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THE BOILOFF PROBLEM WITH METHANE FUEL IN SUPERSONIC AIRCRAFT

by Richard J. Weber

Lewis Research Center

Cleveland, Ohio

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ABSTRACT

The benefits of employing methane fuel in supersonic aircraft are lessened by the tendency of the cryogenic fuel to boil away in flight. Boiloff due to ambient pressure reduction during climb appears to be the most difficult to avoid. Subcooling the fuel and using a soluble pressurant such as air or nitrogen is evaluated. Another solution is zero-ullage storage. Alternatively, it is suggested that the boiloff penalties with nonsubcooled fuel may be acceptable. In the study airplane gross weight is allowed to vary as required to yield the desired range and payload.

THE BOILOFF PROBLEM WITH METHANE FUEL IN SUPERSONIC AIRCRAFT

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SUMMARY

The benefits of substituting methane fuel for kerosene in supersonic aircraft are lessened by the tendency of the cryogenic fuel to boil away in flight. Boiloff due to ambient pressure reduction during climb appears to be the major problem. This type of boiloff can be eliminated by the use of subcooled fuel; however, the tank must then be pressurized at low altitudes to counteract the outside ambient pressure. Most gases are soluble in subcooled methane and so have been considered unsuitable as pressurants in previous studies.

By allowing the gross weight of the airplane to increase, it is suggested that soluble gases (such as ambient air) can be employed with possibly acceptable penalty in direct operating cost (5 percent). In fact, if the air is not allowed into the tank until after takeoff, the penalty is nearly nil; the corresponding need for a pressurant prior to liftoff can be avoided by completely filling the tank with the incompressible liquid fuel. (The cited cost penalties are relative to a typical penalty of 22 percent incurred by using conventional kerosene fuel rather than methane in airplanes of equal range and payload.)

If the complete-filling approach is feasible, it may even be possible to employ it during the entire climb path. The need for any gaseous pressurant is then entirely eliminated (except for the climb fuel).

The difficulties incurred in pressurizing subcooled methane by one or another of the above techniques should be evaluated in comparison to the simple expedient of using non-subcooled fuel and letting it boil off in flight. By again allowing the gross weight to increase, the cost penalty in this case is only 7 percent. In making the calculations, engine and wing sizes were varied with gross weight so that takeoff performance of the airplane was not impaired.

INTRODUCTION

Liquid methane fuel is superior to conventional hydrocarbon fuels (kerosene or JP) in heating value and cooling capacity. Also, it is potentially less costly. Studies by the

Lewis Research Center (refs. 1 and 2) have indicated that these attributes promise up to 30 percent greater passenger capacity and a like reduction in direct operating cost for future commercial supersonic transports. (These improvements are relative to a JP-fueled vehicle of identical takeoff gross weight and range.)

In predicting these improvements it was postulated that suitable techniques to prevent boiloff of the cryogenic methane during flight could be developed with little system weight penalty. Boiloff is caused by two separate factors. The more obvious cause is simply due to heat leaks into the tanks. The equilibrium temperature of liquefied methane at 1-atmosphere pressure is 201° R (112 K). During ground holding conditions the air temperature is in the order of 520° R (289 K), and during Mach 3 cruising conditions the stagnation air temperature is about 1080° R (600 K). At all times, therefore, there is a substantial thermal gradient driving heat into the fuel and thus causing vaporization or boiloff. This difficulty can be alleviated by insulating the fuel tanks; the problems involved with the use of insulation are not discussed in this report.

A second, more subtle, cause of boiloff arises from the reduction in ambient pressure during takeoff and climb of the airplane. The fuel tanks for the presently proposed SST, as is true for most other aircraft, are contained in the wings. The shallow, flat-topped tanks are incapable of withstanding large pressure differentials. Accordingly, the tanks are vented to the atmosphere so that the internal pressure is equal to, or at best only slightly above, the external ambient pressure. If the methane is initially loaded at its normal liquefaction temperature of 201° R (112 K), its vapor pressure is 14.7 psia (10.1 N/cm^2), and it is in pressure equilibrium with the surrounding sea level atmosphere. During climb, however, as ambient and, hence, tank pressures are reduced, vapor is continually evolved and vented overboard such that the temperature and vapor pressure of the remaining liquid methane are reduced to the new equilibrium condition. Reference 2 estimated that this "flashing off" of vapor can lose about 10 percent of the total fuel load and concluded that this eliminates most of the hoped-for benefits due to using methane.

A number of different techniques can be considered for relieving this problem and are reviewed in reference 3. For example, simply strengthening the fuel tanks so that they can withstand the pressure differential would eliminate the need for venting and consequent boiloff. A tank weight penalty is thereby suffered, however (refs. 3 and 4).

Another approach was adopted in references 1 and 2. It was proposed to subcool the methane fuel before loading on the aircraft, so that the fuel vapor pressure is reduced to the lowest tank pressure to be encountered in flight. Boiloff due to venting at high altitudes is thereby entirely eliminated. The converse problem is encountered at low altitudes, however. Instead of an excess of tank pressure at high altitude, there is now a deficiency of tank pressure at low altitude. That is, since the vapor pressure of the subcooled methane is less than 14.7 psia (10.1 N/cm^2), the pressure of the atmosphere tends to crush the tanks inward. To prevent collapse, it is necessary to pressurize the tank back to ambient pressure by means of a separate gas, such as helium.

This system is superior to the strengthened tank approach in that there is no weight penalty (other than the small amount due to the helium system). Use of subcooled methane is an undesirable operational complication, however. Furthermore, the consumption rate of scarce helium is apt to be unacceptably high, unless a rather complex recovery system is employed (ref. 3).

The reason for using helium is that more common gases such as nitrogen are soluble in subcooled methane. For example, in an airplane of 460 000-pound (208 800-kg) takeoff gross weight, if only 5 percent by weight of nitrogen is dissolved in the methane, 10 000 pounds (4 540 kg) of nitrogen is added, which must be charged against a 45 800-pound (20 800-kg) payload. Reference 2, which presented this example, concluded that nitrogen was therefore unacceptable.

This extreme sensitivity of vehicle performance to solubility is a consequence of comparing airplanes of equal takeoff gross weight. However, during the course of the current supersonic transport development program, there has been a steady growth in airplane weight. Consequently, it seems appropriate to inquire whether a relaxation of the constant-gross-weight assumption in the previous methane studies (refs. 1 to 3) might change the viewpoint on boiloff-prevention techniques. In particular this note will reexamine the possibility of using a soluble gas to pressurize subcooled methane. The possibility of accepting boiloff of nonsubcooled methane is also explored.

ANALYSIS AND DISCUSSION

Assumptions

The vehicle considered in this study and the methods of calculation are the same as those of reference 2. The airframe configuration is the SCAT-15F designed by NASA-Langley. It has a fixed arrow wing with a subsonic leading edge (fig. 1). The resulting thick wing is particularly favorable for methane fuel, due to the fairly large wing volume available for fuel storage. Afterburning turbojet engines with a turbine-inlet gas temperature of 2200° F (1205° C) are assumed. Operating constraints (such as takeoff velocity and transonic boom) fixed the engine and wing sizes at values corresponding to a takeoff thrust-weight ratio (nonafterburning) of 0.32 and wing loading of 50 pounds per square foot (2390 N/m^2).

Takeoff gross weight was varied to yield a payload capacity of 231 passengers at a design range of 4000 statute miles (6440 km). Cruise Mach number is 3.0.

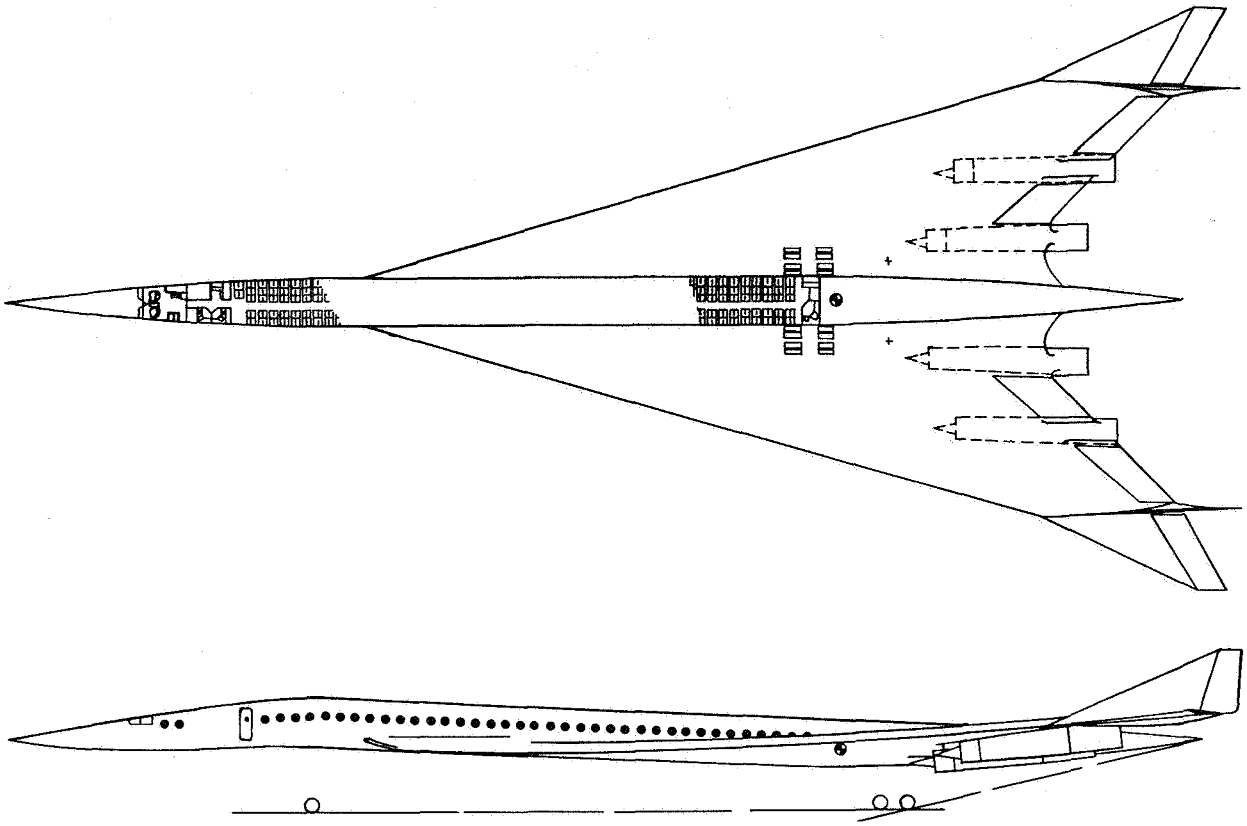

Figure 1. - Representative methane-fueled supersonic transport configuration.

Reference Airplane

To serve as a base point against which to make comparisons, consider a methane-fueled airplane as defined in the preceding section. The most favorable situation is that of no boiloff losses and no fuel system weight penalties (except for a nominal amount of insulation). For this case, the airplane gross weight is calculated to be 460 000 pounds (208 800 kg) and the direct operating cost (DOC)[1] 0.936 cent/seat-mile (0.582 cent/seat-km). Incorporating the various boiloff-control techniques discussed later in this report will then penalize this "ideal" performance.

An indication of whether these boiloff penalties are excessive is offered by considering the performance of a comparably designed kerosene-fueled airplane. If the methane vehicle, even after penalties, is not substantially better than the kerosene craft, there is little point in accepting the complications associated with the use of methane.

Defining a comparable kerosene airplane causes some difficulty, primarily in terms

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[1]Liquid methane cost is conservatively taken as 2 cents per pound (4.4 cent/kg), somewhat higher than a recent estimate by the Institute of Gas Technology.

of engine design. As discussed in reference 2, one of the significant advantages of methane fuel is its superior cooling capacity relative to kerosene. This superiority may be utilized for enhanced cooling of the turbine blades. For example, current technology air-cooled blades have a metal temperature of about 1500° F (816° C) when the turbine-inlet gas temperature is 1900° F (1038° C). Applying the heat-sink capability of methane could permit raising the gas temperature to 2200° F (1205° C) with no increase in metal temperature. The resulting improvement in thermodynamic performance yields smaller, lighter engines and somewhat lower fuel consumption (in addition to the benefit of methane's superior heating value). The kerosene airplane that is comparable to the reference methane airplane thus has a turbine-inlet gas temperature of 1900° F (1038° C). Such a vehicle is calculated to have a 26 percent higher gross weight and 22 percent higher DOC than the reference methane airplane for equal range and payload.

When boiloff penalties are now imposed on the reference methane airplane, its performance will worsen. But the methane concept is still of interest if the penalties are sufficiently less than the 22 percent that would result if kerosene were used. (The reader is cautioned that the 22 percent difference is a purely nominal value that is cited for perspective. The comparison between methane and kerosene changes drastically with variations in such parameters as number of passengers, turbine temperature, fuel cost, etc. In fact, comparing airplanes on the basis of constant gross weight rather than constant payload would raise the 22 percent to 38 percent; however, this is not consistent with the variable-weight approach to boiloff control analyzed herein.)

Pressurant Solubility

From Henry's Law, the fraction x of dissolved gas in a subcooled fluid is proportional to the difference between the total tank pressure p_t and the vapor pressure of the fluid p_v.

$$x = K(p_t - p_v) \tag{1}$$

In order both to minimize the weight of pressurizing gas and the amount of refrigeration required for subcooling, p_v should be as high as possible. A practical limit is set by the internal pressure that can be supported by the tank at high altitude. If the lowest ambient pressure during cruise is 0.5 psia (0.34 N/cm^2) and the tank can withstand a differential of 4 psi (2.76 N/cm^2), then p_v can be 4.5 psia (3.1 N/cm^2). Anything higher would necessitate venting losses during climb.

Assuming that the tank has no effective strength against crushing loads requires that p_t never be less than ambient pressure p_o. On the other hand p_t should be as small as possible to minimize x. Accordingly, the tank should be vented to the atmosphere during flight so that $p_o \leq p_t \leq 4.5$ (in English units). A simple schedule that satisfies this inequality is to let $p_t = p_o$ up to an altitude of 29 000 feet (where $p_o = 4.5$ psia), with closed vents thereafter. Substituting these values into equation (1) yields

$$x = K(p_o - 4.5) \tag{2}$$

The constant of proportionality K is rewritten by specifying that $x = x_{SL}$ when $p_o = 14.7$ psia, so that

$$x = \frac{x_{SL}}{10.2}(p_o - 4.5) \tag{3}$$

or, in SI units

$$x = \frac{x_{SL}}{7.0}(p_o - 3.1)$$

This expression is applied in the airplane performance calculations to specify the variation of dissolved pressurant weight with altitude for any given sea-level solubility x_{SL}.

To obtain an absolute value for the x_{SL} of air in methane, use is made of an estimate by R. Hibbard of NASA-Lewis that $x = 0.15$ when methane is subcooled to 180° R (21° subcooled) at 14.7 psia total pressure. At this temperature $p_v = 4.90$ psia. Substituting these values into equation (1) yields $K = 0.0153$. Setting $p_v = 4.5$ psia in equation (1) then yields $x_{SL} = 0.156$ as the nominal value of sea level fraction of dissolved air. (In SI units we have $x = 0.15$ when methane is at 100 K and 10.1 N/cm^2, where $p_v = 3.38$ N/cm^2, yielding $K = 0.0224$.) Using equation (1), the variation of x_{SL} with fuel temperature is shown in figure 2. For future reference, the variation of methane vapor pressure is also shown.

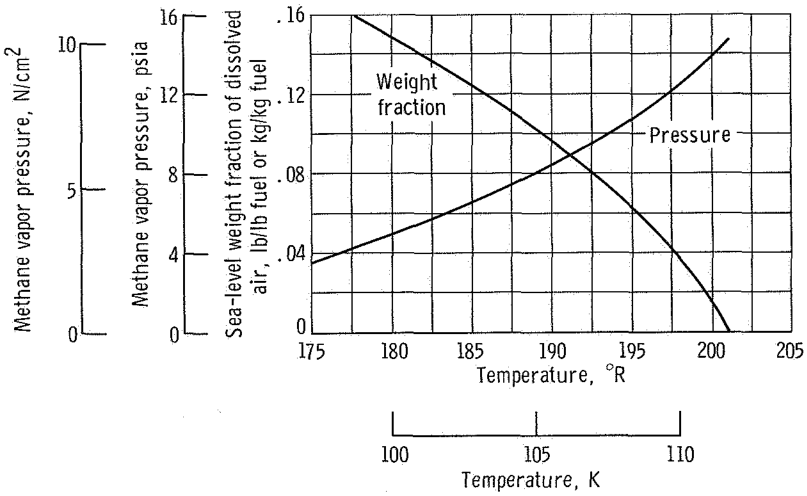


Figure 2. - Solubility of air in subcooled methane. Tank pressure, 14.7 psia (10.1 N/cm^2).

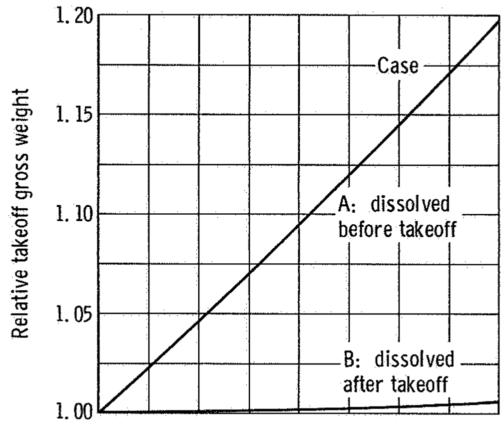
Parametric Airplane Performance

Theory. - Consider a methane-fueled airplane that has no boiloff losses and a minimum increase in fuel system weight above that of a comparable kerosene-fueled airplane. (For example, ref. 3 suggested that this goal might be obtained by using subcooled, helium-pressurized fuel, plus an increase in fuel system-to-fuel weight ratio of 0.02 for insulation, etc.) The gross weight and corresponding direct operating cost are significantly better than the kerosene-fueled version as previously stated. However, the use of helium may be unacceptable.

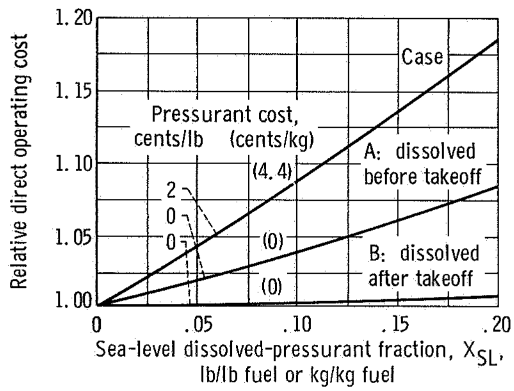
Suppose, instead of using helium, the tanks are simply vented to the atmosphere so that air (with its moisture and CO_2 removed by a filter) acts as the pressurant. A large amount of nitrogen and oxygen will dissolve in the fuel with an equal increase in gross weight. Ideally, hardware weight of the airplane is unchanged and the dissolved gases will come out of solution during the climb (per eq. (3)), so that the airplane weight and performance during cruise are unchanged. Hence, the direct operating cost, which is a function of hardware weight and fuel consumption, is also unchanged.

Practical effects. - In reality, the situation is more complicated. For equal takeoff performance, the greater gross weight requires slightly larger engines and wings. If landing gear weight is conservatively assumed proportional to gross weight, this component becomes heavier. Also, more fuel is expended during the climb. These effects have been incorporated into the data presented in figure 3(a). Relative takeoff gross weight is given as a function of the sea-level fraction of dissolved pressurant x_{SL}.

Two cases are shown. In case A, the air is admitted to the tank and dissolved prior to takeoff. The practical effects of the preceding paragraph are found to be quite serious.



(a) Gross weight.



(b) Direct operating cost.

Figure 3. - Effect of dissolved pressurant on airplane performance.

For example, with a dissolved fraction of 0.15, the weight of air added to the airplane is about 6 percent of its gross weight. However, the total increase in gross weight is 14 percent, due to additional structure and fuel.

In case B it is assumed that the tanks are not vented to the atmosphere until the airplane has lifted off the ground. The increase in gross weight as air is absorbed in the methane is thus delayed until the craft is airborne. The only increase in initial gross weight in this case (fuel plus structure) is due to the slightly higher fuel consumption associated with a lower thrust-weight ratio during acceleration and climb. This case closely corresponds with the results anticipated in the previous Theory section, that is, practically no penalty in hardware weight or fuel consumption.

To achieve case B in practice, some other pressurization scheme must be provided prior to lift-off. The simplest approach is to support the external ambient pressure by the essentially incompressible fuel, itself. This means completely filling the tanks with the subcooled methane, so that there is no gas-filled ullage space. Since any gas initially in the empty tank, such as warm methane vapor or air, would condense or dissolve in contact with subcooled methane, it appears that the usually necessary ullage space could be eliminated. To accommodate inaccuracies in loading or subsequent heat leaks, a spring-loaded relief valve or an expansion bellows could be provided. A separate small tank of fuel (either air pressurized or nonsubcooled) would be used for takeoff with insignificant airplane penalty.

The corresponding relative direct operating costs for the two cases are shown by the solid lines in figure 3(b). Case B is, of course, the most favorable situation; it incurs essentially no penalty for pressurization. Case A does involve a noticeable penalty, but perhaps not an intolerable one. For $x_{SL} = 0.15$, for example, the DOC is increased by 6 percent. As discussed later, however, absorbing air in the fuel can cause difficulties. An alternative is then to employ some other soluble pressurant, for example, nitrogen. Pressurants other than air may be expected to cost something to purchase, however. The dashed line in figure 3(b) is the same as case A except that the pressurant is assumed to cost 2 cent per pound. For $x_{SL} = 0.15$, the penalty in DOC is 13 percent.

Air-Pressurization Problems

Because air is available without cost, its use as a pressurant appeared fairly attractive in the preceding section, especially if the tanks could be self-pressurized until after lift-off. Some difficulties are foreseen, however. For example, as already mentioned, any constituents of the air that solidify at liquid methane temperatures must be removed; this primarily refers to water vapor and carbon dioxide. It is likely that this can be accomplished through filters without undue difficulty. Solutions to some other problems are not so evident.

Safety[2]. - The dissolving of air in methane raises questions about the likelihood of creating explosive, or at least flammable, fuel-oxygen mixtures within the tank. Oxygen is more soluble in subcooled methane than is nitrogen. If equilibrium is reached, the 0.15 value for x_{SL} previously used might comprise 0.10 oxygen and 0.05 nitrogen. In practice, as oxygen is preferentially absorbed, the air in the ullage space becomes nitrogen rich. Unless the ullage space is continually flushed out with fresh air, this equilibrium condition will not be fully reached. Nevertheless, there will be some enrichment of oxygen in the dissolved gases.

Despite this enrichment, the fraction of dissolved oxygen in the liquid is low enough that it is not susceptible to detonation (provided that the oxygen is well-dispersed through the methane).

[2]This section is based on unpublished information provided by R. Hibbard of NASA-Lewis.

In the ullage space there will be a mixture of methane vapor and air. During the initial pressurizing process this volume becomes depleted in oxygen due to preferential absorption in the liquid mixture. The resulting fuel-oxygen mixture in the ullage space is probably too rich to be of concern.

The situation worsens during climb, however. The large amount of oxygen initially dissolved in the liquid is released into the ullage space. The resulting gaseous mixture might be hazardous in the presence of an ignition source. Flushing with nitrogen might be a solution.

The above conclusions are quite speculative. A detailed analysis of mixture variations during flight including nonequilibrium effects has not been made. Indeed, adequate basic knowledge regarding solubilities and transient effects is not available. However, it seems that the possibility of an explosion or fire risk cannot be ruled out.

Required subcooling. - In an earlier section, vapor pressure of the fuel was selected as 4.5 psia (3.1 N/cm^2). This corresponds to a methane temperature of 179° R (99 K), 22° R (12.2 K), below the normal 1-atmosphere boiling point of 201° R (112 K) (fig. 2). However, this is the temperature that is required after a large amount of relatively warm air has been dissolved. Since this mixing tends to warm the methane, its initial temperature prior to adding air must be even lower than 179° R (99 K).

The relation between the temperatures before and after mixing is given by a simple heat balance

$$c_p(T_2 - T_1)_{CH_4} = x_{SL}\left[c_p(T_1 - T_2)_{air} + H_s\right]$$

where T is temperature, c_p is specific heat, H_s is heat of solution, and subscripts 1 and 2 refer to before and after mixing, respectively. The fraction of dissolved air x_{SL} is a function of fuel vapor pressure and, hence, of final temperature T_2. The first term in the brackets refers to the cooling of air from ambient temperature to T_2 while in the gaseous state. The second term H_s accounts for the heat transferred to the methane from the gaseous air as it enters solution at constant temperature.

These relations are illustrated in figure 4, setting c_p equal to 0.24 and 0.83 Btu/lb-$^{\circ}$R (1.00 and 3.47 J/g-$^{\circ}$K) for air and liquid methane, respectively. If the heat of solution is zero, the desired T_2 of 179° R (99 K) can be obtained by starting out with pure methane that has been subcooled to 163° R (91 K), just 1° above the freezing point. The true heat of solution of air in liquid methane is not known. However, it is not expected to differ substantially from the heat of liquefaction, which is in the order of 80 Btu/lb (186 J/g). With this value of heat of solution the figure shows that the desired T_2 cannot be achieved unless the methane is initially frozen. This is not felt to be practical.

One solution to this difficulty is to accept a higher mixture temperature. If the

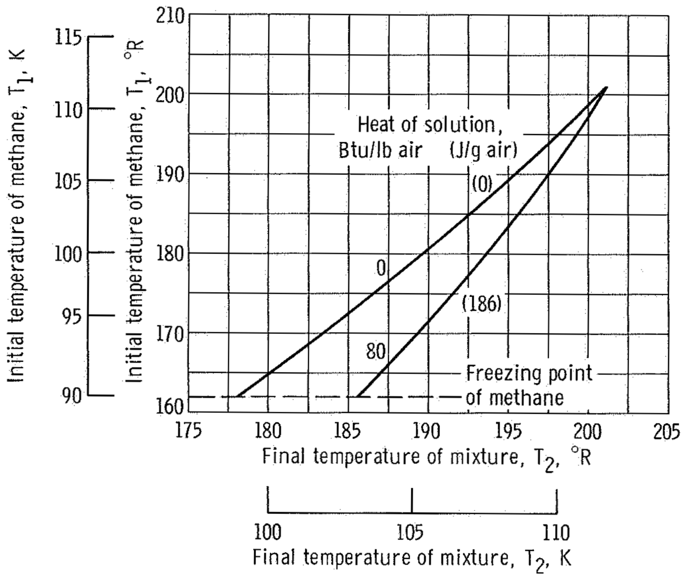


Figure 4. - Warming of subcooled methane after absorbing equilibrium fraction of air. Tank pressure, 14.7 psia (10.1 N/cm^2); initial air temperature, 520° R (289 K).

methane is initially just at the freezing temperature, figure 4 indicates a T_2 of 186° R (103 K). From figure 2 this is found to correspond to a vapor pressure of 6.7 psia (4.62 N/cm^2). The tank must then be capable of withstanding a pressure differential during cruise of 6.7 - 0.5 = 6.2 psi (4.27 N/cm^2). Although it is 50 percent higher than the previously assumed value of 4.0 psi (2.76 N/cm^2), this capability does not appear unreasonable to require.

Note that this problem does not arise if nitrogen is employed as the pressurant. Inasmuch as any nonatmospheric pressurant must be placed on the airplane before takeoff, the nitrogen-methane mixture can be cooled to any desired T_2 by the same refrigeration system that subcools the methane (or equivalently, liquid rather than gaseous nitrogen can be used).

This discussion was simplified in that temperature and pressure rises due to inflight heat leaks into the tank were neglected. With nitrogen pressurization this can be combatted by cooling the mixture to a somewhat lower T_2. With air pressurization some boiloff would have to accepted or the tank must possess even higher pressure capability.

Volume. - As air dissolves in the methane, the volume of the mixture tends to increase. A rough estimate of this increase (in the absence of data) is 8 percent for $x = 0.15$. This is significant because the low-density (26 lb/cu ft or 417 kg/m^3) methane already requires very bulky fuel tanks that are difficult to contain in a supersonic airplane. Increases in tank volume are liable to require a larger airframe, with consequent penalties in structural weight and aerodynamic drag. Evaluation of this factor requires a rather detailed consideration of the airplane design and is beyond the scope of this paper.

Saturated Fuel

All of the problems discussed up to this point were encountered because the fuel was initially subcooled, and hence, a pressurant was required at low altitudes. For comparison it is of interest to examine the case of starting out with nonsubcooled methane, that is, $T = 201^{\circ}$ R (112 K) and $p_v = 14.7$ psia (10.1 N/cm^2). In this instance reductions in tank pressure during climb flash off part of the methane, which is then lost through the vents. The lower the final tank pressure, the greater the boiloff, as shown in figure 5. (These are optimistically low values; heat transfer and other nonisentropic effects would increase boiloff.)

The most desirable cruise tank pressure is 14.7 psia (10.1 N/cm^2), of course, which eliminates all boiloff loss. But the purpose of this paper is to seek an alternative to making the tanks that sturdy (and perhaps heavy). At the nominal cruise tank pressure of 4.5 psia (3.1 N/cm^2) used elsewhere in the study, it is seen that 0.072 of the initial fuel weight is vented overboard during climb. The final fuel condition when entering cruise is then the same subcooled state ($p_v = 4.5$ psia (3.1 N/cm^2), $T = 179^{\circ}$ R (99 K)) as in the previous cases. The vented boiloff can therefore be viewed exactly as if it were a

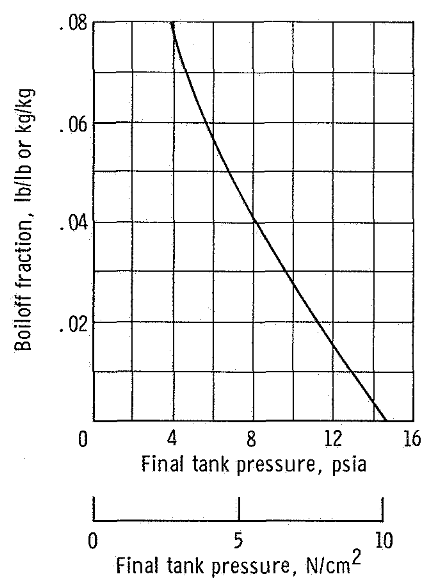


Figure 5. - Methane boiloff due to tank venting. Initial tank pressure, 14.7 psia (10.1 N/cm^2); initial methane temperature, 201° R (112 K) (saturated); isentropic expansion, no heat transfer.

soluble pressurant on initially subcooled fuel. For example, figure 3(b) can be entered at an effective x_{SL} = 0.072/(1 - 0.072) = 0.078 and a "pressurant" cost of 2 cent/lb (4.4 cent/kg) to determine the DOC. The penalty in DOC is 7 percent. The penalty would be even smaller if the vaporized fuel could be employed usefully in the engines rather than merely discarded. (This possibility was mentioned in refs. 1 and 2.)

This approach appears quite attractive. In addition to the modest DOC penalty, there is no hazardous oxygen mixture in the tank, and the complexity of handling and pressurizing subcooled fuel is eliminated.

Descent

Most of the fuel concepts mentioned thus far enter cruise with the methane in a subcooled condition (whether because it was initially subcooled or because boiloff during climb reduced the temperature of the remaining fuel). The question now raised concerns what happens at the end of the flight when the vehicle descends to higher ambient pressures. If the fuel were exhausted at this time, there would be no difficulty. The only requirement would be to leave the tank vented to the atmosphere in order to avoid an external crushing load.

In general, however, all the fuel is not exhausted. The reserves would normally still be on board. Furthermore, on a short flight to an intermediate stop, a large part of the main fuel might be present. The subcooled fuel then requires a pressurant to avoid tank collapse during descent. Helium could be used, if provisions were made to remove it on the ground and replace it before the next takeoff. This seems like an undesirable complication.

Air could be used, as previously discussed, if it is not hazardous. The warming and consequent vapor pressure rise of the fuel can be tolerated during this phase of flight, since the ambient pressure is increasing rather than decreasing. Difficulty might be encountered during the following takeoff, however, with the fuel in its new, less subcooled state. Heat leaks into the tanks further compound the problem. If highly subcooled fuel is truly required, it might be necessary to replace any remaining on-board fuel after each flight. (Warming is not a problem, of course, if boiloff is accepted, as in the previous section on Saturated Fuel.)

Except for heat leaks, two other possibilities suggest themselves to keep the fuel subcooled if boiloff is not acceptable. Pressurizing during descent with liquid nitrogen would not raise the fuel temperature. The expense of the nitrogen must then be borne.

The second approach is the zero-ullage concept already mentioned. In this scheme it will be recalled, subcooled methane was loaded into the tank with no gaseous voids remaining. The external ambient pressure was then supported by the incompressible liquid. In the earlier discussion the tank was vented and air absorbed after takeoff. Instead, it may be feasible to leave the cruise and reserve fuel tanks sealed in this zero-ullage condition until actually required in flight (airplanes normally having a number of small tanks rather than one large one). If a landing were made with some tanks still full, the liquid would again support the external pressure with no separate pressurant required. Fuel expansion due to heat leaks would be accommodated by bellows or relief valves. Fuel in any partially filled tank would be air pressurized during descent and then used during the takeoff portion of the next flight.

In a modification of this approach a separate tank of saturated methane is carried and used for takeoff and climb (see ref. 3). The 14.7 psia (10.1 N/cm^2) vapor from this tank is used to pressurize the subcooled tanks. A standpipe in the subcooled tank accommodates expansion and minimizes contact between the warm methane vapor and the subcooled liquid. Some of the saturated fuel could be saved during the cruise portion and then used to again pressurize the reserves and any remaining main fuel during descent. The need for expansion bellows or air pressurization is eliminated. Since the climb consumes about 30 percent of the total fuel, the high-pressure tank to contain this amount may constitute a measurable structural weight penalty. Other deficiencies of this technique are the need for essentially two kinds of fuel and for an accurate pressure-control system.

CONCLUDING REMARKS

One of the major unsolved problems associated with the use of methane fuel in a supersonic transport is selection of a fuel tankage concept that minimizes the effects of fuel boiloff during flight. Evaporation due to heat leaks can be controlled by means of insulation. Ebullition due to pressure reduction during climb is the real problem.

Design of the tank to contain saturated fuel (vapor pressure of 14.7 psia or 10.1 N/cm^2) even at high altitudes is a very promising approach. However, the structural weight penalties thereby incurred have not yet been fully evaluated. In the event that these penalties are unacceptable, several alternative approaches are conceivable.

Subcooling the fuel to a lower vapor pressure relieves the tank structural difficulty at high altitudes. A suitable internal pressurizing scheme is then required to prevent tank collapse due to high ambient pressure at low altitudes. Insoluble gases such as helium are too scarce for this application or have other drawbacks.

Soluble gases have not been seriously considered in past studies due to the large payload penalties that result if gross weight is fixed. However, closer examination reveals that the penalties in direct operating cost (DOC) are not necessarily prohibitive if gross weight is allowed to increase, especially if air is used as the pressurant. Due to the heating of the fuel as air is absorbed, the tank must be capable of containing a pressure differential of 6 to 7 psi (4 to 5 N/cm^2) to prevent boiloff. The DOC rises by about 5 percent with this approach. (Use of chilled nitrogen gas would permit lower tank pressures but might further raise the DOC, depending on the cost of nitrogen.)

The DOC penalty can be almost entirely eliminated if the air is not absorbed into the fuel until after takeoff of the airplane. This could be accomplished by initially filling the tanks completely (zero ullage), so that the incompressible liquid resists the atmospheric pressure. If this is feasible for the short period of time preceding takeoff, a simple extension suggests that it may be also feasible during the additional 20 minutes of climb. In this case no gaseous pressurization is required at any time (except for partially emptied tanks during descent). This scheme is particularly attractive through minimizing any safety hazards from air pressurization.

Finally, all of these zero-boiloff schemes should be compared to the simple technique of just ignoring the problem, that is, use saturated methane and let the vapors boil off. An estimated 7 percent penalty in DOC is incurred, which might be reduced by higher tank pressure or by burning the vapors in the engines.

The techniques presented in this paper generally impose an apparently greater cost penalty on methane-fueled aircraft than do the systems discussed in previous studies. However, selection of the most attractive approach must await more detailed evaluations that incorporate such factors as development effort, reliability, and safety.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 4, 1968,
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