Thermal-Stability Aspects of Commercial Kerosine for the Supersonic Transport

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A recent investigation in a specially instrumented supersonic transport (SST) fuel-system test rig has revealed thermal-stability problem areas in the fuel tanks and engine components. These problem areas are discussed with respect to their significance to the development of the SST. Results from the SST Fuel System Test Rig compared to the results of small-scale fuel thermal-stability devices point out that greater accuracy and repeatability are necessary to evaluate realistically fuel suitability for the SST. With improved thermal-stability measurement accuracy and repeatability, design margins can be reduced. The interdependence of fuel quality control and aircraft fuel-system and engine design points out the need for continued fuel-systems research directed at the development of suitable small-scale thermal-stability test devices.

Introduction

GREAT emphasis has been placed on fuel thermal stability in the development of the SST. This emphasis is well-founded when considering all the potential problems that can result from an aircraft fuel-system design that is thermally incompatible with the fuel used. Designing the SST for commercial kerosine requires a knowledge of potential problems as well as a means of predicting the performance of the fuel in all portions of the aircraft fuel system. Circumventing these problem areas may require design compromises. The degree of compromise is a function of how accurately the fuel specification defines the thermal-stability characteristics of the fuel for the specific design under consideration. The thermal-stability test method, therefore, can have a profound influence on the initial and operational cost of the SST.

Fuels meeting an American Society for Testing and Materials-Coordinating Fuel Research (ASTM-CFR) Coker[1] fuel rating of 300/400 are used in today's commercial jet aircraft, where the only severe thermal environment experienced by the fuel is in the engine. In the SST, where a fuel of equivalent cost is desired, not only is the engine fuel subjected to elevated temperature, but the fuel in the tanks will also be subjected to elevated temperatures, and in some cases, depending on design, even more severe temperature environments may be experienced in the tanks. Therefore, it is vitally important that proper tools for fuel thermal-stability measurement are available in the development phase of the SST.

The Federal Aviation Agency (FAA) recently sponsored an SST fuels investigation to identify potential fuel-system problem areas and determine the suitability of small-scale thermal-stability test devices in predicting the performance of fuel in the SST. This investigation has given rise to questions as to the importance of indicated problem areas from the system performance standpoint and the confidence level with which known thermal-stability test devices can be used for the SST. The purpose of this paper is to discuss the FAA-SST Fuels Program and the significance of the results in the development of the SST. The discussion is divided into two sections. The first section is concerned with a discussion of the FAA-SST Fuels Program including the Fuel Data Correlation Program, and the second section is concerned with a discussion of significance of the results.

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FAA-SST Fuels Program

The major purposes of the FAA-SST Fuels Program was to determine fuel quantity requirements for a SST and to establish whether existing fuel thermal-stability test methods could be calibrated against a simulated SST fuel system. The test program that was developed to serve these purposes consisted of designing and fabricating a fuel-system test rig to simulate the anticipated environmental conditions representative of the SST, and conducting a series of tests on four fuels representing high-, medium-, and low-quality commercial aviation kerosines (Table 1). Concurrently, five fuel thermal-stability test devices were used to evaluate the same fuels being tested in the SST Fuel Test Rig.

SST Fuel System Test Rig Description

The focal point of the SST Fuels Testing Program was the SST Fuel System Test Rig (Fig. 1). This system was designed, constructed, and operated by North American Aviation Inc., to simulate the thermal environment experienced by the fuel in the tanks and components of a supersonic transport fuel system. Two basic subsystems, airframe and engine, made up the SST Fuel System Test Rig.

The airframe subsystem consisted of a 400-gal fuselage tank, a 100-gal wing tank, a 74-μ surface filter, and a fuel-to-oil heat exchanger. The tanks were internally equipped with aircraft booster pumps and a level control valve. Externally the tanks were equipped with a heated vent system, vibrators, and radiation heaters. The heaters simulated aerodynamic heating and were located on the upper and lower surfaces of the wing tank and on the curved surfaces of the

Table 1 Test fuels evaluated

Test fuels	ASTM-CFR rating[a]
FA-S-2A	425/525
RAF-176-64	375/475
RAF-176-63	350/450
FA-S-1	325/425

[a] Rating based on temperature level 25°F less than level at which a Cod 2 or 12-in. Hg/300 min was exceeded.

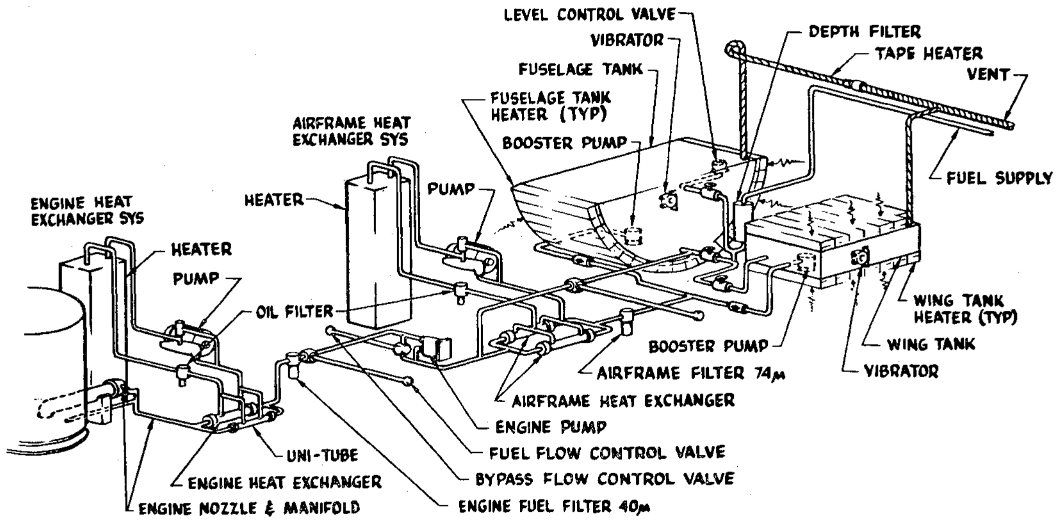


Fig. 1 SST airframe and engine fuel-system test rig.

fuselage tank. All nonheated surfaces were insulated. The heat exchanger consisted of two aircraft shell-and-tube-type heat exchangers and a closed-loop, electrically heated oil system. The oil system simulated the heat energy from the auxiliary airframe subsystems such as electronic and hydraulic. The airframe subsystem was constructed from stainless steel, with the exception of the aluminum booster pumps and nonmetallic seals.

The engine subsystem consisted of a vane-type, high-pressure aircraft fuel pump, a flow control valve, a 40-μ surface filter, a heat exchanger, and a heated line (manifold) and nozzle. As in the airframe system, all components and lines are constructed from stainless steel except for the pump, which was constructed from tool steel, graphite, aluminum, and tungsten. Copper and copper alloys were restricted from the system. The engine heat exchanger consisted of one aircraft shell-and-tube-type heat exchanger and a closed-loop, electrically heated oil system. The engine oil system was the same design as the airframe system and simulated the heat energy from the engine hydraulic and lubricating subsystems. All lines and components were insulated in the entire system.

Test rig instrumentation included two types: control and performance. Control instrumentation was provided to maintain and monitor the specified test environment. Examples of this type are bulk fuel temperatures, wing tank wall temperatures, flow rate, and altitude. Performance instrumentation was provided to measure changes in operation of test components so that the performance of the test fuel could be determined. Examples of this type are pressure differentials across components, oil temperatures, and heat exchanger-tube-wall temperatures. The test rig had approximately 190 instrumentation points.

In operation, the test rig simulated aircraft conditions in terms of time, temperature, and pressure. Each test cycle consisted of filling the fuel tanks and transferring the fuel through the system under time, temperature, and pressure conditions approaching a 3500-naut-mile, 159- to 179-min supersonic flight. The test rig was operated on a constant fuel weight flow and heat energy input basis such that as component performance degraded there would be no effect on the fuel flow rate and heat input, which is simulative of an actual aircraft. A simplified flow schedule was obtained by averaging the total flow during each of the acceleration, cruise, and descent conditions of a typical flight, resulting in three flow rates per test cycle.

The test rig was operated at the 500° and the 400°F basic temperature environments specified by the Coordinating Research Council (CRC)[2] (Figs. 2 and 3). These temperature curves show the bulk fuel temperature out of each successive component in the test rig which is rejecting heat to the fuel. The maximum fuel temperature approached fuselage tank or component surface temperatures that were approximately 30° to 50°F higher than the bulk fuel. The unwetted tank wall temperatures of both tanks, for the 500° and 400°F temperature environments, were 500° and 350°F, respectively. In the wing tank, fuel puddles approached the unwetted tank wall temperature.

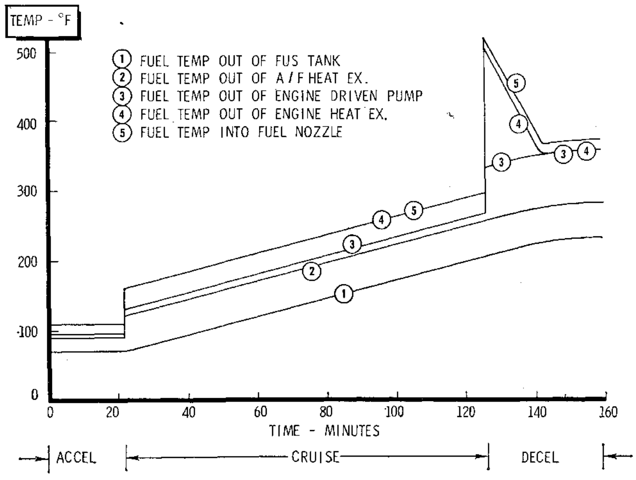


Fig. 2 CRC 500°F temperature environment.

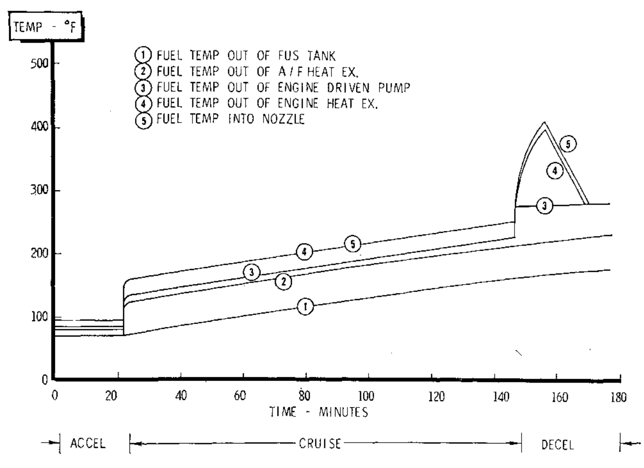


Fig. 3 CRC 400°F temperature environment.

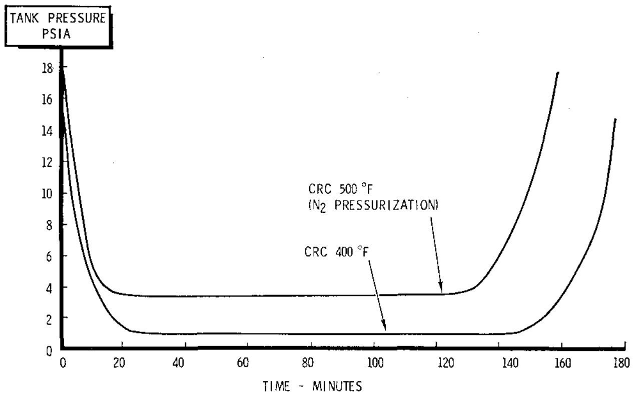


Fig. 4 Tank pressure profiles.

Tank pressure profiles for the two temperature environments are shown in Fig. 4. During the 500°F temperature environment testing, the fuel tank ullages were inerted with nitrogen by maintaining a nitrogen pressure of 2.5 psi above the test altitude and using nitrogen gas for simulated descent. For the 400°F temperature environment no inerting was required and air was used for simulated descent.

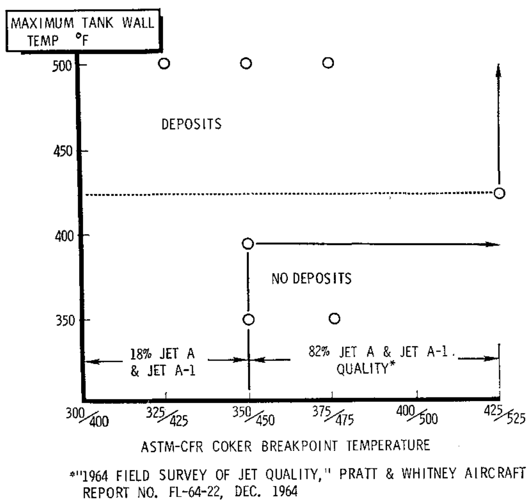
Test Results

A total of 332 test cycles were conducted on four fuels, as shown in Table 2. The results of the test program showed that in the 500°F environment (Fig. 2), fuel deposits were formed in the tanks and on all engine components, regardless of the fuel tested. At the 400°F environment (Fig. 3) no deposits were indicated using a fuel rated as 375/475 on the ASTM-CFR Coker (it is noted that a very slight discoloration was observed in the manifold and heat exchanger outlet). In the following paragraphs, results of the SST Fuel System Test Rig airframe and engine subsystem will be discussed from the standpoint of their applicability to specific design considerations.

Airframe Subsystem

Vent lines

The vent lines contained a buildup of fuel deposits which were concentrated in the cool areas (250° to 350°F) of the vent adjacent to the tanks. It was speculated that the deposit formation was the result of hot fuel vapor from the wing tank condensing and subsequently polymerizing. Those portions of the vent lines approaching a temperature of 500°F did not reveal deposits. The significance of these results relative to the vent design is that the routing of vent lines may become critical, especially in cooler zones, and may require inspection access.



*"1964 FIELD SURVEY OF JET QUALITY," PRATT & WHITNEY AIRCRAFT REPORT NO. FL-64-22, DEC. 1964

Fig. 5 Estimated fuel tank deposit temperature zones.

Fuel tanks

The fuel tanks will be discussed on the basis of the fuselage tank (wet tank) and the wing tank (dry tank), which was emptied of usable fuel ($\frac{1}{2}$ of 1% of capacity remaining) prior to each heating cycle. The fuselage tank did not show evidence of deposits except in the vent area. The deposits in the vent area are considered to be the result of condensing hot wing tank vapors that were transferred to the fuselage tank due to pumping of fuel from the fuselage tank. It is considered significant that no deposits were formed even though temperatures approaching 500°F existed in the dry wall areas. This would indicate that the existence of dry hot spots in the tanks may not be significant to the fuel thermal stability problem.

The wing tank or "dry tank" did reveal varying amounts of deposits regardless of the fuel quality (ASTM-CFR Coker rating) at the 500°F environment. In one test series a fuel rated at 400/500 on the ASTM-CFR Coker produced deposits at tank wall temperatures of 425°F. Figure 5 shows the results of tank tests conducted at unwetted tank wall temperatures of 350° to 500°F. The significance of these data is that there appears to be a nonsensitive temperature zone (390° to 425°F) where deposits may form although there was a significant increase in fuel quality. This may suggest that under these temperature, time, and pressure conditions, the fuel undergoes thermal cracking as was indicated during the FA-S-1 fuel test by a fivefold olefin increase in the residue fuel.

From the designer's standpoint, thermal cracking of puddle fuel is not serious, providing dilution takes place prior to the formation of tank deposits. Therefore, if the time-temperature limitations (no deposits) of a fuel under tank conditions can be determined, the designer's flexibility is increased.

The flaking of deposits was unpredictable based on these tests, as evidenced by flaking occurring in only one test series. With the exception of the vent line and fuel tanks, deposit formation could always be detected by a change in performance. The fact that deposit formation could not be detected in the fuel tanks and vent lines suggests a possible hazard during flight because of the unpredictability of a deposit flaking problem.

The airframe filter and heat exchanger were basically deposit-free during the test series. Filter plugging would have occurred, however, if the 500°F-environment tests continued. Although no fuel tank deposits are expected in actual operation of the SST, it may be advisable to consider secondary filtration upstream of critical components in the airframe system.

Engine Subsystem

The fuel test results in the engine subsystem were inconclusive because of a variation in the engine pump performance. Comparison of fuel thermal stability based on component per-

Table 2 Program summary

Test series	No. of cycles	Fuel quality: CFR Coker rating	CRC test environment, °F
1	110	350/450	500
2	42	375/475	400
3	55	375/475	500
4	90	425/525	500
5	35	325/425	500

formance, therefore, is in question. The operating characteristics of the engine components, however, are worthy of mention.

Engine pump

The gear pump used in the first two test series contained copper alloy materials and was considered to have added an indeterminable variable in the test results. Bearing wear and parts damage problems were encountered in the vane-type engine pump that was used in the last three test series. These problems may have been caused by the test environment, fuel characteristics, or pump design; but whatever the cause, the result was the formation of the unpredictable quantities of fuel particulate matter and debris that masked the performance of the fuel in downstream components. The significance of the pump data is that the mechanism of pump performance degradation and its effect on the fuel are of considerable importance and bear further investigation.

Filter

The increase in pressure drop across the 40-μ engine filter was usually the first indication of system performance degradation in the test rig. This increase was considered to be due to engine pump performance. One significant finding was that the filter was not successful in filtering out the fuel particulate matter generated in the pump, as evidenced by the deposits in the fuel lines leading to and from the filter. It was noted that as the engine filter progressively clogged, thereby becoming a more efficient filter, the downstream components performance degradation rate decreased.

Heat exchanger

An increase in pressure drop and a decrease in heat-transfer efficiency were evident in the test program. In those tests, where a heat-exchanger performance change occurred, the increase in pressure drop was comparable to the loss in heat-transfer efficiency. This relationship becomes important in heat-exchanger sizing, as shown in Fig. 6, in determining which parameter limits the heat-exchanger life. The relationship was calculated using the SST Fuel System Test Rig engine heat-exchanger specifications. In actual practice, a heat exchanger would probably not be designed based on rate of deposit buildup because of the problem of accurately predicting this parameter over a long duration. A more practical approach is to operate the heat exchanger below the critical temperature of the fuel.

Fuel nozzle

The nozzles revealed an increase in pressure drop in all 500°F environmental tests conducted. In spite of the pump problem, the nozzle performance reflected the fuel thermal stability quality as measured by the ASTM-CFR Coker. In the test series where the engine pump deposit generation was the greatest, the nozzle pressure drop increase was the lowest. A similar occurrence existed with the same fuel in tests conducted using the Esso Heat Transfer Unit (HTU) thermal-stability test device. The explanation given was that the deposit-forming constituents in the fuel had been removed

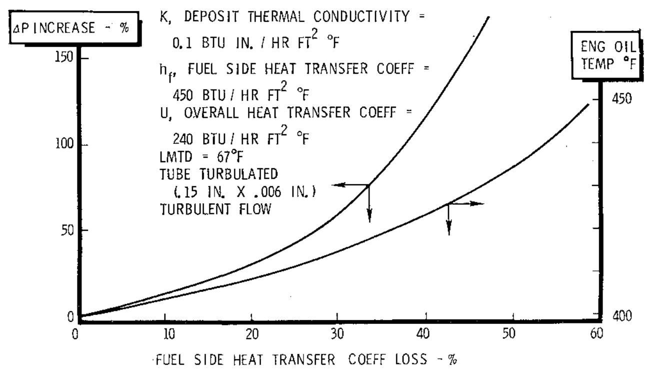


Fig. 6 Effect of h_f loss on engine oil temperature and pressure drop.

and deposited upstream in the system leaving the fuel relatively free of its deposit-forming tendencies.

Fuel Data Correlation Program

The task of establishing whether existing fuel thermal-stability test methods could be calibrated against a simulated SST fuel system was the next step in the SST Fuels Program. This task required an analysis of available fuel data generated by the SST Fuel System Test Rig and five fuel thermal-stability test devices. The results of a quantitative analysis were inclusive because of insufficient data, differences in the test devices, and inconsistencies in the performance of the components in the SST Test Rig.

The qualitative analysis was conducted to determine whether the thermal-stability test devices could rank the fuels in the same order as the SST Fuel System Test Rig. During this analysis, test parameters in addition to those normally used were examined for purposes of ranking of the fuels. It was determined that each device could rank the fuels in the same order as the SST Fuel System Test Rig fuel tanks (Table 3). Because of inconsistencies in the engine pump performance, correlations of the engine pump and all downstream components were considered in question.

Based on the limited data in the Fuel Data Correlation Program, no conclusion could be made recommending a fuel thermal-stability test device that was considered suitable for the SST. It appears that a suitable fuel thermal-stability test device for the SST will require increased accuracy in characterizing fuel characteristics and increased repeatability in the thermal-stability measurement.

Significance of the FAA-SST Fuels Program

The SST fuels investigation has increased the general understanding of the fuels problems in the SST and has given rise to additional research work in this field. Specifically, two points have become apparent as a result of the SST Fuels Program. The first is that if the maintenance costs of the SST are to be maintained on a reasonable level, the generation of deposits in the fuel system must be prevented. The second point is that if the SST will be expected to use present Jet A and Jet A-1 specification fuels, increased accuracy in characterizing as well as increased repeatability of the fuel thermal-stability quality measurement must be provided. Designing an SST fuel system that will basically be free of deposits for its design life, recognizing normal maintenance, requires a full knowledge of the mechanisms of fuel decomposition; but more important is the need for a full knowledge of the fuel thermal-stability quality control techniques that will be used. The fuel thermal-stability measurement precision, for example, must be factored in the equations used to establish the maximum operating temperature of the fuel system. An additional factor must be applied to compensate for the specific fuel environmental conditions such as high-

Table 3 Criteria for ranking fuels with wing tank

Test device	Criteria
Minex	Initial decrease in h_f
HTU	Rapid change in h_f
5-mliter bomb	25% loss in light transmittance
Coker	Code 2 and 12-in. Hg maximum
Research coker	Code 2 and 3-in. Hg max, 200°F reservoir

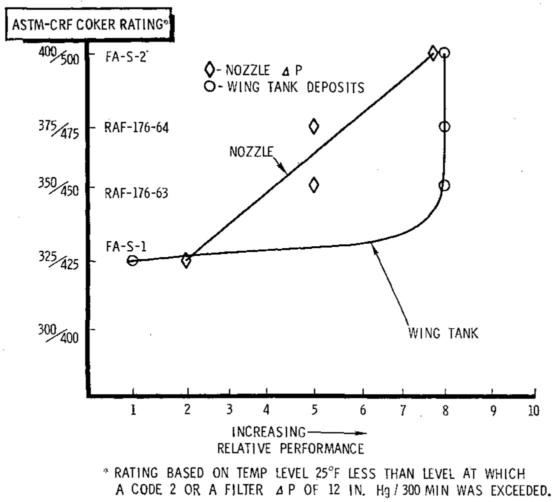


Fig. 7 Comparison of wing tank and nozzle with coker.

temperature tank conditions. In an SST design where a temperature difference of 20°F in the fuel system may mean the addition of thousands of pounds in aircraft weight, the accuracy and precision of the fuel thermal-stability measurement can have a great effect on the economics.

Designing the SST based on fuels with marginal thermal-stability characteristics may impose great penalties on the system. The consequence of using such marginal fuels as measured on the ASTM-CFR Còker is illustrated in Fig. 7 by the great difference in relative performance in the SST Fuel System Test Rig wing tank. As a contrast to this relationship, the relative performance of the fuels in the nozzle is plotted, showing a more linear relationship that suggests the need for fuel thermal-stability characterization based on aircraft components.

The same relative relationships existed for the other fuel thermal-stability test devices involved in the SST Fuels Program. This relationship is not surprising considering the different test conditions that exist, e.g., the wing tank fuel is stagnant, whereas the thermal-stability test devices are flowing systems (except the Phillips 5-mliter bomb). Also, it is noted that these devices were developed to represent engine rather than fuel tank environmental conditions.

It is the author's opinion that some fuels that can meet Jet A fuel thermal-stability requirements are not representative of today's commercial aviation kerosine fuels and should be screened out by a fuel thermal-stability test device. This is especially important if the SST must be qualified to use minimum quality Jet A fuels. It is considered that this screening can be accomplished without significant changes in the availability of Jet A and Jet A-1 for the supersonic transport and will give the aircraft designers greater flexibility.

What Is Being Done?

Presently, several programs are in progress in an attempt to solve the problems associated with the selection and development of small-scale fuel thermal-stability test devices. The Air Force Research and Technology Division is conducting a research program on a large-scale advanced aircraft fuel system simulator concurrent with several developmental programs on existing small-scale thermal-stability devices.

The CRC, under Air Force sponsorship, is conducting a research program to determine the parameters affecting aircraft fuel tank vapor-phase deposits. The program may result in a requirement for small-scale fuel tank vapor-phase thermal-stability test devices. As related to the fuel thermal-stability problem, these programs can provide valuable assistance to the airframe and engine designers to proceed confidently with the development of the SST fuel system.

From the standpoint of the aircraft tank and engine designs, it is very encouraging to know that the reported maximum aircraft tank and engine fuel temperatures are in the 350° to 400°F temperature range. Based on this temperature range and on the fuel tests conducted at the 400°F environment, the use of at least 80% of the currently available aviation kerosine fuels[3] looks very encouraging.

Conclusions

The solutions to the supersonic transport design problems associated with the thermal stability of commercial aviation kerosine lie in the hands of the aircraft and engine designers. Because of the apparent lack of suitable fuel thermal-stability test methods, design problem definition becomes nebulous and the designer must increase design margins. If we are to proceed confidently toward the performance and economic goals that have been established, suitable fuel thermal-stability test methods must be made available during the design phase of the SST. The accomplishment of this major step plus the recent improvements by the aircraft and engine designers in reducing the fuel temperature environment can clear the way to the successful use of commercial aviation kerosine in the U. S. supersonic transport.

References

[1] *1966 Book of ASTM Standards* (American Society for Testing and Materials, Pittsburgh, Pa., January 1966), Pt. 17, pp. 608–629.

[2] Coordinating Research Council Inc., "Anticipated fuel system environment for the supersonic transport," CRC Rept. LD-147 (1965).

[3] Jonke, G. F., "1964 field survey of jet fuel quality," Pratt & Whitney Aircraft Rept. FL-64-22 (December 1964).