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Cleveland, Ohio

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ABSTRACT

The use of liquid-methane fuel promises economic improvement, but its cryogenic nature causes on-board storage problems. Should the fuel be loaded in a saturated condition, much fuel will flash off due to pressure reductions during climb. Pressurized tanks or subcooled fuel will solve this problem. Subcooled fuels require a pressurizing gas. Low solubility gases have low availability and must be salvaged. Bladders or stand-pipes to reduce the contact area may be used with soluble or condensible pressurizers. Analytical studies indicate that these methods, when used separately or in combination, offer potential solutions to the tankage problem.

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TANKAGE SYSTEMS FOR A METHANE-FUELED SUPERSONIC TRANSPORT*

by Joseph D. Eisenberg and Rene E. Chambellan

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SUMMARY

Because liquid methane has a greater heating value and heat-sink capacity than gasoline-kerosene fuel (JP), use of liquid-methane fuel in the supersonic transport promises economic improvements. However, the cryogenic nature of liquid methane results in aircraft fuel tankage problems. At all flight conditions a lightweight insulation is required to limit the flow of heat into the methane. On the ground and during subsonic flight, a defrosting system, in addition to the insulation, is needed to avoid external ice formation.

A major problem exists if the fuel is loaded in a saturated condition. During climb, much fuel will evaporate as the tank pressure decreases with increasing altitude. 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 and neon) are scarce and should be used only if they are salvaged. Bladders or stand-pipes to reduce contact area may be used with soluble gas pressurizers (e. g., nitrogen) or condensible pressurizers (e. g., methane gas).

Analytical studies have been made of three example systems: (1) saturated methane loaded into nonintegral high-pressure tanks, (2) subcooled methane pressurized by a no-loss helium system, and (3) a combination of saturated liquid methane loaded into high-pressure tanks and subcooled liquid methane with methane gas pressurization by means of a stand pipe.

No definitive weight comparisons were made among the various systems because this would require detailed design studies. However, these preliminary calculations indicate that a tankage system can be devised that allows most of the potential gain expected from the use of methane fuel. A gain in the number of passengers of up to 28 percent over that of an aircraft using JP fuel appears possible. More research is necessary, but it appears that there are no fundamental barriers that prevent solution of the tankage problem.

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*Presented at AIAA meeting on Aircraft Design for 1980 Operations, Washington, D. C., Feb. 12-14, 1968.

INTRODUCTION

The trunkline aircraft companies are constantly seeking the 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 with current aircraft. This vehicle will utilize essentially the same gasoline-kerosene fuels (frequently identified as JP) now used in subsonic craft. One way of improving the payload fraction and the economy of future versions of the supersonic transport is to use a fuel that is superior to JP fuels in heating value, heat-sink capacity, cost, and availability, and at the same time is safer and more dense. Although meeting all these requirements appears unlikely, the studies reported in references 1 and 2 have indicated that liquid-methane fuel 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 inflight fire hazard.

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

TABLE I. - FUEL PROPERTIES

Property	English Units		International Units	
	Methane	JP	Methane	JP
Heat of combustion	21 200 Btu/lb	18 750 Btu/lb	49 350 J/g	43 647 J/g
Heat sink	1100 Btu/lb	250 Btu/lb	2560 J/g	582 J/g
Spontaneous ignition temperature	1660° R	940° R	922° K	522° K
Lean flammable limit, fuel-air ratio	0.028	0.035	0.028	0.035
Rich flammable limit, fuel-air ratio	0.095	0.270	0.095	0.270
Density	26 lb/ft^3	50 lb/ft^3	416 kg/m^3	801 kg/m^3
Boiling point (1 atm (0.1 MN/m^2))	201° R	810° R	112° K	450° K
Freezing point (1 atm (0.1 MN/m^2))	163° R	375° R	91° K	208° K
Heat of vaporization	219 Btu/lb	120 Btu/lb	511 J/g	281 J/g
Liquid specific heat	0.82 Btu/(lb)($^\circ$R)	0.47 Btu/(lb)($^\circ$R)	3.44 J/(g)($^\circ$K)	1.97 J/(g)($^\circ$K)
Gas solubility percent by weight in methane subcooled 25° R (14° K):				
Nitrogen	~10	0.02	~10	0.02
Helium	~0.003	0.00005	~0.003	0.00005

Not all methane properties are favorable. Its density is only half that of JP, which requires more tank volume, and its 1-atmosphere (100-kN/m^2) boiling point is 201° R (112° K), which is more than 300 R$^\circ$ (167 K$^\circ$) below ambient temperature on the ground. These properties result in a tendency for it to boil away 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, which was designed by the NASA Langley Research Center. It is shown in figure 1 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 lower density methane is used, most of the available volume in the wing and fuselage must be used. Seventy percent of the fuel is in the wing; this requires the 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 less volume and would have to be stretched in some fashion with a consequent weight and drag penalty.

Takeoff gross weight, lb (kg)	460 000 (208 652
Range, n mi (km)	3500 (6482)
Engine	Afterburning turbojet
Engine turbine inlet temperature	
JP, °R (°K)	2660 (1478)
Methane, °R (°K)	3260 (1811)

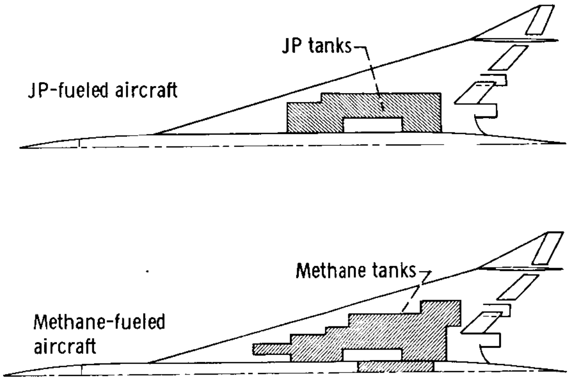


Figure 1. - Aircraft.

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

These gains are a function of the fuel-systems fraction which is the weight of the aircraft fuel system per unit weight of fuel carried. Figure 2 displays the number of passengers as a function of the fuel-systems fraction 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.

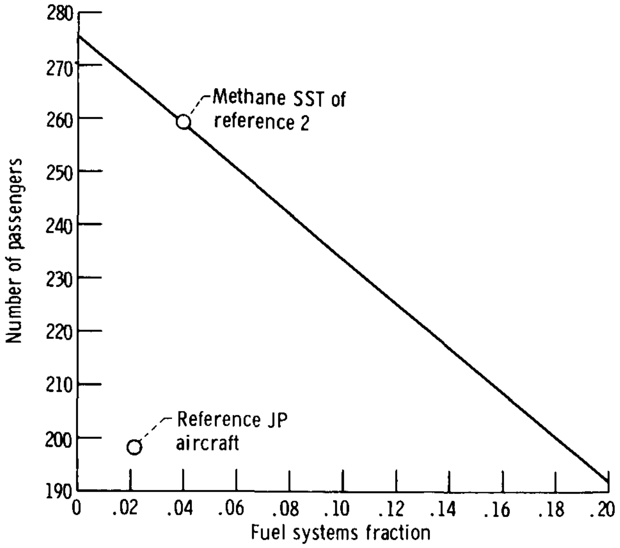


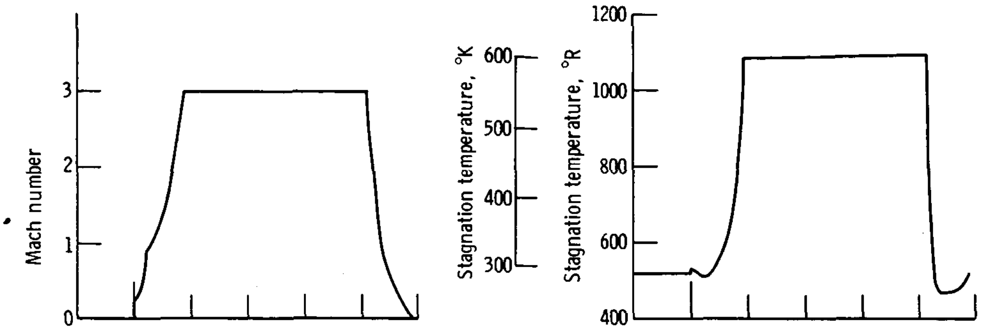
Figure 2. - Effect of fuel system weight on airplane payload.

It was evident from the study of references 1 and 2 that the methane offered several important advantages to the engine, but that it 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.

TANKAGE PROBLEM

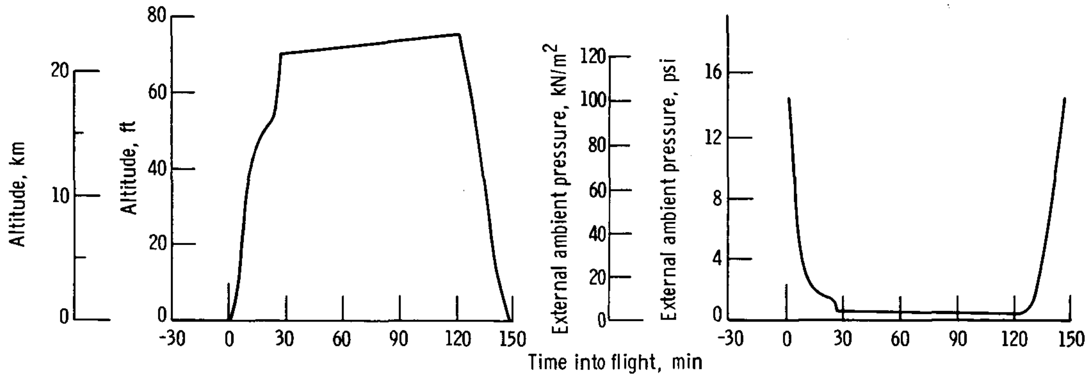
An initial uniform weight penalty is imposed on all the methane fuel systems to be discussed because of the need for pumps and plumbing which transport the fuel from the tanks to the engines. If the same fuel systems as presently planned for the JP SST are used and if insulation weights are excluded from the calculation, this penalty is equal to 2.09 percent of the fuel weight (ref. 2). In addition to this penalty, the weights of insulation, boiloff, pressurizing gas, tank, and unique systems associated with the various storage schemes must be evaluated. Preliminary estimates of these weights will be given for several storage schemes. However, the detailed design studies necessary to completely define each system are beyond the scope of this paper.

The unique problems in designing methane tanks can be described by reference to the external environmental history for a typical flight (fig. 3). One problem results



(a) Mach number.

(b) Temperature.



(c) Altitude.

(d) Pressure.

Figure 3. - Airplane environment.

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° R (112° K) at 1 atmosphere (100 kN/m^2). Figure 3(a) shows the Mach number as a function of time into the flight. The great majority of the flight is flown at velocities greater than Mach 1 with the cruise speed 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 when the temperature adjacent to the skin can be nearly 1100° R (611° K). High thermal gradients also exist at takeoff when the skin temperature, even at the coldest earth-surface temperature in a polar area, will be about 200 R° (111 K°) warmer than the fuel.

The other environmental problem is the reduction in external pressure as the aircraft climbs. Figure 3(c) presents the aircraft altitude as a function of time into flight. The climb is very rapid with cruise altitude being above 70 000 feet (21 336 m). The pressures resulting from the altitudes are shown in figure 3(d). They start at 14.7 psi (101.4 kN/m^2) on the ground and drop to about 0.5 psi (3.4 kN/m^2) at cruise altitude.

TEMPERATURE

During pretakeoff ground hold at an average earth-surface temperature, the fuel is about 300 R° (167 K°) colder than the ambient temperature. This can cause two problems. The wing surface may be cooled below the freezing temperature of water which would cause 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 inflow to prevent excessive fuel evaporation. Because the problem of heat potential is accentuated during cruise, insulation must be adequate for the entire flight.

In figure 4 (from ref. 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 (1588 kg) of boiloff from heating when 3500 pounds (1588 kg) of insulation are used. In this example, the physical characteristics of silica aerogel were used. Reference 2 states that insulation weight could be as high as 5300 pounds (2404 kg) if practical installation problems force the use of less effective insulations. On the other hand, if new, better insulation materials are developed, weights may be 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 (83 916 kg) 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 one exception which will be noted later.

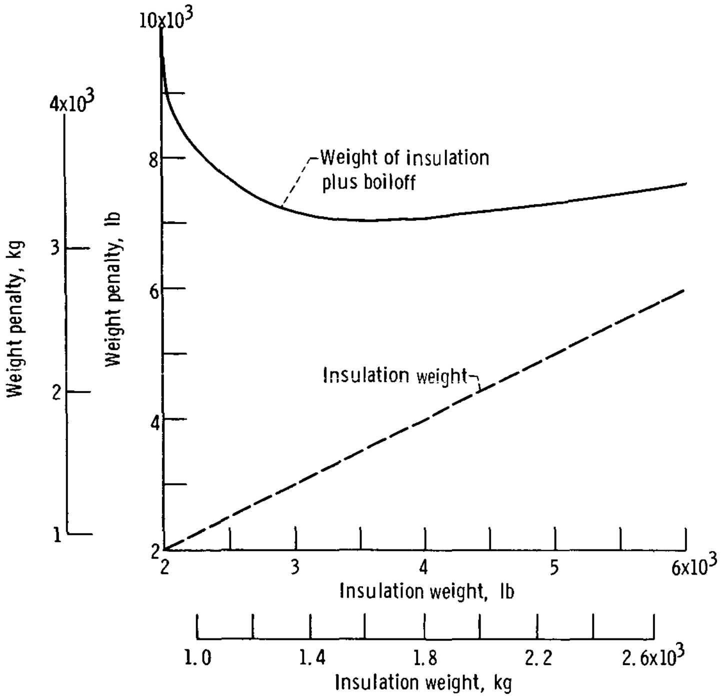


Figure 4. - Fuel insulation and boiloff due to heating.

PRESSURE CHANGES

The second category of problems is that associated with the reduction in ambient pressure from takeoff 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. Because aircraft wings and thus the majority of the integral tanks can, in general, hold a pressure differential of only 4 to 6 psi (27.6 to 41.4 kN/m^2), the internal pressure must be reduced as the aircraft climbs, thus reducing the boiling temperature of methane. 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, 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 as follows:

Saturated liquid methane:
   *(1) Vent vapors overboard
   (2) Reliquefy vapors
   (3) Pump vapors to the engine
   (4) Pressurized wing
   *(5) Pressurized tanks

Subcooled liquid methane:
   (1) Nonsoluble, noncondensable pressurants
      (a) Hydrogen
      (b) Neon
      *(c) Helium
   (2) Soluble or condensable pressurants
      (a) Floating balls
      *(b) Stand pipe
      (c) Bladder

(Asterisks denote methods employed in selected example systems.) 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, that of venting the vapors, is the system just used to show the magnitude of the problem. It may be conceived that 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 that penalty incurred in accepting the boiloff itself.

It is also possible that the boiloff could be pumped to and burned in the engines. However, because 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 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 in the section Selected Tankage Systems.

Subcooled Liquid Methane

The problem of boiloff during climb also can be completely eliminated by loading the fuel in a subcooled condition, corresponding to a lower vapor pressure. The internal tank pressure can then be lowered during climb 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, attention must be given to the situation that exists at takoff and low altitudes. Here, the vapor pressure is lower than atmospheric pressure and a gas is required to fill any voids and to pressurize the empty tanks in order to prevent the tank from collapsing. For JP fuel, the pressurizing gas is normally air. In some aircraft tank designs nitrogen is considered. However, neither gas is suitable for subcooled methane because both oxygen and nitrogen are highly soluble in it, about 10 percent by weight in methane which has been subcooled 25° R (14° K) (table I). The consequent loss in aircraft performance is great. Relatively insoluble gases include hydrogen, helium, and neon. The use of hydrogen is unlikely because it is highly flammable. Helium and neon are relatively rare. If, for example, a fleet of fifteen hundred 460 000-pound (208 652-kg) supersonic transports fly an average of three flights per day and use 24 pounds (11 kg) of helium per trip, nearly 40 million pounds (18×10^{6} kg) 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 pressurizer cannot be allowed to escape. A scheme for using helium 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 balls or cans. The tank could be full and a standpipe could be used for pressurization. Again only a small area is exposed to the pressurizing gas. A bladder could be used to eliminate all pressurizer contact with the fuel. If these methods are used, air that is free of water and carbon dioxide 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 be able to retain their mechanical properties, including strength and flexibility, from 163° to 1000° R (91° to 556° K). All 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; 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 standpipe is used in the subcooled tanks to reduce the area exposed to the pressurizing gas. This allows the use of warm methane gas as a pressurizer. This method will also be explained in more detail in the discussion of selected tankage systems that follows.

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 complete designs. 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 1 atmosphere (100 kN/m^2) of pressure, climb boiloff loss is eliminated. However, because 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 1 atmosphere (100 kN/m^2) pressure. If 2 atmospheres (200 kN/m^2) of pressure rather than 1 can be contained, this increase in pressure is equivalent to having 17° R (9° K) 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 inches deep by 16 inches wide by 88 inches long (0.61 m deep by 0.41 m wide by 2.24 m long) where the length is in the spanwise direction.

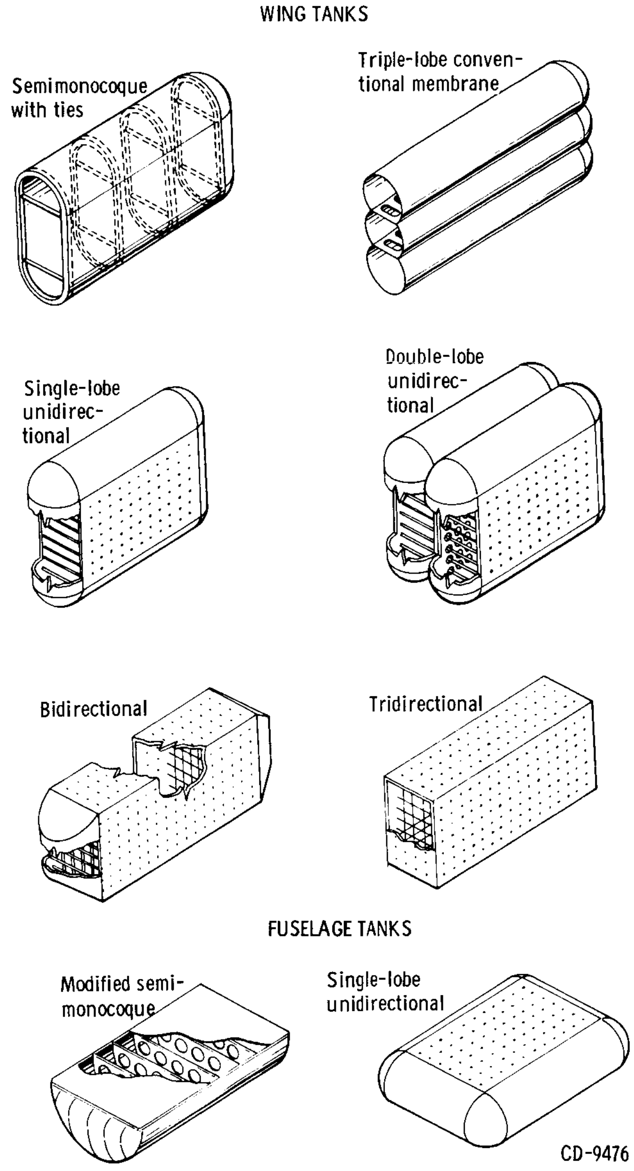


Figure 5. - Pressurized wing tank and fuselage tank configurations.

Three types of tanks designed to fit into this space have been studied (fig. 5). These tanks are defined as the conventional membrane tanks, where the principal loads in the skin are tensile; the modified semimonocoque tanks, composed of a framework of rings and stringers covered by a pressure-tight skin; 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 undirectional 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 titanium-6 aluminum-4 vanadium and titanium-5 aluminum-$2\frac{1}{2}$ tin were considered for the design of metallic tanks with an allowable tensile working stress of 50 000 psi (345×10^3 kN/m^2). A minimum sheet metal thickness of 0.010 inch (0.0254 cm) was assumed. The nonmetallic filament tanks were assumed to be made from Nomex, Dacron or nylon yarn 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 these separate tank configurations, it should be noted, guarantee separation of the insulation from the fuel because the insulation is placed on the tank exterior.

The various tank designs are compared in table II in terms of their volumetric efficiency and the ratio of tank weight to the contained-fuel weight (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 1 and 2 standard atmospheres (100 and 200 kN/m^2). 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 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 2 atmospheres (200 kN/m^2) internal pressure. This was due to the minimum gage assumption.

In general, tank structural fractions run from about 3 percent at 1 atmosphere (100 kN/m^2) to 4 percent at 2 atmospheres (200 kN/m^2). Also, tanks with the higher volumetric efficiency tend to have the higher tank structural fractions, and these factors may offset each other if the void space is limited. The actual trade-off between volumetric efficiency and tank structural 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 an internal pressure of 15 psi (103 kN/m^2), it has a tank structural fraction of 2.92 percent. Adding this to the 2.09-percent 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

TABLE II. - COMPARISON OF VARIOUS PRESSURIZED TANK CONFIGURATIONS

[All tanks are of titanium unless otherwise noted.]

Type of tank[a]	Tank pressure, psi (kN/m^2)			
	15 (103)		30 (207)	
	Volumetric efficiency, percent	Tank weight to fuel weight ratio	Volumetric efficiency, percent	Tank weight to fuel weight ratio
Wing tanks				
Modified semimonocoque	81.8	0.0241	81.1	0.0256
Triple lobe conventional membrane	81.1	.0279	81.1	.0279
Single lobe unidirectional filamentary restrained membrane	81.8	.0241	81.1	.0256
Double lobe unidirectional filamentary restrained membrane	91.1	.0312	91.1	.0341
Bidirectional filamentary restrained membrane	93.0	.0292	93.0	.0366
Tridirectional filamentary restrained membrane	99.6	.0322	99.5	.0446
Nonmetallic fabric filamentary restrained membrane	81.1	.0282	81.8	.0556
Fuselage tanks				
Modified semimonocoque	99.8	0.0205	99.7	0.0372
Single lobe unidirectional filamentary restrained membrane	79.7	.0110	79.7	.0127
Bidirectional filamentary restrained membrane	93.6	.0162	93.6	.0250
Nonmetallic fabric filamentary restrained membrane	79.7	.0258	79.7	.0509

[a] See fig. 5.

designed for 30 psi (207 kN/m^2), the temperatures can rise from the loading temperature of 201° to 218° R (112° to 121° K). 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 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 2 atmospheres (200 kN/m^2) pressure are superior to those designed for just 1 atmosphere (100 kN/m^2). From figure 2, the 6.42 total systems fraction gives a passenger increase of 26 percent.

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

Certain problems unique to this system that require the detailed evaluation of a specific aircraft have not been taken into account. These are tank installation weights, plumbing connection weights, tank reliability, inspection, replacement, and effects of volume restrictions. However, if these penalties are not severe, the system is certainly a promising tankage system for liquid-methane.

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 scarce and must not be wasted.

Using the 460 000-pound (208 652-kg) supersonic transport, calculations of the weight of helium pressurizing gas required as a function of time into the flight were made for two different cases and are presented in figure 6. A constant helium gas temperature of 200° R (111° K), which is slightly higher than that of the subcooled methane and a 5-percent ullage space are assumed. During ground hold, the pressurant simply

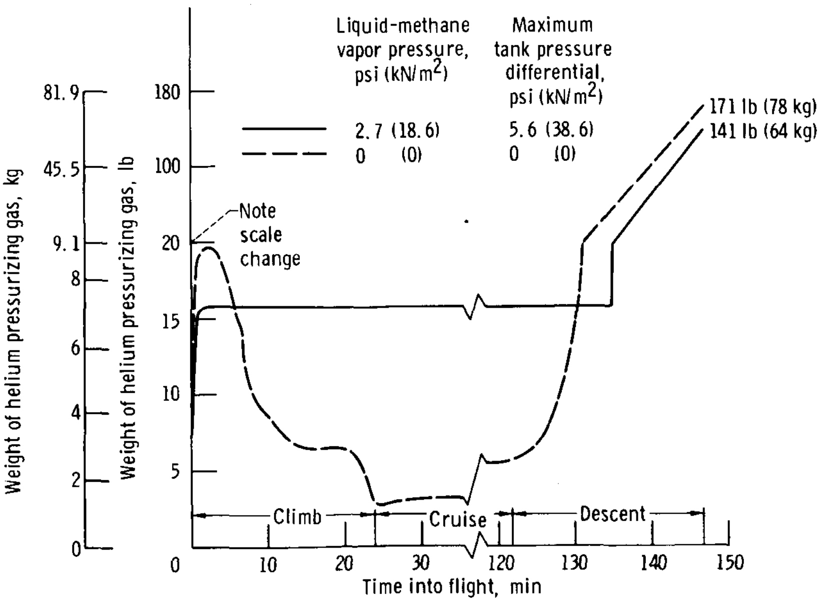


Figure 6. - Weight of 200° R helium pressurizing gas required in fuel tanks as function of time into flight.

fills the ullage spaces to prevent tank collapse and to allow the fuel to be pumped. As the plane begins its takeoff and early climb, the pressure remains close to 1 atmosphere (100 kN/m^2) 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 helium 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 in 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 (9 kg) of helium gas are required for pressurization. Later in the flight, near the completion of climb, only 3 pounds (1 kg) of helium are required. Thus in this case, a 17-pound (8-kg) loss of helium would occur.

The actual method used is represented by the solid curve in figure 6. A typical vapor pressure of 2.7 psi (18.6 kN/m^2) 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 (38.6 kN/m^2) which is within the 4 to 6 psi (27.6 to 41.4 kN/m^2) range that the basic JP 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 portions of both curves indicate what occurs if gas temperature remains constant during descent. Helium would have to be added because the external pressure is constantly increasing. However, because this helium would be recovered on landing, there is no loss problem.

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

The complete system is shown in figure 7. The helium gas is initially released from its high-pressure tank into the fuel-tank ullage space. As it warms up, it is collected, compressed to reduce heat exchanger size, and passed through the heat exchanger where it is cooled by boiling some of the fuel headed for the engines. The helium is then expanded and reintroduced into the fuel tank in this 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

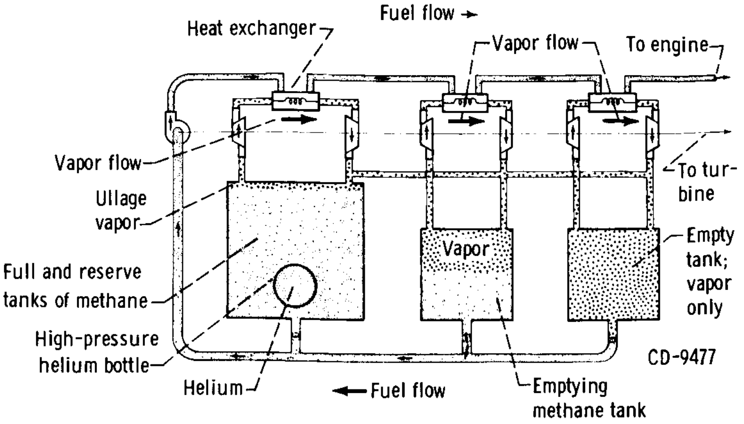


Figure 7. - No-loss helium pressurized system.

rate of cooling required up to descent 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 as the let-down begins even though the ambient pressure is increasing; therefore, an increase in the internal tank pressure, and thus an increase in gas temperature, can be tolerated. The difficulty arises because 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 (54 kg) and the tank in which it is carried is estimated to weigh 970 pounds (440 kg), the total weight being about 0.6 percent of the gross fuel weight. The helium is at liquid methane temperature.

An examination of the system shows 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 it is further 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 of this increase in fuel weight on aircraft performance is to assume that it is equivalent to a 0.4-percent increase in systems fraction. Taking the total of these systems fractions and using figure 2 shows that a 28-percent gain in the number of 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 containing the fuel for cruise and descent and the reserve fuel, about 70 percent of the total fuel aboard the aircraft, are completely filled so that absolutely no void spaces exist. This fuel is subcooled about 30 R^{O} (54 K^{O}), but because 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 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

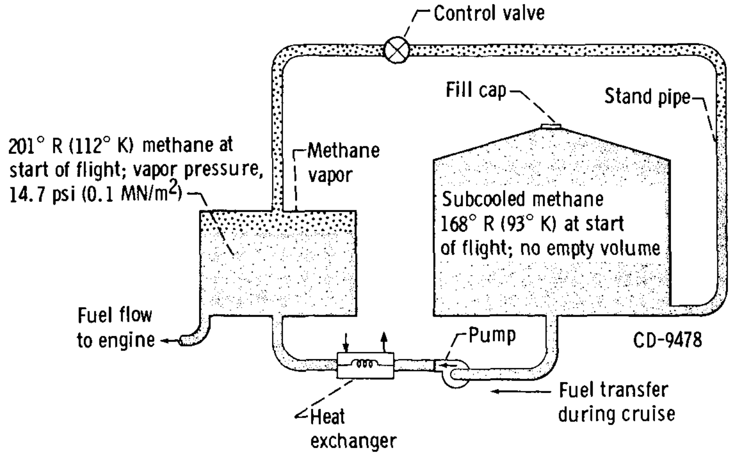


Figure 8. - Combined saturated-subcooled liquid-methane tankage system.

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, because the area in the standpipe is small relative to its depth, slosh would not be expected to occur to any great extent, and stratification would, therefore, allow the use of the warm gaseous fuel.

A second tank contains all the climb fuel (about 30 percent of the total) at a temperature of 201° R (112° K) with a resulting vapor pressure of 14.7 psi (100 kN/m^2). The tank is strong enough to hold at least the 1-atmosphere (100 kN/m^2) pressure thus eliminating pressure boiloff from this tank. The 1-atmosphere (100 kN/m^2) methane vapor from this tank is used to pressurize the first tank 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 tank, because the letdown 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 1 atmosphere (100 kN/m^2) on landing, a method for heating the fuel stored in the high-pressure tank 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 tank is of the bidirectional filamentary restrained membrane type designed for 2 atmospheres (200 kN/m^2) (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 2.8-percent increase in payload.

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 control of internal tank pressure and methane-gas pressurizer in the subcooled sections.

As in the other systems, all 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.

CONCLUDING REMARKS

From studying the application of methane to supersonic transports, it appears that the use of methane is advantageous from the standpoints of energy per mass unit weight, engine and combustor operation, and heat sink for cooling critical parts of the high-speed aircraft engines. Its cost 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.

The major problem to be overcome is that of fuel boiloff due to pressure reductions during climb. Several alternative approaches have been examined that involve various degrees of complexity and various weight penalties. These systems are high-pressure, nonintegral tanks used with saturated fuel; helium pressurization with subcooled fuel with the helium being salvaged; and a combination system utilizing subcooled methane pressurized via a standpipe by methane gas from a saturated methane tank. Utilizing these methods, passenger increases of between 26 and 28 percent over that of the JP aircraft seem possible with methane. Detailed design studies will be necessary to confirm these initial weight estimates and to examine such important practical factors as reliability, maintainability, inspection, and control requirements.

It may be concluded, then, that although a statement cannot be made, as yet, as to which system is the best answer to the problem of methane tankage, the results of studies made so far indicate that several approaches appear feasible and that these methods allow a passenger increase of up to 28 percent. Much research remains to be done, but it appears that the tankage problem will not prevent the gainful use of liquid methane in future aircraft.

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