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TANKAGE SYSTEMS FOR A METHANE FUELED SUPERSONIC TRANSPORT

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TECHNICAL PAPER proposed for presentation at Meeting on Aircraft Design for 1980 Operations sponsored by the American Institute of Aeronautics and Astronautics
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Abstract

Although liquid methane fuel promises an economic improvement, its cryogenic nature results in on-board storage problems. A lightweight insulation is required (1) to limit heat influx to the liquid methane, and (2) together with a defrosting system to eliminate external ice formation. The problem remains that, should this fuel be loaded in a saturated condition, as the aircraft climbs and pressure is reduced, much fuel will flash off. Either using pressurized tanks or subcooling the fuel will solve this problem. With subcooled fuel a pressurizing gas is required. Low solubility gases (e.g., helium, neon) have low availability and may be used only if completely salvaged. Bladders or stand pipes to reduce contact area may be used with soluble gases (e.g., nitrogen) or condensible (e.g., methane gas) pressurizers. Analytical studies indicate that both the pressurized tank and subcooled fuel approaches, separately or in combination, offer potential solutions to the tankage problem.

Introduction

The trunkline aircraft operator is constantly seeking that airplane that flies faster and farther with greater economy than the airplane that is in current use. The American version of the supersonic transport now in development is intended to provide a 200 percent increase in speed, with no loss in economy compared to current aircraft. This vehicle will utilize essentially the same gasoline/kerosene-type fuels (frequently identified as JP) now used in subsonic craft. One way of improving the payload fraction and the economy of follow-on versions of the supersonic transport is to use a fuel that is superior to JP type fuels in heating value, heat sink capacity, cost and availability, and at the same time is safer and more dense. Although meeting all of these requirements appears unlikely, the studies reported in references 1 and 2 have indicated that liquid methane is a fuel that can meet some of these criteria.

Table I compares the properties of JP and methane fuels. The heating value of liquid methane is 13 percent higher than that of JP and the heat sink capacity is about four times as great. The range of flammability and the spontaneous ignition temperature suggest no increase in in-flight fire hazard.

The prices of both JP and liquid CH_4 are subject to debate, but they appear to be about the same on a cost per unit weight basis. Although not comprehensively examined yet, the availability of methane around the world is expected to be as good as that of JP.

Not all of the methane properties are helpful. Its density is only half that of JP, requiring more tank volume, and its one atmosphere boiling point is 201° R, more than 300° R below ambient on the ground, resulting in a tendency for it to boil away and be lost during flight.

The potential benefits afforded by the use of methane in a Mach 3 SST were examined in reference 2. The airplane configuration used in that study and in the present one is the SCAT 15F design of the NASA Langley Research Center. It is shown in Figure 1 together with its pertinent data. If JP is used as the fuel, only part of the void space in the wing is required for fuel storage. If the lower-density methane is used, most of the available volume in the wing and fuselage is used. Seventy percent of the fuel is in the wing, and this requires use of some very shallow sections. Of the aircraft configurations considered for the SST the SCAT 15F had the largest volume available for fuel storage. Other aircraft configurations might have even less volume so that the vehicle would have to be stretched in some fashion with a consequent weight and drag penalty.

It was estimated in reference 2 that the passenger capacity of a methane fueled aircraft could be increased by 31 percent and the direct operating cost reduced by 25 percent, compared to a JP fueled aircraft. This included the benefit of both methane's higher heating value and its greater cooling capacity. This cooling capacity, it was assumed, allowed more turbine blade cooling than is possible with a JP aircraft and this permitted higher turbine inlet gas temperature which resulted in lighter engines.

These gains are a function of the fuel systems fraction which is the weight of the aircraft fuel system per pound of fuel carried. Figure 2 displays the number of passengers as a function of the fuel systems fractions and reveals that substantial systems weight increases over JP can be accepted without losing all benefit of methane; although, of course, the lighter the system the greater the gain.

It was evident from the study of references 1 and 2 that the CH_4 offered several important advantages to the engine but posed some significant problems in terms of fuel tankage. It is the purpose of this paper to discuss the tankage problems in greater detail than has been previously done and to examine a number of possible solutions to these problems.

The Tankage Problem

The tankage problems, as previously noted, arise basically because of the lower density and the cryogenic nature of CH_4. Several aspects of this problem will be discussed.

Although substantial increases in systems weight can be tolerated, nevertheless any design techniques employed to contain the fuel must not incur too heavy a weight penalty or the potential benefits can be lost. A penalty to all systems is that of the pumps and plumbing to get the fuel from the tanks to the engines. Assuming use of the same techniques as those to be used in the JP SST and excluding insulation, from reference 2, this penalty is equal to 2.09 percent of the fuel weight. In addition to this are the weights of: insulation, boiloff, pressurizer, tank, and unique systems associated with the various storage schemes. These weights will be evaluated except for those which require detailed design for their definition. Since some weights cannot be evaluated within the scope of this paper, the weights presented are used only to show the magnitude of the penalties associated with each method, and no definitive comparison of methods can be made.

The unique problems in designing methane tanks can be described by reference to the external environment history for a typical flight shown in figure 3. One problem results from the difference between the temperature of the air adjacent to the skin of the airplane, which can be as high as the stagnation temperature, and the fuel temperature which is 201° Rankine at one atmosphere. Figure 3(a) shows the aircraft Mach number as a function of time into the flight. It is seen that the great majority of the flight is flown at velocities greater than Mach 1 with the cruise at Mach 3. It is these high velocities that cause the high stagnation temperatures shown in figure 3(b). Temperature differences are greatest at the supersonic cruise condition where the temperature adjacent to the skin can be nearly 1100° R. High thermal gradients also exist at take-off when the skin temperature, even on the coldest winter day in a polar area, will be about 200° R warmer than the fuel.

The other environment problem is the reduction in external pressure as the aircraft climbs. Figure 3(c) presents the aircraft altitude as a function of time into the flight. The climb is seen to be very rapid with cruise altitude being above 70,000 ft. The pressures resulting from the altitudes are shown in figure 3(d). They start at 14.7 psi on the ground and drop to about 0.5 psi at cruise altitude.

Temperature

During pre-take-off ground hold, at an average earth surface temperature, the fuel is about 300° colder than the ambient temperature. This can cause two problems. The wing surface may be cooled below the freezing temperature of water causing ice formation on it. This can be countered by insulation and an electric deicing system.

The second problem, as previously noted, is the heat flow potential into the tank. Insulation is required here to reduce the rate of heat flow in order to prevent excessive fuel evaporation loss. Since the problem of heat potential is accentuated at cruise, protection must be adequate for the entire flight.

In figure 4, from reference 1, the use of insulation to control fuel vaporization is shown. These curves indicate that there is a minimum total weight of insulation plus evaporated fuel. The minimum penalty is 3500 pounds of boiloff from heating utilizing 3500 pounds of insulation. In this example, the physical characteristics of silica aerogel were used. Reference 2 states that insulation weight could be as high as 5300 pounds if practical installation problems force the use of less effective insulations. On the other hand, if new insulations are developed, weights will be even less. Another method, also mentioned in reference 1, is to reduce the insulation to the point where the boiloff rate at cruise is just equal to cruise engine demand. Vapor pumps could then be used to pressurize and pump the vapor to the engines. The total weight penalty, vapor pumps plus insulation, is greatly reduced. The ground hold problem would remain, however. For this discussion, an insulation weight equal to 2.0 percent of the roughly 185,000 pounds of methane and an equal amount of boiloff will be assumed for all cases of boiling fuel. This 2.0 percent insulation fraction will also be used in all nonboiling cases, with but one exception which will be noted.

Pressure Changes

The second category of problem is that associated with the reduction in ambient pressure in going from take-off to cruise altitude. Consider what occurs in an aircraft if the tankage concept is that usually used for ground storage of a cryogenic, an insulated container vented to the surrounding atmosphere. The methane is loaded as a saturated liquid into the aircraft tanks, which are, according to current plans for the JP supersonic transport, integral with the wing and fuselage. Since aircraft wings and thus the majority of the integral tanks can, in general, hold a pressure differential of only 4 to 6 psi, as the aircraft climbs the internal pressure must be reduced thus reducing the boiling temperature. The fuel will then boil off a sufficient amount to reduce its temperature to that of the new boiling point. If the maximum pressure differential is 4 psi, 9.0 percent of the weight of the fuel would be lost. If the pumping system weight, the weight of insulation and the weight of boiloff from both heating and pressure are all added together and figure 2 is entered with the resulting 0.151 systems fraction, it is seen that the passenger gain is only 14 or about a 7 percent gain above the JP SST. Most of the potential gains have been lost.

Possible Tankage Systems

It is necessary, then, to design the tankage systems that will minimize the weight penalties. A number of possible systems are categorized and presented in table II. These systems are divided into two major categories describing the condition of the methane when loaded aboard the aircraft as either a saturated liquid or a subcooled liquid. The subcooled systems are further subdivided according to the type of pressurizing gas or the method of pressurization used.

Saturated Liquid Methane

The first case, under Saturated Liquid Methane, that of venting the vapors overboard, is the system used above to show the magnitude of the problem.

It may be conceived that this evaporated fuel could be reliquefied by refrigeration, but preliminary estimates of the system weights and the power demands associated with the required rates indicate that these penalties would far exceed the penalty incurred in accepting the boiloff itself.

It is also possible that the boiloff could be pumped to and burned in the engines. However, since the greater amount of evaporation is associated with the reduction in pressure due to climb, the aircraft climb path must be so constrained that the boiloff rate does not exceed the engine fuel requirement. The problems associated with pumping and pressurizing this evaporated gas for engine use could be formidable; but at the present time, they have not been fully evaluated.

One method to prevent the evaporation associated with the decreased ambient pressure at altitude is to provide tanks that can hold one or more atmospheres of pressure. This can be done either by strengthening the aircraft structures that contain the fuel or by using nonintegral, high-pressure tanks. Nonintegral tanks have been devised and will be discussed in more detail later.

Subcooled Liquid Methane

This problem of boiloff during climb can also be completely eliminated by loading the fuel subcooled, corresponding to a lower vapor pressure. Then during climb the internal tank pressure can be lowered to the reduced vapor pressure without causing boiloff. This is basically the same situation that exists when loading JP fuel aboard an aircraft. With this method, however, new attention must be paid to the situation that exists at take-off and low altitudes. Here the vapor pressure is lower than atmospheric and a gas is required to fill any voids in order to prevent tank collapse and to pressurize the emptying tanks. For JP fuel, the pressurizing gas is normally air. Occasionally, nitrogen is considered. However, neither gas is suitable for subcooled methane since both oxygen and nitrogen are highly soluble in it, about 10 percent by weight in methane subcooled 25° R (table I). The consequent loss in aircraft performance is great. Relatively insoluble gases include H_2, He and Ne. Hydrogen is questioned on grounds of safety due to its inflammable nature. He and Ne are relatively rare. If, for example, a fleet of fifteen hundred 460,000-pound supersonic transports fly an average of three flights per day and use 24 pounds of helium per trip, then nearly 40 million pounds of helium would be used per year, or an amount about equal to that produced per year at the present time. Thus, if the scarce gases are to be used, the pressurant cannot be allowed to escape. A scheme for using He and retaining it will be outlined.

Another method for making use of soluble or condensable pressurizing gases is to reduce or eliminate the area of gas in contact with the liquid methane. The surface could be covered with floating objects such as a large number of balls or cans. The tank could be full and a stand pipe used for pressurization. Again only a small area is exposed to the pressurizing gas. Or a bladder could be used eliminating all contact. If these methods are used, dry, CO_2 free air, or even warm gaseous methane, could be used for pressurization.

In a NASA-Lewis funded project, the use of bladders to separate soluble gases from cryogenic fluids is being investigated. With movable metal bladders rolling seals must be developed. Plastic bladders must seal well, be low in porosity after numerous cycles, be easy to replace, and they must retain their mechanical properties including strength and flexibility from 163° to 1000° R. All of these demands have not yet been met in any one material. Also, a tank must be clear of any members that could prevent bladders from filling the entire volume; and this requirement would be a restriction on the structural design.

Combination Systems

These methods of handling methane may also be used in combination. In one method (proposed in a NASA Lewis patent disclosure), methane is loaded at its normal boiling point in some tanks and subcooled in others. A stand pipe is used in the subcooled tanks to reduce the area exposed to the pressurizing gas and this allows the use of warm methane gas. This method will also be discussed in more detail.

Selected Tankage Systems

As examples of possible systems for the handling of liquid methane, three are now presented in more detail. These analyses are still far from being sufficient for design purposes. The areas of interest that were beyond the scope of this study differ from system to system; and they will be noted.

High Pressure Tanks

The high pressure tanks of reference 3 illustrate one method for using methane loaded aboard the aircraft as a saturated liquid and avoiding the evaporation loss associated with the ambient pressure reduction during climb. If the tank can hold one atmosphere, climb boiloff loss is eliminated. However, since heat leaks into the tank also cause boiloff or else cause an increase in internal pressure, it may be desirable to have tanks designed to withstand more than one atmosphere pressure. If two atmospheres of pressure rather than one can be contained, this increase in pressure is equivalent to having 17° R of subcooling available to combat heating.

As noted previously, most of the liquid methane is stored in the wings. A typical wing void available for fuel storage is assumed for the tank computations. This is essentially a rectangular prismoid in shape 24" deep × 16" wide × 88" long where the length is in the spanwise direction.

Three types of tanks designed to fit into this space, shown schematically in figure 5, have been studied. They are defined as "modified semimonocoque tanks" composed of a framework of rings and stringers covered by a pressure-tight skin, conventional "membrane tanks" where the principal loads in the skin are tensile, and "filamentary restrained membrane tanks" where the outer skins of either metal or sealed nonmetallic fabric are restrained by wires or threads attached to the opposite skin. These filamentary restrained tanks are called unidirectional if only one pair of opposite surfaces is so supported and bidirectional and tridirectional when two or three pairs of opposite sides, respectively, are interconnected by these filaments.

Titanium alloys such as 6 Al-4V and 5 Al-2 1/2 Sn were considered for the design of metallic tanks with an allowable tensile working stress of 50,000 psi. A minimum sheet metal thickness of 0.010 inch was assumed. The nonmetallic filament tanks were assumed to be made from Nomex, Dacron or Nylon yard with the external surfaces of the tank sealed with an elastomer which remains pliable over the range of service temperatures. These fabric tanks would also require a special protection system to prevent the temperature of the materials from rising to a point such that structural degradation could occur. All of these separate tank configurations, it should be noted, guarantee separation of the insulation from the fuel since the insulation is placed on the tank exterior.

The various tank designs are compared in table III in terms of their volumetric efficiency and the ratio of tank weight to the contained fuel weight ratio (the tank structural fraction). Volumetric efficiency is the ratio of the net internal volume of the tank to the net internal volume of the void space available for fuel storage. The characteristics of the tanks were determined for internal gage pressures of one and two standard atmospheres. All tanks are metallic except the two cases specifically noted.

Consider the wing tanks. The highest volumetric efficiency, 99.5 percent is obtained with the the metallic tridirectional filamentary restrained membrane tanks. The lowest volumetric efficiencies, about 81.5 percent are realized with the conventional membrane tank, the modified semimonocoque tank, the single lobe unidirectional filamentary restrained tank, and the nonmetallic fabric filamentary restrained membrane tank. The volumetric efficiencies for these four tank types are all about the same because the tank external configurations are very similar. For all the configurations, the volumetric efficiency is virtually independent of tank internal pressure. Tank weights increased with tank pressure for all configurations except the conventional membrane type tanks where the stresses were about 50 percent of the maximum allowable at two atmospheres internal pressure. This was due to the minimum gage assumption.

In general, tank structural fractions run from roughly 3 percent at one atmosphere to 4 percent at two atmospheres. Also, tanks with a higher volumetric efficiency tend to have a higher tank structural fractions and these factors may offset one another if void space is limited. The actual trade-off between volumetric efficiency and tank fraction has not been investigated.

The bidirectional filamentary restrained membrane tank will be used as an example of this high pressure tank system. This tank has a relatively high volumetric efficiency, 93 percent. If it is designed for 15 psi internal pressure, it has a tank structural fraction of 2.92 percent. Adding this to the pump and plumbing systems fraction, the 2.00 percent insulation fraction and the 2.00 percent fraction of heating boiloff, a systems fraction of 9.00 percent results. If this tank is designed for 30 psi, the temperatures can rise from the loading temperature of 201° R up to 218° R. This is sufficient heat sink to prevent all boiloff from heat during ground hold and flight with an insulation fraction reduced to 0.67 percent. Thus both the pressure boiloff and the heat boiloff are eliminated. The tank fraction, however, has risen to 3.66 percent, but the systems fraction is reduced to 6.42 percent. Thus, considering the weight penalty and providing that the minimum gages cannot be reduced, tanks designed for two atmospheres pressure are superior to those designed for just one atmosphere. From figure 2, the 6.42 percent total systems fraction gives a passenger increase of 26 percent.

In table III and figure 5, fuselage tanks and their characteristics are presented. These have lower tank structural fractions than the wing tanks.

Certain problems unique to this system and requiring evaluation by examining a specific aircraft in some detail have not been taken into account. These are tank installation weights, plumbing connection weights, tank reliability, inspection, replacement and the effects of volume restrictions. However, if these penalties are not severe, the system certainly offers a promising answer to liquid methane tankage.

No Loss Helium System

In an effort to avoid the weight penalties associated with high-pressure tanks, a technique was devised to use helium-pressurized subcooled methane with special provisions to avoid any loss of helium throughout the flight. Although there is a possibility that helium may eventually be obtained inexpensively from very low yield sources, the approach here is that, as previously noted, helium is a scarce natural resource and must not be wasted. Using the 460,000 pound supersonic transport, calculations of the weight of helium pressurizing gas required versus time into the flight were made for two different cases and are presented in figure 6. A constant helium gas temperature of 200° R, a temperature just slightly higher than that of the subcooled methane, and a 5 percent ullage space are assumed. Initially during ground hold, the pressurizer simply fills the ullage spaces to prevent tank collapse and allow pumping of the fuel. As the plane begins its take-off and early climb, the pressure remains close to one atmosphere and helium is added from a separate high-pressure storage container into the emptying fuel tanks. As the aircraft climbs higher, the ambient pressure falls at a more rapid rate than can be achieved internally by allowing the He aboard to expand into the empty spaces resulting from fuel usage. Thus, if ambient pressure were to be maintained, helium would have to be released.

This case is represented by the dashed curve of figure 6. Here the vapor pressure of the methane is assumed to be negligible (as would be the case if a methane slush could be loaded). Early in the flight 20 pounds of helium gas are required for pressurization. Later in the flight, near the completion of the climb, only 3 pounds of helium are required. Thus, in this case a 17 pound loss of helium would occur.

The actual method used is represented by the solid curve. Here a typical vapor pressure of 2.7 psi is assumed, and no limit is placed on the pressure differential across the tank resulting from the climb. However, the resulting maximum pressure differential across the tank wall is only 5.6 psi which is within the 4-6 psi range that the basic JP type integral tanks can withstand. Thus, no structural weight increase is incurred. No helium is lost during the flight and the helium in the empty tanks can be recovered after landing.

The right hand portion of both curves indicate what occurs if gas temperature remains constant during descent. Here helium would have to be added since the external pressure is constantly increasing. Since, however, this helium would be recovered on landing, there is no loss problem.

This picture, however, was overly simplified since it was based on the assumption of a constant helium temperature. Actually, once a tank empties and no longer contains any low temperature methane, the temperature of the gas will tend to rise rapidly and cause a correspondingly rapid rise in pressure. Even in the nonempty fuel tanks the helium temperature will rise slightly since the external skin temperature rises as the aircraft increases speed. A method for constantly compressing, cooling and re-expanding the helium gas back into the tanks is used to maintain a constant low helium temperature.

The whole system in a very schematic form is shown in figure 7. The helium gas is initially released from its high-pressure bottle into the fuel tank ullage space. As it warms up it is then collected, compressed to reduce heat exchanger size, and passed through the heat exchanger where some of the fuel headed for the engine is boiled thus cooling the helium. The helium is then expanded and reintroduced into the fuel tank in its cooled state. The expansion takes place through a turbine which supplies most of the work for the compressor, thus reducing the amount of work the engines must supply. If the compression ratio is as high as 15, the reduction in specific impulse during cruise would be only 0.4 percent. The rate of cooling required up to let-down is never more than 49 percent of the heat sink available from the heat of vaporization of the fuel required by the engines, or 10 percent of the total heat sink capacity of this fuel.

The solution of the heat problem could prove even more severe at let-down even though the ambient pressure is increasing, and, therefore, an increase in internal tank pressure and thus an increase in gas temperature can be tolerated. The difficulty arises from the fact that in most descent modes the engines are cut back close to idle. The heat flowing into the helium, then, could not be removed by the fuel required for flight, and the pressure of the gas would rise more rapidly than the ambient pressure causing an excessive pressure differential across the tank wall. However, if a powered descent mode is used, such as using thrust reversers, this problem would no longer exist. Even if the low power setting mode is maintained, there is still a solution. Fuel could be sent into the heat exchangers, boiled and dumped. The amount of fuel required is a function of the speed with which the airframe adjacent to the fuel cools down following a reduction in boundary layer temperature. If the aircraft temperature drop is rapid, 0.3 percent of the total fuel weight would meet the heat sink requirements for the let down.

The total weight of helium to be carried aboard the aircraft is 120 pounds and the tank in which it is carried is estimated to weigh 970 pounds, the total weight being about 0.6 percent of the gross fuel weight. The helium is at liquid methane temperature.

Examining the system it is seen that although the structural weight increase due to pressurized tanks has been avoided, other weight penalties have been incurred. In addition to the initial 2.09 percent systems fraction and the 2.0 percent insulation fraction, there is the 0.6 percent helium systems fraction and possibly a 0.3 percent boiloff fraction associated with let down. If, further, it is assumed that the pressure ratio for compressing the gas is actually 15 with an associated loss of 0.4 percent in specific impulse, then a 0.4 percent increase in fuel is required. A conservatively high method of accounting for the effect upon aircraft performance of this increase in fuel weight is to assume it equivalent to 0.4 percent increase in systems fraction. Taking the total of these systems fractions, 5.39 percent, it is seen from figure 2 that a 28 percent gain in passengers results.

Until the weight of the controls for the helium tank and the weights of the ducts, vapor pumps and heat exchangers of the helium system are determined, and until the reliability of the system is studied, no meaningful comparisons can be made with the other example systems. However, it is seen that this method, too, offers a possible solution to the problem of methane tankage.

Combined System

Figure 8 presents a system that uses a combination of saturated liquid methane loaded into high-pressure tanks, and subcooled liquid methane with methane gas pressurization by means of a standpipe. At takeoff the tanks, represented by A, containing the fuel for cruise and descent and the reserve fuel, about 70 percent of the total fuel aboard the aircraft, are completely filled. This fuel is subcooled about 30°, but since there are no voids above the liquid methane, the ambient pressure against the tank walls is supported by the nearly incompressible fuel itself. Thus, a pressurizing gas with all of its problems is not required within these tanks.

In order to control the internal pressure during that portion of the flight in which the ambient pressure is greater than the methane vapor pressure, a standpipe is used with warm methane impinging on the surface of the fluid in the standpipe. Ordinarily in the flat fuel tanks the sloshing of the fuel prevents stratification and the warm methane gas condenses out. However, in the standpipe due to its small area slosh would not be expected to occur to any great extent, and stratification would, therefore, allow the use of the warm gasified fuel.

Other tanks, B, contains all of the climb fuel (about 30 percent of the total) at a temperature of 201° R with a resulting vapor pressure of 14.7 psi. The tanks are strong enough to hold at least the one atmosphere pressure thus eliminating pressure boiloff from this tank. The one atmosphere methane vapor from these tanks is used to pressurize tanks A at low flight altitudes.

At the end of climb, the external pressure is lower than the vapor pressure of the subcooled fuel. The vapor pressure is then sufficient to prevent tank collapse. During cruise the pumps expel the fuel from the subcooled tanks and send it into the high-pressure tanks.

At the end of cruise all fuel remaining is stored in the high-pressure tanks. There is sufficient storage volume in the high-pressure tanks, since the let down fuel plus reserve fuel is less than two-thirds the amount of climb fuel. In order that the vapor pressure in the tank will be no less than one atmosphere upon landing, a method for heating the fuel stored in the high-pressure tanks is included.

This system, then, eliminates any need for an inert pressurizing gas while storing most of the fuel in a subcooled state in integral tanks. Only 30 percent of the fuel requires the penalty of a high-pressure tank. Assuming that the high-pressure tanks are of the bidirectional filamentary restrained membrane type designed for two atmospheres (discussed previously), the tank structural fraction and the insulation fraction for the aircraft are 1.10 percent and 1.60 percent, respectively. Adding these to the 2.09 percent systems fraction results in a total of 4.79 percent, just slightly lower than the helium pressurized system, allowing a 28 percent increase in paylaod.

This combined system has some of the problem areas of both the high-pressure tank system and the subcooled system; namely, the weights associated with the installation of the high-pressure tanks and their reliability, and the controlling of internal tank pressure and pressurizing methane gas in the subcooled sections.

As in the other systems, all of these factors have to be taken into account in evaluating and comparing it. However, here again, is a system that appears capable of making the use of liquid methane advantageous.

Conclusions

From studying the application of methane to supersonic transports, it appears that the use of methane is advantageous from the standpoints of energy per pound, engine and combustor operation, and heat sink for cooling critical parts of the high speed aircraft engines. Its price per pound is at least as low as that of JP fuels. The factors most likely to determine whether it can be used successfully are the problems of weight and systems complexity associated with the liquid methane tankage.

Due to its cryogenic nature, methane is subject to boiloff from heat leaks and from reductions in pressure. Insulation is required to control the heating rate and high-pressure tanks or subcooling can be used to eliminate boiloff. If subcooling is used a pressurizing gas is required. Only the scarce gasses such as helium are relatively insoluble in subcooled methane. If they are used systems are required to conserve them. If a soluble or condensible gas is used the contact between the pressurizing gas and the subcooled methane must be minimized or eliminated. The boiloff or the tankage weights cannot be great or the potential gains of methane will be lost. Further, the systems cannot be so complex that reliability cannot be achieved.

The several alternative approaches that have been examined here involve various degrees of complexity and various weights. No valid weight comparison can be made between one system and another, since some of the factors affecting weight require complete designs for their evaluation. However, these preliminary calculations do indicate a possible increase in passengers of up to 28 percent. Thus a substantial improvement could still be expected even if some increases in system weights should be required. Actually these methods here represent merely the first probings into the problem of liquid methane tankage aboard a supersonic transport. It is to be expected that improvements on these systems or the invention of better systems will occur and actually reduce the weight penalties mentioned here.

It may be concluded then, that although there are no definitive answers, the results of studies made so far indicate that several approaches are feasible. Much research remains to be done, but it appears that the tankage problem will not prevent the use of liquid methane in future aircraft.

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Property	Fuel	
	Methane	JP
Heat of combustion, Btu/lb	21,200	18,750
Heat sink, Btu/lb	1,100	~250
Spontaneous ignition temperature, °R	1,660	940
Lean flammable limit, fuel-air ratio	0.028	0.035
Rich flammable limit, fuel-air ratio	0.095	0.270
Density, lb/ft^3	26	50
Boiling point (1 atm), °R	201	810
Freezing point (1 atm), °R	163	375
Heat of vaporization, Btu/lb	219	120
Liquid specific heat, Btu/lb-°R	0.82	0.47
Liqui Gas solubility percent by weight. Methane subcooled 25° R:		
Nitrogen	~10	0.02
Helium	~0.003	0.00005

Table I. Fuel Properties

Saturated Liquid Methane	Subcooled Liquid Methane
*1. Vent vapors overboard	1. Nonsoluble, noncondensable pressurizers
2. Reliquefy vapors	a. Hydrogen
3. Pump vapors to the engine	b. Neon
4. Pressurized wing	*c. Helium
*5. Pressurized tanks	2. Soluble or condensable pressurizers
	a. Floating balls
	*b. Standpipe
	c. Bladder

*Denotes methods employed in selected example systems

Table II. Summary of Liquid Methane Tankage Systems

Tank Type (see fig. 5)	Tank Pressure = 15 psi Volumetric Efficiency %	Tank Pressure = 15 psi Tank Weight / Fuel Weight	Tank Pressure = 30 psi Volumetric Efficiency %	Tank Pressure = 30 psi Tank Weight / Fuel Weight
Wing Tanks				
Modified semimonocoque	81.7	0.0318	81.7	0.0417
Triple lobe conventional membrane	81.1	0.0279	81.1	0.0279
Single lobe unidirectional filamentary restrained membrane	81.8	0.0241	81.1	0.0256
Double lobe unidirectional filamentary restrained membrane	91.1	0.0312	91.1	0.0341
Bidirectional filamentary restrained membrane	93.0	0.0292	93.0	0.0366
Tridirectional filamentary restrained membrane	99.6	0.0322	99.5	0.0446
Nonmetallic fabric filamentary restrained membrane	81.8	0.0282	87.8	0.0556
Fuselage Tanks				
Modified semimonocoque	99.8	0.0205	99.7	0.0372
Single lobe unidirectional filamentary restrained membrane	79.7	0.0110	79.7	0.0127
Bidirectional filamentary restrained membrane	93.6	0.0162	93.6	0.0250
Nonmetallic fabric filamentary restrained membrane	79.7	0.0258	79.7	0.0509

Table III. Comparison of Various Pressurized Tank Configurations

All tanks are of titanium unless otherwise noted

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Take off gross weight, lb	460,000
Range, nautical miles	3500
Engine	Afterburning turbojet
Engine turbine inlet temperature, °R	
JP	2660
Methane	3260

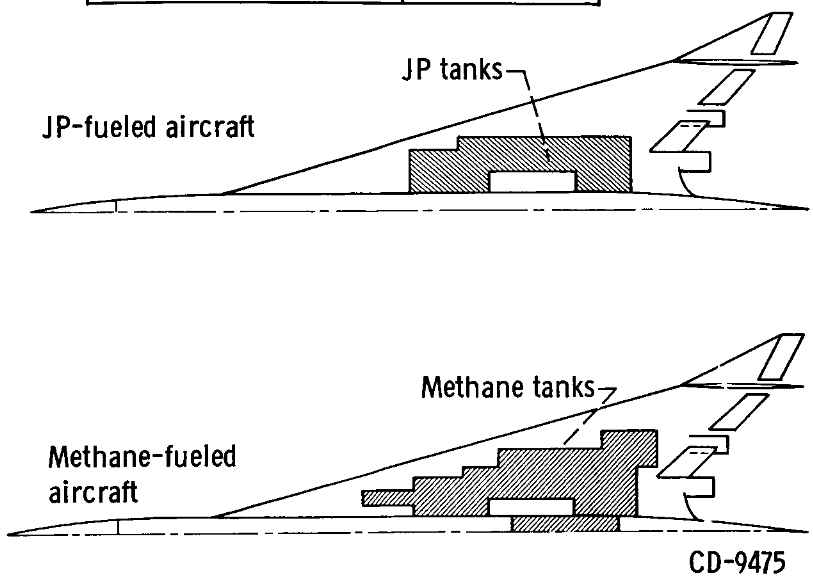

Figure 1. - Aircraft.

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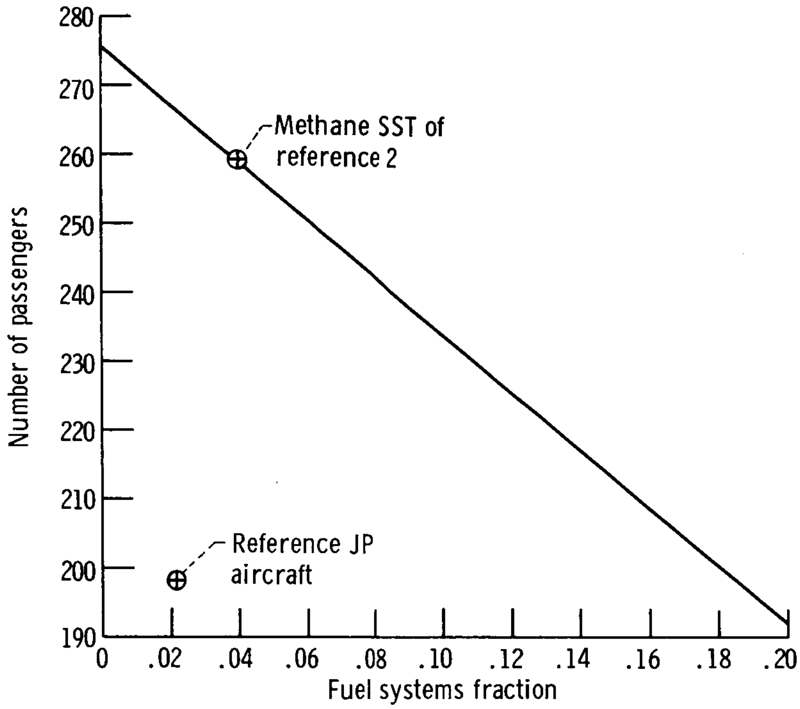
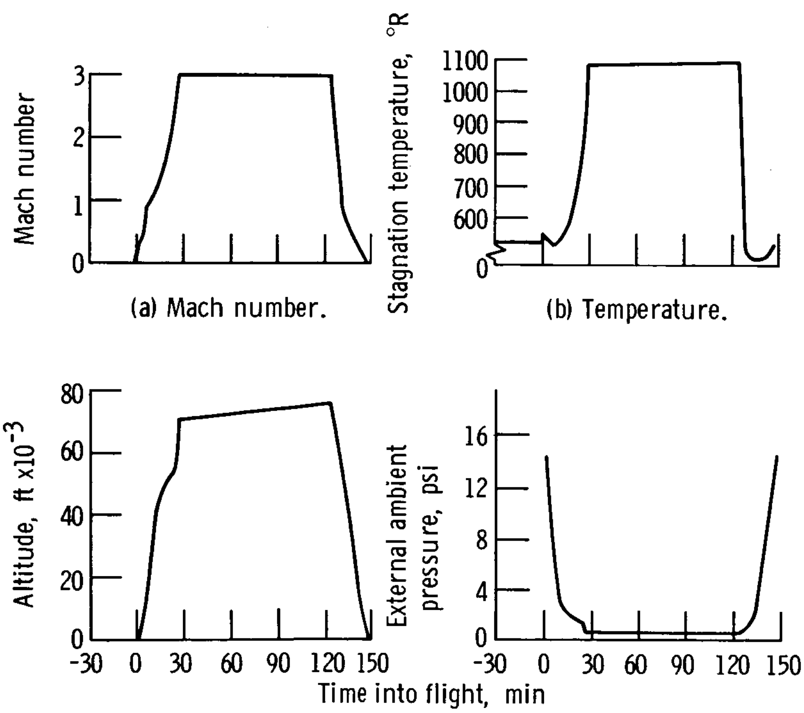


Figure 2. - Effect of fuel system weight on airplane payload.



(a) Mach number.

(b) Temperature.

(c) Altitude.

(d) Pressure.

Figure 3. - Airplane environment.

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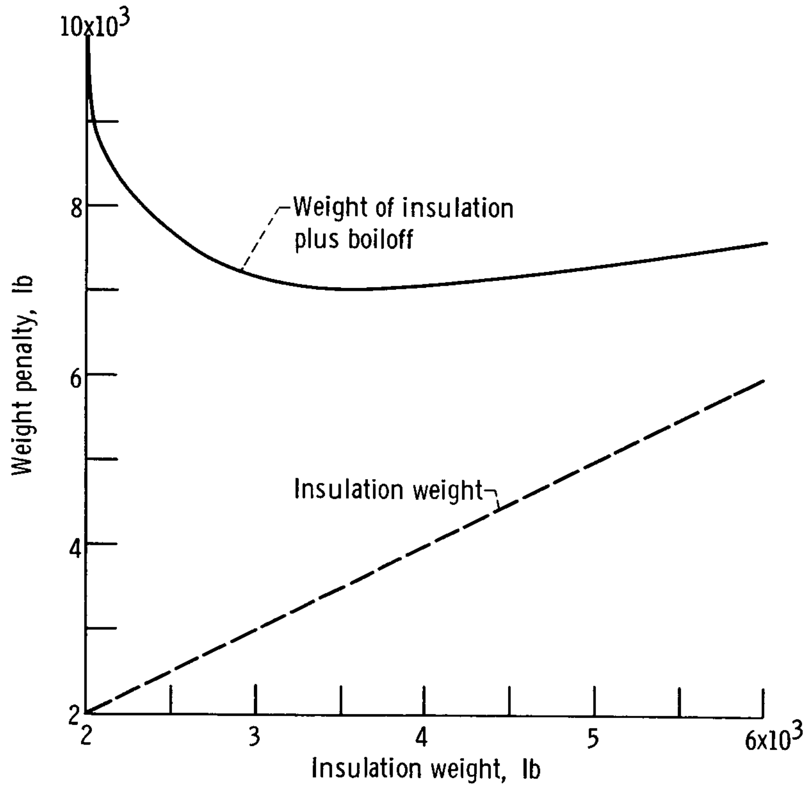

Figure 4. - Fuel insulation and boiloff due to heating.

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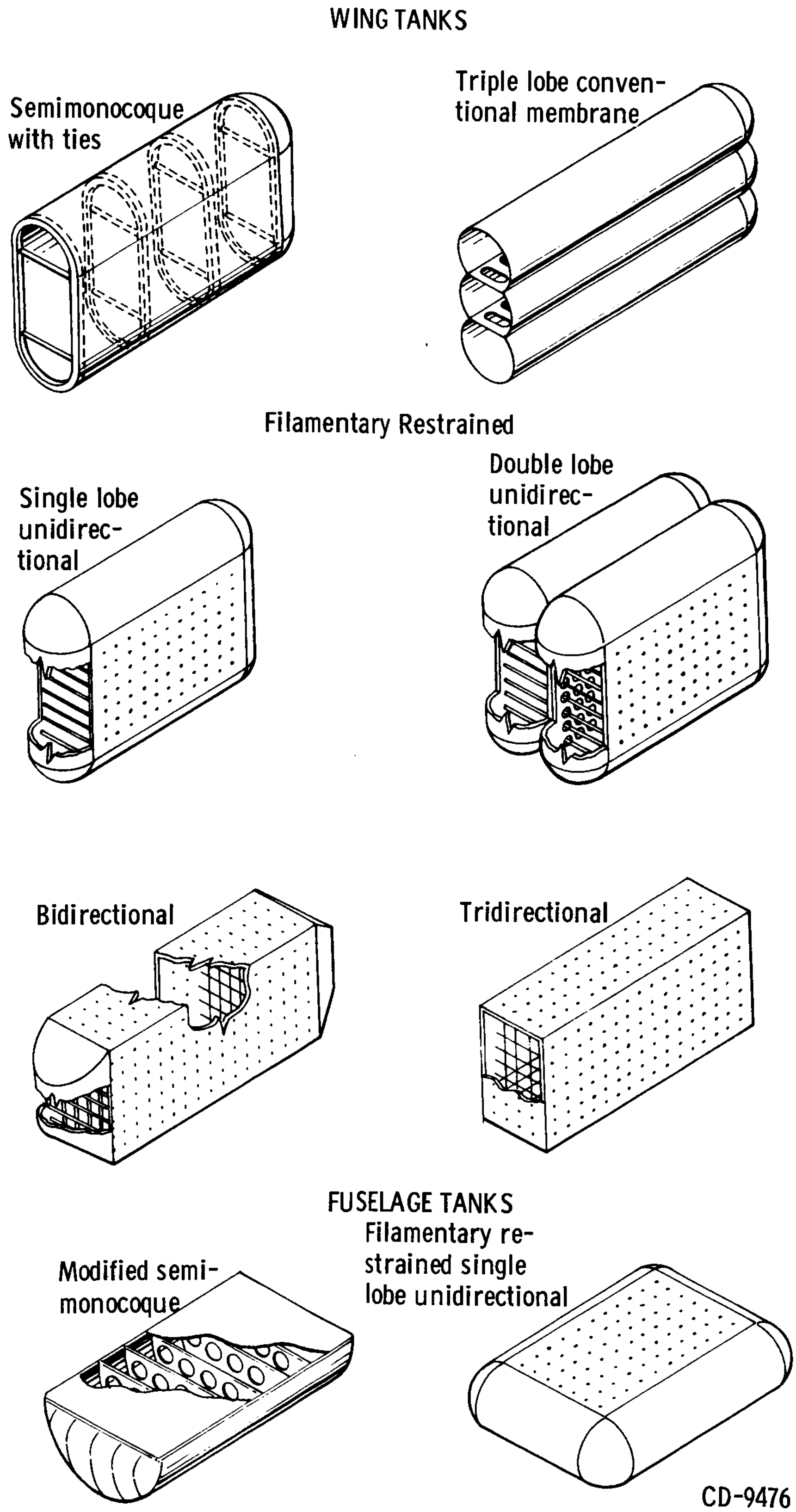

Figure 5. - Pressurized wing tank and fuselage tank configurations.

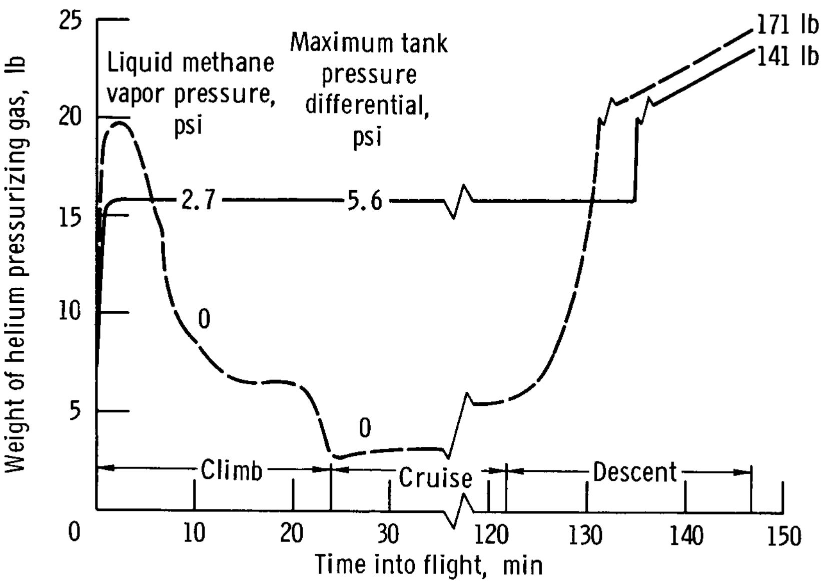

Figure 6. - Weight of 200° R helium pressurizing gas required in fuel tanks as a function of time into the flight.

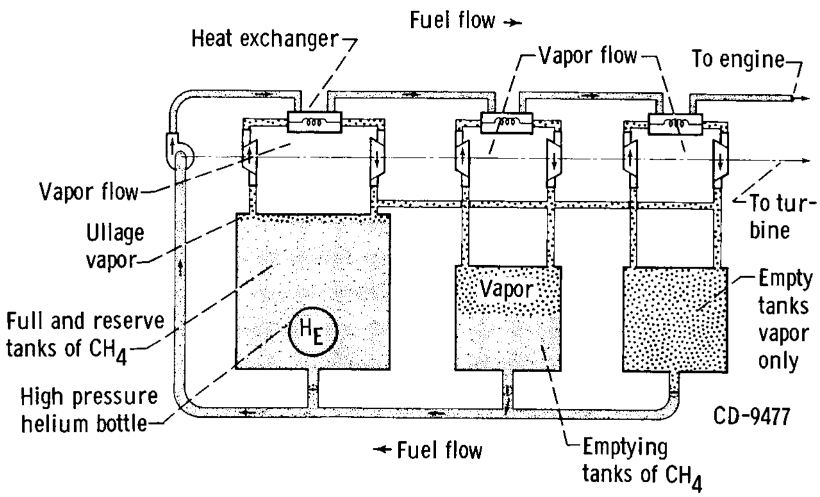

Figure 7. - No-loss helium pressurized system.

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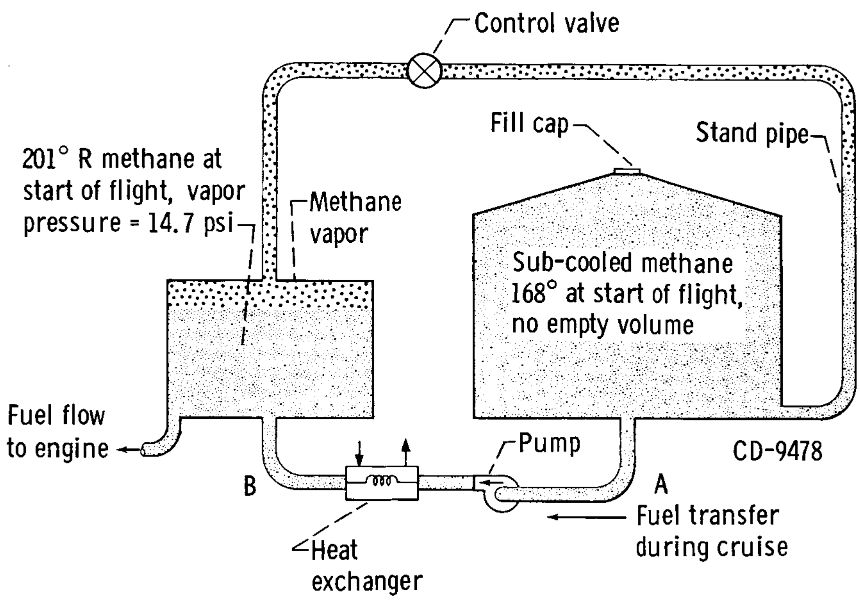

Figure 8. - Combined saturated-subcooled liquid methane tankage system.