were deemed to be sufficiently in-hand to project their usage in the 2000-2010 time frame. LCH₄ usage would require much development regarding aircraft storage and pumping, airport infrastructure requirements, potential and perceived safety problems and regulatory aspects. Thus LCH₄ fuels, while offering certain advantages such as increased flight speeds, would require more time for implementation possibly beyond the year 2015. The general workshop conclusion was that both TSJF and LCH₄ should continue to be studied, but for different time frames.

2. For TSJF evolution of a quantitative test method for determining thermal stability is very much required. The widely used Jet Fuel Thermal Oxidation Tester (JFTOT) produces qualitative pass/fail results and is not readily adaptable to usage with higher thermal stability fuels. What is required is a test method capable of simulating thermal stability conditions encountered in high speed flight. These are: Long residence times in fuel systems to which the fuel is subjected to moderate to high heat loads; and, conditions of very high heat flux at short residence times which fuels encounter in their passage through fuel struts and injectors.

3. Considerable workshop discussion centered around issues regarding what the thermal stability of current fuel being supplied to airports around the world actually is. Opinions were offered that refinery products available for aircraft usage has changed considerably over the last several years. The principal reason offered for this is that the manufacture of large quantities of non-leaded gasoline has made a better product available. Thus, it was suggested that fuels from airports around the world be obtained and their thermal stability determined. Fuel samples should also be obtained and their thermal stability determined. Fuel samples should also be obtained from refineries and, where possible, their thermal stability should be compared to the airport fuels. Direct comparisons would be difficult to make in many instances due to the co-mingling of various jet fuels at airports. However, direct comparisons could yield conclusions regarding the deterioration of fuel thermal stability due to shipment and airport storage.

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4. On-line treatment of jet fuels to improve their thermal stability was also recommended. Implicit in the recommendation is the difficulty and cost that would be presented by supplying two commercial transportation fuels—one for the subsonic fleet and one for the supersonic fleet. On-line treatment would consist of processing Jet A fuel either prior to or during fuel loading. Treatment techniques cited included deoxygenation and/or clay filtering. Both techniques have previously indicated substantial improvements in thermal stability. However, much work is required to quantify the potential improvement.

5. Flight mach number, heat loads, methods and type of aircraft tankage, fuel system type, etc. require definition prior to being able to define specific fuel needs. This data will become available as aircraft studies, currently in process, proceed. In the interim, fuels with increased thermal stabilities, compared to Jet-A, of 50°F, 100°F and 150°F were defined. Regarding LCH₄ fuels, recommendations centered on determining airport infrastructure issues and costs, safety and regulatory aspects prior to the initiation of research to enhance their implementation.

The workshop also identified seven potential non-cryogenic high speed liquid fuel candidates, which are listed in Table I. The associated features, research needs, and delta cost also are included.

AIRPORT INFRASTRUCTURE AND SAFETY IMPACTS ON HSST

Since fuel price can represent 30% to 45% of the Direct Operating Costs (DOC) for an advanced HSCT (at fuel prices from 0.50¢ to \$1.00 per gallon, Figure 1) it is important that all major cost factors be considered. Thus, it was necessary to estimate the incremental cost associated with infrastructure and operations at the airport. This was accomplished by a team consisting of NASA LeRC and Langley Research Center personnel as well as Boeing and McDonnell Douglas personnel. Consensus results are summarized in three figures and one table: Figure 2 shows that the infrastructure and storage costs are function of daily LCH₄ usage in tons per day. The four solid data points were those reached by consensus, a, b, c were the linearized facility cost growth factors (or six-tenths factor) for each segment; similar infrastructure and handling costs for TSJF are presented in Figure 3. TSJF costs were determined to be substantially lower than those for LCH₄ and were assumed to be independent of daily fuel consumption rates. The total fuel costs (including refinery/liquification plant prices plus airport infrastructure costs) and sensitivity ranges are shown in Figure 4. These fuel costs with the sensitive price ranges that are being used in the ongoing HSCT studies are shown in Table II.

From the Tables I and II, and Figure 1, it is likely that highly hydrogenated jet fuel can increase thermal stability an additional 150°F higher than current jet fuels. For implementation, both TSJF and LCH₄ must be environmental viable. That means, the fuel has to be clean burning with very low concentrations of metal and sulfur content. The injection of particles and/or metals into the stratosphere can produce potentially adverse effects on the environment. In addition to the airport fuel infrastructure cost determinations, airport safety issues were also investigated. The general consensus of airport safety considerations for the usage of TSJF and LCH₄ are concluded in below:

SAFETY CONSIDERATIONS FOR THERMALLY STABLE JET FUELS

- In general, fuel characteristics affecting safety (volatility, flammability, toxicity, etc.) should be no different than those of present jet fuels.
- Separate limited-use transfer and distribution systems add to the need for leak and hazard sensing and controls.
- Airport clay filtration treatment requires environmental controls for filter changing and cleanup.
- Airport processing, such as deoxygenation, adds concerns for leak, over pressure, and over temperature sensing and protection.
- Thermal stability additive treatment may require handling and environmental protection from toxic chemicals.

GENERAL PROVISIONS FOR LIQUID METHANE SAFETY

- Under present and proposed legislation, it is unlikely that storage of large quantities of liquid methane would be permitted at airports.
- The standards in national fire protection association NFPA 59A are the bases for nearly all domestic and foreign liquid natural gas storage and handling.
- Local regulations may be more restrictive than NFPA 59A, especially near populous coast cities.
- Airport safety regulations are presently undefined.

- Solving the technical and economic problems of safe handling of liquid methane may not satisfy the political, regulatory and environmental issues.

FUEL SYSTEM AND THERMAL MANAGEMENT REQUIREMENTS

At subsonic flight speed, the fuel properties required to satisfy engine demands are heat of combustion, combustion characteristics, lubricity, viscosity, heat capacity, vapor pressure, thermal stability, freeze point, and flash point, etc. As flight speeds increase into the targeted Mach 2-3+ regime, in addition to these engine requirements, fuels have to satisfy various demands for cooling. Included in these cooling demands are cooling of aircraft/propulsion systems; thermal control of fuel storage and distribution systems; and cooling of propulsion lubrication systems. Thus, a proper thermal management of the high speed aircraft/propulsion system is required to satisfy these various cooling demands. This thermal management system has to provide sufficient heat sinks to absorb the rejected heat loads from the aircraft/propulsion system. At subsonic or low supersonic flight speeds, heat sinks are primarily provided by ambient air and fuel. Below Mach 2, ambient air is adequate to satisfy most of the cooling demands. The fuel plays a secondary role as a heat sink. Between Mach 2 to 3+, the rapid increased stagnation temperature reduces the cooling capability of the captured air, therefore placing more demands on the fuel as a heat sink. The heat sink capacity of fuels depends on several factors. These are: storage condition in fuel tank, fuel thermal stability, maximum heat adsorption, fuel flow rate, etc. These factors are not yet completely defined. Thus, subsequent studies in the following areas are needed to define thermal management requirement:

1. Interactive airframe/propulsion studies.
2. Quantification of thermal demands of both the airframe and propulsion system.
3. Optimization of thermal demands of both the airframe and propulsion system.
4. Definition of critical system components.
5. Definition of critical operating condition.
6. Definition of the shortcomings of existing fuels.

ANALYTICAL WORK

It is difficult to predict future aviation fuel prices. However, it is possible to use a computer code to estimate aviation fuel costs. At LeRC a Refinery Simulation Program (Gordian code) was used to estimate future fuel costs. This program will be used to predict the flow streams and material, energy, and economic balances of a typical petroleum refinery, with particular emphasis on production of aviation turbine fuel of varying end point and hydrogen content specifications. The program has provision for shale oil and coal oil in addition to petroleum crudes. The primary features of the Gordian code are:

1. The flexibility to configure a refinery involving any or all of the process units commonly employed in the production of gasoline, jet fuels, and mid-distillates.
2. The ability to produce jet fuel blends of varying end-point specification and varying specified hydrogen content as part of the total slate of products.
3. The ability to handle synthetic crudes (shale and coal derived) with varying severities of hydroprocessing.
4. The determination of overall refinery energy efficiency.
5. The determination of sulfur, nitrogen, and hydrogen material balances for each process unit and for the overall refinery, and
6. The capability of conducting economic calculations.

In 1988, this code was modified to include three additional capabilities:

- a. Allow the initial boiling point of jet blend to be specified.
- b. Allow the hydrotreated and hydrocracker units to specify the level of severity of hydro-treating.
- c. Simplify updating the parameters used to estimate the economics (i.e. construction costs, chemical costs, labor costs).

A case study utilizing this code is presented below. The case study considered both petroleum crude and shale crude processes in a mid-size refinery to produce JP-7 type jet fuel. The produced jet fuel properties have the following constraints:

Initial boiling point is 360°F, end point is 550°F, freezing point below -43°C, aromatic content below 5%. The minimum hydrogen weight percent of 14% is then varied to determine economic impact. Figure 5 shows a schematic diagram of the refinery configuration for this study. The feed rate is 70,000 barrel/day (BPD) of East Texas petroleum based crude and 30,000 BPD Garrett shale oil. The process units used are listed in Table III. The capacity for each process unit is defined at 110% of the actual feed rate in all the cases studied. The product stream rate from each process unit and its properties are listed in Table IV; the economic analysis of changing hydrogen

weight percent of blended jet fuels are listed in Table V; it should be noted that in Table V, the estimated cost is not included in the cost of crudes. As an anticipated result, the higher the hydrogen weight percent of the fuel, the higher the cost and the lower the amount of jet blend product.

SUMMARY

The results of HSCT fuels studies can be summarized as follows:

1. Both thermally stable jet fuels (TSJF) and liquid methane (LCH₄) should continue to be studied as viable candidates for supersonic commercial transports. Endothermic fuels are viable for military missions but, due to their high cost and the preliminary stage of development regarding their usage, are not current candidates for commercial aircraft. TSJF fuel technologies were deemed to be sufficiently in-hand to project their usage in the 2000-2010 time frame. LCH₄ usage would require much more development regarding aircraft storage and pumping, airport infrastructure requirements, potential and perceived safety problems and regulatory aspects. Thus, LCH₄ fuels require more time for implementation-possibly beyond the year 2015.

2. The widely used JFTOT is a qualitative on/off indicator, which is not readily adaptable to usage with higher thermal stability fuels. An innovative device which can quantitatively determine fuel thermal stability in high speed flight is much needed.

3. It was concluded that determination of the thermal stability for current fuels being supplied to airports around the world be accomplished via two approaches: first, obtain fuel samples from airports around the world and determine their thermal stability. Second, fuel samples from refineries should also be obtained, and their thermal stability should be compared to the airport fuels.

4. On-line treatment of jet fuels to improve their thermal stability was desired. This treatment would consist of processing of Jet A fuel either prior to or during fuel loading. Various treatment techniques cited, however, much work is required to quantify the potential improvement.

5. Flight mach number, heat loads, fuel system type, and thermal management requirements etc., require definition prior to being able to define specific fuel needs. The subsequent studies are currently in process. In the interim, fuels with increased thermal stabilities, compared to Jet A, of 50°F, 100°F and 150°F were defined.

6. Subsequent airports infrastructure studies concluded that generally, TSJF fuel characteristics affecting safety should be no different than those of present jet fuels. For LCH₄, airport safety regulations are presently undefined, the application of LCH₄ in HSCT would require much development regarding aircraft storage and pumping, airport infrastructure requirements, potential and perceived safety problems and regulatory aspects.

7. The Gordian code can be used to predict the flow streams and material, energy, and economic balances of a petroleum refinery, with particular emphasis on production of aviation turbine fuel, this code can be up-dated to include the cost prediction for various fuel treatments.

LITERATURE CITED

- (1) Computer Model for Refinery Operations With Emphasis on Jet Fuel Production, NASA CR-135334 (1978).

TABLE 1 - HIGH SPEED LIQUID FUEL CANDIDATES.

| FUEL | COST + | FEATURES | RESEARCH NEEDS |
|------------------------------------|--|--|---|
| JET A CLAY FILTERED | SMALL + | Uses Current Fuel Supply, No Special Handling or Storage Modest Improvement in Fuel Thermal Stability | Determine Impacts on Thermal Stability of Clay Filtering, Determine Cost Increase |
| JET A DEOXYGENATED | SMALL + | Same as Above; on Board Inerting Required Modest Improvement in Fuel Thermal Stability | Same as Above |
| JET A DEOXYGENATED & DESULPHURIZED | UP TO +0.10\$/gal | Same as Above; Special Storage, Tankage Required Larger Potential Improvement in Fuel Thermal Stability | Same as Above |
| HIGH VAPOR PRESSURE FUEL | SMALL + | Large Potential Thermal Stability Improvement; Special Storage, Handling & Tankage Required | Define Storage & Handling Requirements; Define Refinery Streams of Interest |
| HIGHLY HYDROTREATED JET FUEL | 0.10\$ + + + + | Very Large Thermal Stability Increase to Mach 4 Flight Special Storage with Inerting | Determine Effects of Severe Hydrotreating on Thermal Stability, Lubricity, Etc. |
| JP-7 | 0.10\$ + + 1.09\$/gal + 0.16 - 0.30\$/gal SHIPPING | Same as Above | Same as Above - Determine Effects of Hydro-treating Less Severly Determine Price Reductions with Increased Quantity |
| RAFFINATE / SASSOL / OTHER STREAMS | NO IDENTIFICATION OR DESIGNATION | | Identify Other Viable Refinery Streams |

TABLE 2 - FUEL COST ESTIMATES, FEBRUARY 4, 1988.

| Fuel | Refinery Type of Special Treatment | Baseline Increased Storage & Handling Cost (\$/Gal) | Reference ^a Price (\$/Gal) | Total Cost (\$/Gal) | Price Range for Sensitivity |
|------------------|--|---|---------------------------------------|---------------------|-----------------------------|
| JET A | NONE | 0.00 | 0.60 | 0.60 | 0.50 to 0.75 |
| TSJF + 50 °F | -More Stable TSJF From Refinery -Clay Filters at Airport; Additive or Deoxygenation at Storage Tank | 0.00 | 0.60 | 0.60 | 0.50 to 0.85 |
| TSJF + 100 °F | Hydrotreated | 0.01 | | 0.71 | 0.60 to 0.95 |
| TSJF + 150 °F | Highly Hydrogenated at Refinery Plus Deciated Storage and Handling at Airport | 0.025 | 0.90 | 0.925 | 0.70 to 1.10 |
| OTHERS | Alternate ^b Refinery Stream | | | | |
| LCH ₄ | From Liquefaction Plant | 0.10 ^c | 0.58 | 0.68 | 0.50 to 1.00 |

^a From November 4, 1987 meeting includes \$0.01 for airport to aircraft costs.

^b Insufficient data to estimate.

^c 7000 tons per day

TABLE 3 - THE PROCESS UNITS, UNITS CAPACITIES, AND PRODUCT RATES OF THE CASE STUDY.

| Refinery Process Unit | Actual Feed Rate (bpd) | Capacity (bpd) |
|--|------------------------|-------------------|
| Petroleum Crude Unit | 70000.0 | 77000.0 |
| Shale Crude Unit | 30000.0 | 33000.0 |
| Petro. Vac. Dist. Unit | 30100.0 | 33100.0 |
| Shale Vac. Dist. Unit | 16260.0 | 17900.0 |
| Catalytic Cracker | 14156.5 | 15600.0 |
| Gas Oil Hydrocracker | 9909.5 | 10900.0 |
| Shale Gas Oil Hydrocracker | 1000.0 | 1100.0 |
| Distillate Desulfurizer | 7990.1 | 8800.0 |
| Kerosene Hydrotreater | 500.0 | 550.0 |
| Shale Kero. Hydrotreater | 2500.0 | 2800.0 |
| Hydrogen Plant | 48.8 ^a | 54.0 ^a |
| Coker | 2000.0 | 2200.0 |
| Initial Boiling Point = 360.0 °F Endpoint = 550.0 °F Hydrogen Constraint = 14.46 wt% | | |
| Petroleum Crude Used: East Texas Shale Crude Used: Garrett Shale Oil | | |

^a Hydrogen flowrate given in MMSCFD.

TABLE 4 - COMPONENT STREAMS OF JET BLEND USING THE PARAMETER GIVEN IN TABLE 5.
 [IBP = 360 °F; EP = 550 °F; MIN. HYD. WT% = 14.46.]

| Process Unit Origin | Stream Name | Volumetric Flowrate into Jet Blend (bpd) | Hydrogen Weight Percent | Freezing Point (°C) | Aromatic Weight Percent |
|-----------------------------|------------------------|--|-------------------------|---------------------|-------------------------|
| Shale Oil Hydrocracker | Hydro. trt. hvy. kero. | 13 | 15.60 | -45.6 | 15.0 |
| Shale Oil Hydrocracker | Hydro. trt. lt. kero. | 177 | 14.85 | -45.6 | 15.0 |
| Gas Oil Hydrocracker | Hydro. trt. lt. kero. | 4063 | 14.57 | -45.6 | 5.0 |
| Shale Kero. Hydrotreater | Hydro. trt. lt. kero. | 886 | 14.29 | -37.8 | 1.5 |
| Kerosene/Naptha Hydro tr. | Naptha | 133 | 14.14 | -31.1 | 1.6 |
| Gas Oil Hydrocracker | Desul. hvy. kero. | 813 | 14.09 | -45.6 | 5.0 |
| Shale Kerosene Hydrotreater | Hydro. trt. hvy. kero. | 26 | 14.05 | -27.2 | 1.5 |
| | Pool Properties | 6111 | 14.46 | -43.5 | 4.7 |

TABLE 5 - ESTIMATION OF OPERATING AND INVESTMENT CARRYING COSTS AS A FUNCTION OF THE HYDROGEN WEIGHT%.

[IBP = 360 °F; EP = 550 °F.]

| Minimum Hydrogen Weight % | Jet Blend Freezing Point (degrees °C) | Aromatic Content of Jet Blend (%) | Total Amount of Jet Blend Produced (bpd) | Total Operating and Investment Carrying Charge per Barrel of Jet Blend Produced ^a |
|---------------------------|---------------------------------------|-----------------------------------|--|--|
| 14.35 | - 28.2 | 4.3 | 7520.70 | 9.74 |
| 14.40 | - 33.6 | 4.3 | 6899.10 | 10.62 |
| 14.45 | - 42.8 | 4.3 | 6258.48 | 11.18 |
| 14.50 | - 43.5 | 4.7 | 5541.12 | 12.12 |
| 14.55 | No naphtha in Jet Blend | | | |

^a Does not include cost of crude oil.

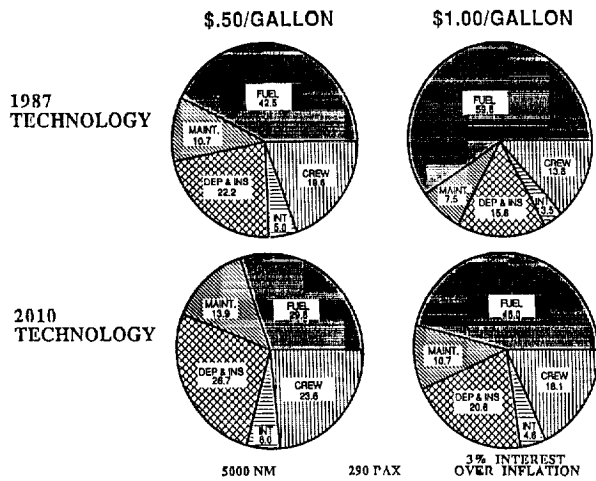


Figure 1. - Impact of fuel price on HSCT DOC + I.

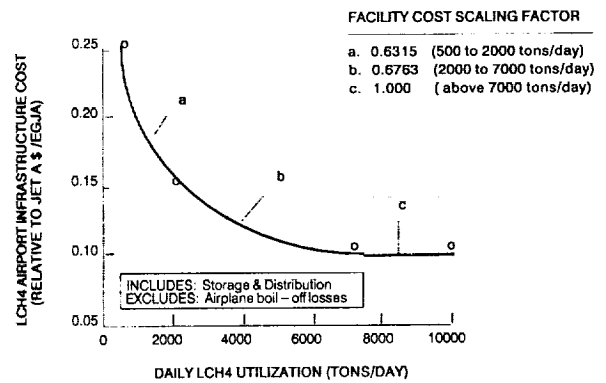


Figure 2. - Estimated increase in LCH4 airport infrastructure cost relative to jet A fuel.

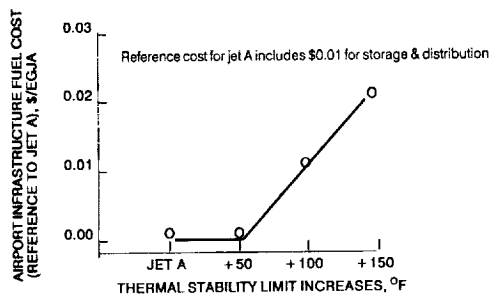


Figure 3. - Estimated increase in TSJF airport infrastructure cost relative to jet A with increase in thermal stability limit.

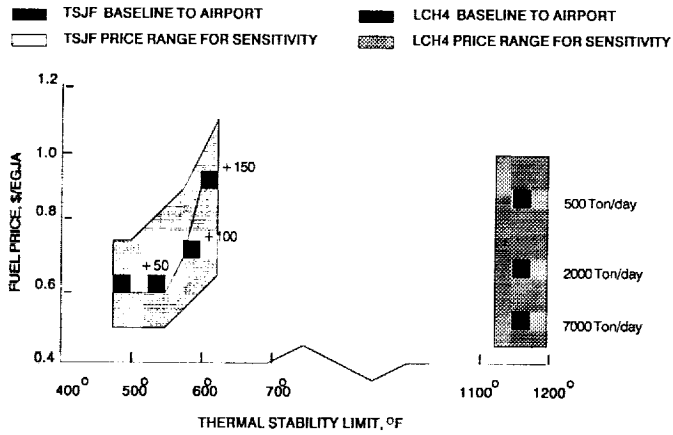


Figure 4. - Fuel price assumptions.

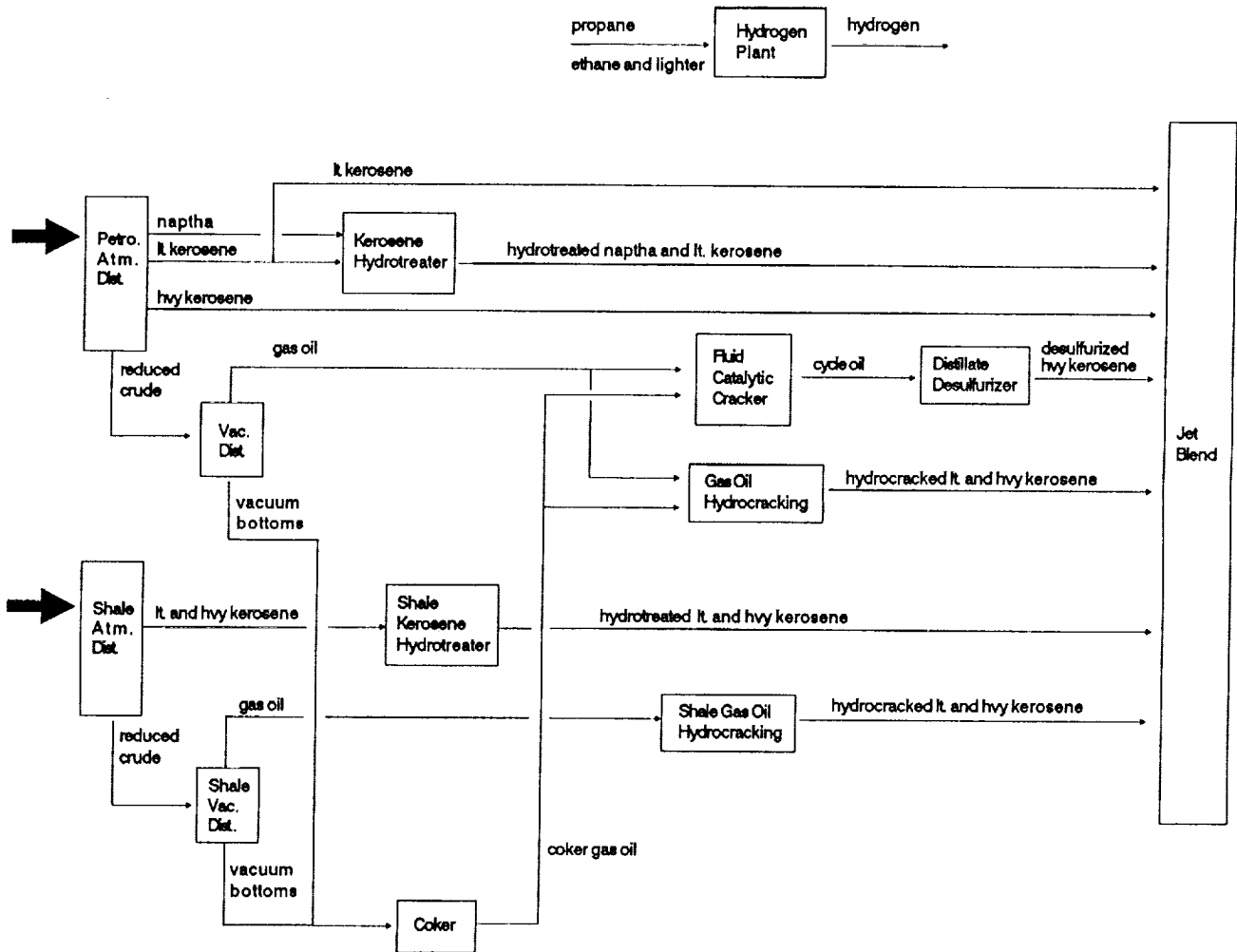


Figure 5. - Schematic diagram of refinery configuration.



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| 15. Supplementary Notes Prepared for the Symposium on the Structure of Future Jet Fuels II sponsored by the American Chemical Society, Miami Beach, Florida, September 10-15, 1989. | | | | | |
| 16. Abstract The National Aeronautics and Space Administration (NASA) is currently evaluating the potential of incorporating High Speed Civil Transport (HSCT) aircraft in the commercial fleet in the beginning of the twenty-first century. NASA sponsored HSCT enabling studies currently underway with airframers and engine manufacturers, are addressing a broad range of technical, environmental, economic and related issues. Supersonic cruise speeds for these aircraft were originally focused in the Mach 2 to 5 range. At these flight speeds, both jet fuels and liquid methane were considered potential fuel candidates. Subsequent analyses have led to further definition of flight speeds and fuel candidates. For the year 2000 to 2010, cruise Mach numbers of 2 to 3+ are projected for aircraft fuel with thermally stable liquid jet fuels. For 2015 and beyond, liquid methane fueled aircraft cruising at Mach numbers of 4+ may be viable candidates. Operation at supersonic speeds will be much more severe than those encountered at subsonic flight. One of the most critical problems is the potential deterioration of the fuel due to the high temperature environment. HSCT fuels will not only be required to provide the energy necessary for flight, but will also be subject to aerodynamic heating and, will be required to serve as the primary heat sink for cooling the engine and airframe. To define fuel problems for high speed flight, a fuels workshop was conducted at the NASA Lewis Research Center during October 14 and 15, 1987. The purpose of the workshop was to gather experts on aviation fuels, airframe fuel systems, airport infrastructure, and combustion systems to discuss high speed fuel alternatives, fuel supply scenarios, increased thermal stability approaches and measurements, safety considerations, and to provide directional guidance for future R&D efforts. Subsequent follow-up studies defined airport infrastructure impacts of high speed fuel candidates. This paper summarizes the results of these activities. In addition, an initial case study using a modified in-house refinery simulation model Gordian code (1) is briefly discussed. This code can be used to simulate different types of refineries, emphasizing jet fuel production and relative cost factors. <i>ARE SUMMARIZED.</i> | | | | | |
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