NASA TECHNICAL NOTE

NASA TN D-5641

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NASA TN D-5641

ANALYTICAL HEAT TRANSFER INVESTIGATION OF INSULATED LIQUID METHANE WING TANKS FOR SUPERSONIC CRUISE AIRCRAFT

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1970

1. Report No. NASA TN D-5641	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle ANALYTICAL HEAT TRANSFER INVESTIGATION OF INSULATED LIQUID METHANE WING TANKS FOR SUPERSONIC CRUISE AIRCRAFT		5. Report Date January 1970
		6. Performing Organization Code
7. Author(s) Eugene J. Pleban		8. Performing Organization Report No. E-5258
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		10. Work Unit No. 720-03
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Note
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Liquid methane boiloff from wing tanks was computed for typical SST missions for cruise Mach numbers of 2.7, 3.0, 3.5, insulation thicknesses varying from 0.5 to 2 in. (1.27 to 5.08 cm), various vent pressure settings, and saturated and subcooled fuel. Boiloff rates during fuel fill and ground hold are discussed. Boiloff losses less than $1\frac{1}{2}$ percent are possible for cruise Mach numbers up to 3.5 for an insulation thickness of 1 in. (2.54 cm).

17. Key Words (Suggested by Author(s)) Cryogenic fuels; Liquid Methane; Supersonic transport	18. Distribution Statement Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	37	$3.00

*For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151

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SUMMARY

A detailed heat transfer analysis was made of insulated wing tanks for storing liquid methane fuel in a supersonic cruise aircraft. The analysis considered a range of insulation thickness from 0.5 to 2 inches (1.27 to 5.08 cm), insulation specific weights from 2 to 8 pounds per cubic foot (32 to 138 kg/m^3), internal tank pressures from ambient to 30 psia (20.7 N/cm^2), and both saturated and initially subcooled methane for typical SST missions with cruise Mach numbers of 2.7, 3.0, and 3.5. It was determined that the total vented boiloff losses could be kept to less than $1\frac{1}{2}$ percent of the initial fuel in the wing tanks for cruise Mach numbers up to 3.5 for 1 inch (2.54 cm) of insulation thickness under the following conditions:

(1) The fuel stored in the wing tanks (assumed to be about one half of the total fuel load) is used during the early part of the mission.

(2) Either the fuel is initially subcooled 25° F (14 K) or the saturated liquid fuel is subjected to a constant 1 atmosphere of tank internal pressure.

It was also determined that due to a higher fuel usage rate during the early part of the mission with high cruise Mach numbers, increasing the cruise Mach number from 2.7 to 3.5 did not result in increased boiloff.

Loading fuel for 20 minutes into insulated tanks that have an initial temperature of 70° F (294 K) and followed by an additional 10 minutes of ground hold resulted in a boiloff (that could be recovered) of less than $1\frac{1}{2}$ percent of the fuel loaded into the tanks. The maximum boiloff rate would be less than one thirty-fifth of the fill rate. It was verified, however, that regardless of the insulation thickness (within reasonable limits) the wing surface temperature depression during fill and ground hold can cause moisture freezing or frosting problems under some weather conditions.

INTRODUCTION

This report presents an analysis of insulated cryogenic fuel wing tanks that could be used in a liquid methane fueled, supersonic cruise aircraft such as a commercial supersonic transport (SST). Specifically, the insulation weight, fuel boiloff, pressure and temperature histories for several insulation thicknesses and fuel states are compared.

The significant performance gains in range and payload and problems connected with the use of liquid methane fuel in a supersonic cruise aircraft are presented in references 1 and 2. One of the significant problems requiring investigation for methane fueled aircraft is the efficient storage of the fuel in insulated tanks. Airborne liquid methane storage systems and designs of lightweight tanks for wing and fuselage are presented in references 3 to 5. Up to the present time, however, the whole insulation problem (which includes the tanks, the insulation, and the fuel) has not been subjected to study in depth.

The purpose of this report is to analyze the performance of a high-grade insulation with various thicknesses and thickness distributions applied on tanks of the size that could be installed in the wings of a large supersonic cruise aircraft. From such an analysis it is possible to obtain an indication of the thickness of insulation required, the weight of insulation required and the resulting fuel boiloff as a fraction of the fuel stored, and the pressure-temperature histories of the fuel in insulation tanks during flight missions. Information of this type is required (1) to determine if modifications should be made to mission analyses, such as presented in references 1 and 2, to provide for a more accurate estimate of insulation weight and fuel boiloff, and (2) to provide information on acceptable thickness distributions around tanks and the temperature distribution in the insulation for use in the experimental development of insulation systems for methane fueled aircraft.

Data for this report were generated by the use of a computer code, developed for this insulation analysis, that simulated the heat transfer effects of an SST mission on an insulated wing tank. This simulation included the effects of tank fill, ground hold, take-off and climb, supersonic cruise, descent, fuel usage during the mission, and heat soak of empty tanks. The insulation was assumed to have the conductivity, diffusivity, and specific weight of polyurethane foam, which is one of the better lightweight insulations that does not require a vacuum. Although the upper temperature limit of polyurethane precludes its use for SST fuel tanks, its heat transfer and weight properties represent goals expected to be attained in current NASA-sponsored research. The analysis considered insulation thicknesses from 0.25 to 2 inches (0.64 to 5.08 cm) varying in specific weight from 2 to 8 pounds per cubic foot (32 to 128 kg/m^3). Calculations were made for saturated liquid methane loaded into tanks with vent pressures during flight set at 4 psi (2.8 N/cm^2) above ambient, 15 psia (10.3 N/cm^2), and 30 psia (20.7 N/cm^2), and for initially subcooled liquid methane (25° F (14 K) subcooling) with vent pressures during flight of 4 psi (2.8 N/cm^2) above ambient. Flight cruise Mach numbers of 2.7, 3.0, and 3.5 were considered for supersonic-transport-type missions having a range of 3476 nautical miles (6400 km).

METHOD OF ANALYSIS

The comparison of liquid methane boiloff that occurs with various insulated tank designs was made. The behavior of liquid methane under various tank pressures was observed by the analysis of results obtained from computer simulations of wing fuel tanks subjected to SST missions at cruise Mach numbers of 2.7, 3.0, and 3.5. Appendix B describes the transient heat transfer method used in the simulation. The thermodynamic equations applied to the fluids in the tanks are found in appendix C. (All symbols are defined in appendix A.) The flight characteristics of a typical SST with a gross weight of 500 000 pounds (230 000 kg) were used to define a mission for simulation purposes. The wings of the SST were considered to have sufficient space to accommodate about one half of the total amount of liquid methane fuel required. A mission analysis for a Mach 2.7 cruise flight showed that the fuel in the insulated wing tanks would be consumed in approximately the first 74 minutes (without boiloff losses) of a 165-minute, 3476-nautical-mile (6400-km) flight.

The mission simulation is such that the wing tanks and liquid methane are subjected to the following series of events: fuel fill and ground hold time, takeoff, climb to cruise, cruise (at Mach 2.7, 3.0, or 3.5), descent, landing, and refuel for the next mission if required. Data and parameters computed at specific time intervals during the simulation include (1) a temperature history of the wing panels and insulated tank, (2) heat transfer coefficients at several critical heat transfer boundaries, (3) heat fluxes at each surface, and (4) average temperatures of liquid and gaseous methane fuel and liquid methane levels in the tanks as fuel is used.

Mission

The various SST missions (flight plans) used for simulation purposes are shown in figure 1. A mission analysis computer code using methods outlined in reference 2 provided the instantaneous trajectory values of Mach speed, range, altitude, decrease in airplane weight, angle of attack, and other data and parameters. Local Mach number on upper and lower wing surfaces, and local temperature and pressure ratios, were computed by the methods of reference 6 using these trajectory values. The Mach 2.7 flight plan

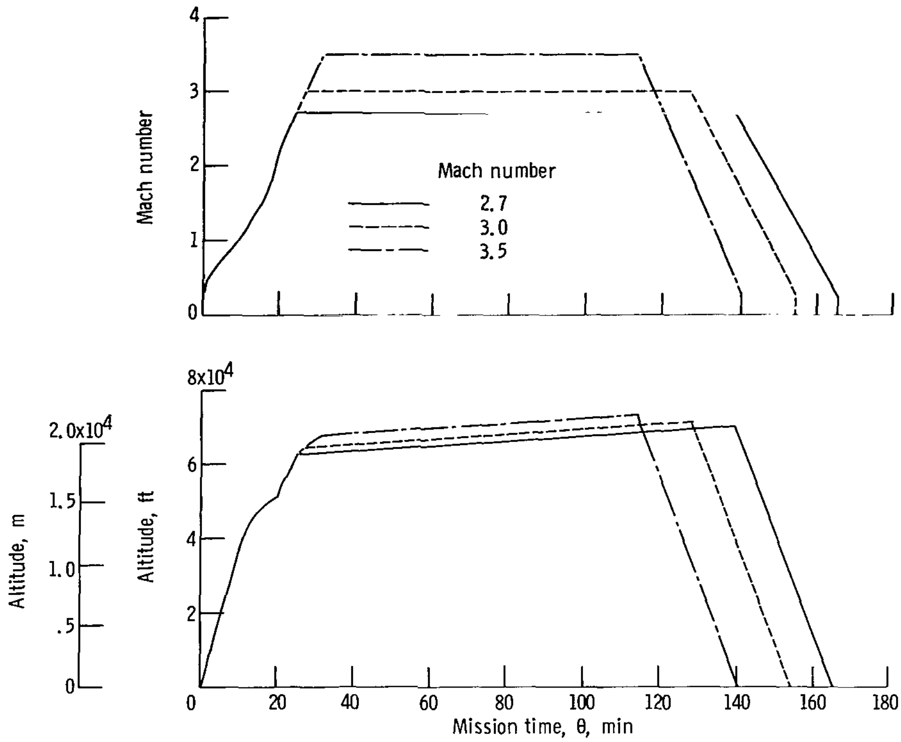


Figure 1. - Flight plans for missions at cruise Mach numbers of 2.7, 3.0, and 3.5.

was based on the characteristics of a specific kerosene (JP) fueled SST design that flies at cruise altitudes of 60 000 to 70 000 feet (18 300 to 21 300 m) over a 3476-nautical-mile (6400-km) range. The Mach 3.0 and 3.5 flight plans were obtained by computing applicable cruise altitudes and fuel usage based on wing loading, airplane gross weight, and total range of the Mach 2.7 airplane. The cruise altitude was determined from lift coefficient variations as influenced by flight Mach number, constant wing loading and its effect on the required dynamic pressure, and air density. Fuel usage at Mach 2.7 and the optimum lift-drag ratio for the three cruise Mach numbers was used to determine fuel usage for the other flight plans from the inverse relation of fuel usage with lift-drag ratio.

Fuel Weight Conversion and Wing Fuel Fraction

The model used for this analysis was patterned after an SST that was designed for JP fuel. Reference 1 reports an impulse increase of 12 to 14 percent when liquid methane is substituted for JP. For a 12 percent specific impulse increase and equal thrust requirements, a fuel weight saving of 11 percent is realized. Based on an average specific weight of 50.1 and 25.9 pounds per cubic foot (800 and 415 kg/m^3) for JP and liquid methane, respectively, a 73 percent increase in fuel storage volume is required for the liquid methane fueled airplane. For this analysis it was assumed that the proportion of methane fuel carried in the wing tanks, about one half of the total fuel, was the same as for the JP airplane.

Tank Models

The assumed wing tank model consists of a rectangular shaped, nonintegral tank with external insulation mounted between wing beams. The shape and dimensions of the tank were governed by a typical SST wing cavity. Since the tank walls are very thin (0.01 to 0.03 in., 0.025 to 0.076 cm), they were removed from the actual thermodynamic model, which means the insulation can be considered to be either external or internal.

Tank design. - Wing tank size and cross section is dependent upon the airplane aerodynamic and structural design. Based upon preliminary structural analysis of a fixed-wing SST of 500 000 pounds (230 000 kg) gross weight and 60 pounds per square foot (2870 N/m^2) wing loading, a tank cross section 15 inches (38 cm) wide by 25 inches (63.5 cm) high appears reasonable for analysis purposes. The assumed tank cross section is shown on figure 2.

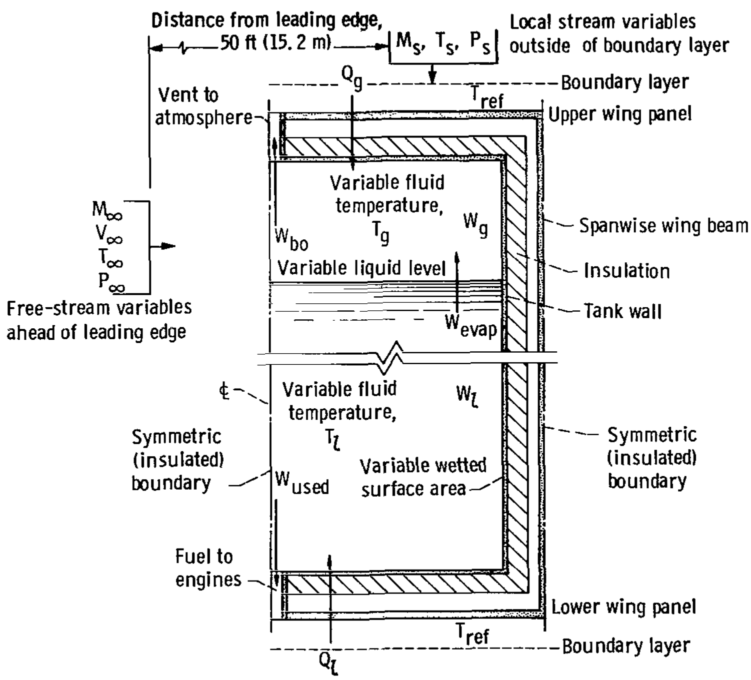
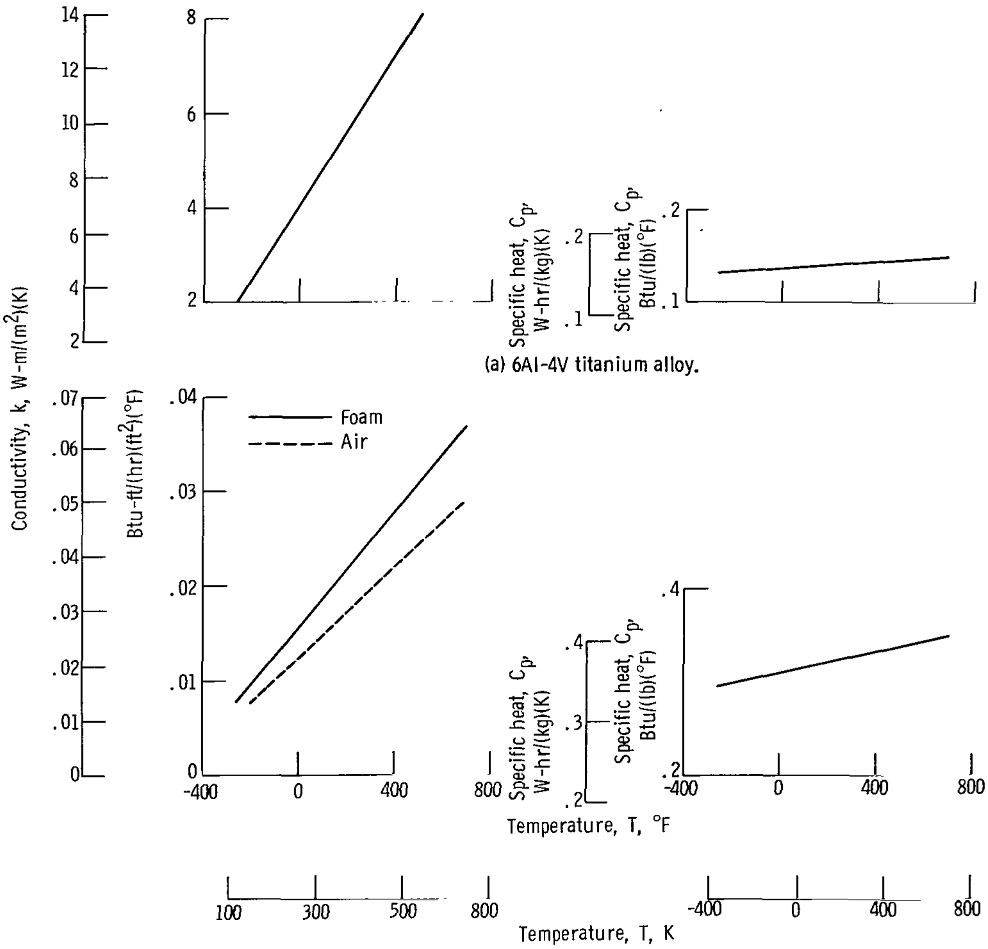


Figure 2. - Heat transfer model.

Based on this cross section and a 4 percent ullage space, a total tank length of 1667 feet (510 m) provided the correct wing tank volume. If it is assumed that the chordwise beams are 8 feet (2.4 m) apart, the number of 8-feet- (2.4-m-) long wing tanks required is approximately 210. The tank ends, which represent 8 percent more heat transfer area adjacent to the fuel but only $3\frac{1}{2}$ percent of the total heat added to the liquid methane, have been neglected in the analysis to simplify the model. Fuel was used from all the tanks simultaneously.

Insulation. - Properties of polyurethane foam insulation were obtained from reference 7. For polyurethane foam with a specific weight range of 2 to 8 pounds per cubic foot (32 to 128 kg/m^3), the temperature-dependent thermal properties are shown on figure 3. Reference 7 shows no discernible trend in foam thermal conductivity or specific heat as specific weight varied. The INTRODUCTION states the reasons for using the



(a) 6Al-4V titanium alloy.

(b) Polyurethane foam and air.

Figure 3. - Thermal properties of air, polyurethane foam and 6Al-4V titanium alloy used in analysis.

thermal properties of polyurethane. Heat transfer effects through the insulation due to free convection and moisture migration are excluded. Specific weight was varied to study its effect on insulation thickness optimization.

The insulation was assumed to be bonded to tank walls. The inside tank dimensions remained constant for all tank models. Five tank models were developed: four with constant insulation thicknesses of 0.25, 0.5, 1, and 2 inches (0.64, 1.27, 2.54, and 5.08 cm); and one model with 1.0-inch (2.54-cm) insulation on top and bottom faces and 0.5 inch (1.27 cm) on the sides. The latter model evolved from an attempt to provide a more uniform heat flux into the tank, thereby reducing the insulation weight penalty. The calculations with 0.25-inch (0.64-cm) insulation thickness were made only to establish minimum insulation plus boiloff weight trends. This insulation thickness was not considered in other calculations.

Wing structure. - Wing panels and beams, as shown in figure 2, are lumped into 0.125-inch- (0.32-cm-) thick plates of titanium alloy for modeling purposes. Refer to figure 3(a) for 6Al-4V titanium alloy properties.

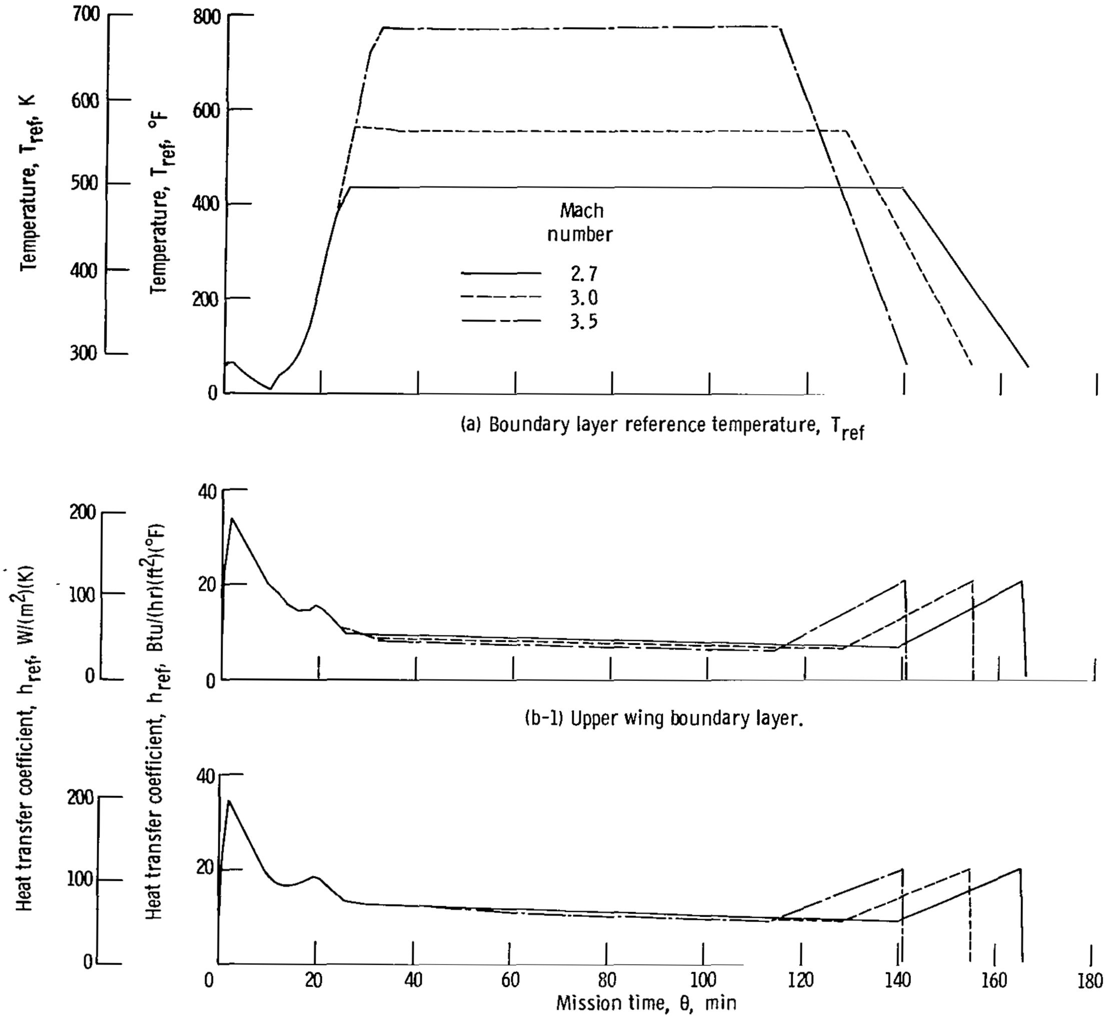
Heat Transfer Modes

Meaningful answers are obtained from a transient heat transfer analysis only if the modes of heat transfer between various components of the model are correctly defined. Preliminary studies were performed to establish reasonable heat transfer coefficients and likely modes of heat transfer. Results of these studies are presented below.

Aerodynamic heating. - Proposed SST delta-wing aircraft designs with a 60-pound-per-square-foot (2870-N/m^2) wing loading have a wing chord length in excess of 100 feet (30.5 m) at the wing fuselage interface. Heat transfer studies to obtain equilibrium temperatures on the wing at supersonic cruise show a variation in temperature across the wing, in the wing tank area, of about 30° F (17 K). A flat plate 50 feet (15.2 m) from the leading edge near the wing fuselage interface was found suitable to use in aerodynamic heating computations for both upper and lower wing heat transfer surfaces adjacent to the wing tanks. The 1962 standard atmosphere as defined in reference 8 was used to define the free-stream properties of air at various mission altitudes.

The method used for computing aerodynamic heating was found in reference 9. It is an explicit method based on local free-stream conditions at a point above the wing flat plate that yields a boundary layer reference temperature T_{ref} and a heat transfer coefficient h_{ref} at each time interval while the transient heat transfer computations step through time. The transition Reynolds number from laminar to turbulent boundary layer heat transfer was taken as 22.5×10^6, as suggested in reference 9.

In addition to these fixed data, variable data as specified in the section Mission were converted to linear equations for use between computing time intervals. Typical values of heat transfer coefficients and wing temperatures are shown in figure 4.



(a) Boundary layer reference temperature, T_{ref}

(b-1) Upper wing boundary layer.

(b-2) Lower wing boundary layer.

(b) Boundary layer reference heat transfer coefficients, h_{ref}.

Figure 4. - Typical aerodynamic heating data for missions at cruise Mach numbers of 2.7, 3.0, and 3.5.

Radiation interchange between the upper wing skin and outer space and between the lower skin and the Earth's albedo were included. Irradiation by the Sun was also considered, including the decrease in atmosphere effects during the climb from sea level to cruise altitude.

Wing panels to insulation surface. - Two modes of heat transfer were considered. Contact resistance under light pressure was simulated by the use of an overall heat transfer coefficient obtained from reference 10. A small air gap (0.12 in., or 0.32 cm) between the insulation and structure was simulated by a combined air conduction and radiation heat transfer mode. Computation of a special Grashof number for vertical and horizontal enclosed air space, found in reference 11, indicated free convection was inhibited.

Tank walls to gaseous and liquid methane. - Grashof number computations indicate free-convection heat transfer between tank surface and gaseous methane in the ullage space. The liquid methane is continuously subjected to a mixing environment, which may be vibratory or due to filling or extracting of fluid by local pumping equipment; therefore, forced-convection heat transfer was assumed between the tank surface and liquid methane. Sloshing and rapid fuel removal effects on the amount of fuel evaporated were simulated by assuming that a portion of the tank wall above the equilibrium surface level, equivalent to approximately 1 inch (2.54 cm), remained wetted.

Fluid Thermodynamics

Liquid and gaseous methane state points, mass transfer across the interface, gaseous methane vented, and changes in internal tank pressures were computed by the method shown in appendix C. The liquid methane in the tanks was assumed to exist either as a saturated liquid at the tank vent pressure setting or as a pressure-subcooled liquid, defined as the state in which the vapor pressure of the liquid is less than the ullage gas pressure. Tables of methane properties were obtained from reference 12.

Two kinds of vent pressure schedules are available as input. A constant vent pressure setting and a variable vent pressure scheme that sets the vent pressure continuously to a constant value above the outside ambient pressure during a mission. Vent pressure changes on liquid methane cause mass transfer across the gas interface (which results in boiloff), change the absolute boiling temperature of the liquid methane remaining, and pressure-subcool the fuel.

The computation scheme allows fuel used by the engines to be extracted from either the wing tanks or the fuselage tanks in any arbitrary mix desired. A "tank volume change" list was provided, as part of the input data, to schedule the extraction of fuel from the wing tanks. This tank volume change schedule also proportioned the heat transfer areas adjacent to the ullage gas and to the remaining liquid in the tank. Also, this schedule controlled the transient heat transfer program interruption times whereby instantaneous values of gaseous and liquid methane state points were computed. Heat applied to the gaseous and liquid methane through their respective adjacent heat transfer areas was computed by integration of the local heat flux over a time interval. Iteration was used to improve the computed value of heat applied to the fuel since it was a function of the resulting fuel temperatures being computed.

Temperature stratification in the fuel was neglected because of anticipated vibrations, large filling and use rates, and higher bottom-heating fluxes. The computation of gaseous and liquid methane state points was based on the following assumptions:

(1) No heat transfer across the interface between gas and liquid

(2) No condensation

(3) Gas pressure always equal to or higher than the vapor pressure of liquid but less than or equal to the vent pressure setting

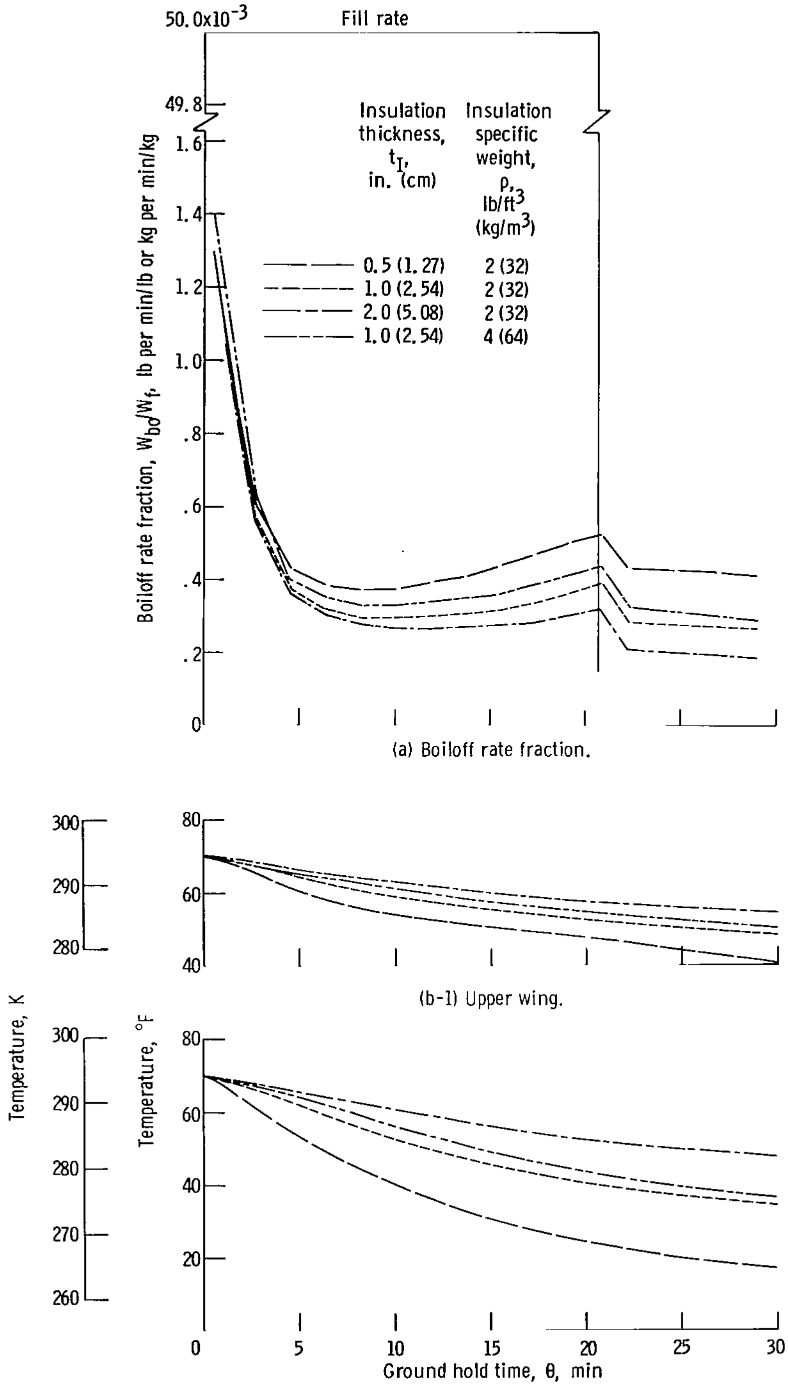
RESULTS AND DISCUSSION

Tank Fill and Ground Hold

One of the problems encountered with the use of a cryogenic fuel, such as liquid methane, is in the boiloff encountered in filling a tank whose wall temperatures are higher than the boiling temperature of the cryogenic fuel. Figure 5 shows the results of calculations on the boiloff rates during fill and ground hold for wing tanks having an initial uniform temperature of 70° F (294 K) throughout the tank and wing structure. The fill rate fraction $\dot{W}/W_f$ for these calculations was assumed to be 0.05 minute^{-1} ((lb per min)/lb, (kg per min)/kg), which would result in a full tank in about 20 minutes. Figure 5(a) shows maximum boiloff rates at the beginning of fill at a rate of about 0.0014 minute^{-1}. This maximum boiloff rate is approximately one thirty-fifth of the fill rate. The average boiloff rate for the 30-minute fill and ground hold varies from about 0.0003 to over 0.0004 minute^{-1}, which is less than one one-hundredth of the average fill rate.

Figure 5 shows high boiloff rates during the early part of fill, when the cold fuel initially comes in contact with the warm surface of the tank. At this point the ratio of wetted surface to fuel volume is high. The boiloff rate then decreases and reaches a minimum, during filling, when the tank is about one half full (10 min fill time). This minimum occurs when the tank is one half full because of the configuration and heat paths. As the tank is being filled, the insulation becomes colder and is therefore a lesser heat sink. As a result the boiloff decreases. At about the half-full point, however, conduction from the upper wing surface through the web into the tank sides begins playing a more important role. This conductive heat transfer, in addition to the steadily increasing tank surface area exposed to liquid methane, causes boiloff rates to increase slightly. The boiloff rates reach a second peak when the tank becomes filled, because then the maximum surface area is in contact with the fuel. As the insulation cools the boiloff again decreases, and the rate is still decreasing 30 minutes after filling began.

The total boiloff fractions W_{bo}/W_f (ratio of weight of fuel boiled off to the fuel weight in a full tank) are listed in the following table for the three insulation thicknesses investi-



(a) Boiloff rate fraction.

(b-1) Upper wing.

(b-2) Lower wing.

(b) Wing skin temperatures.

Figure 5. - Boiloff rate fraction and wing skin temperatures during tank fill and ground hold for various insulation thicknesses and specific weights.

gated, for two insulation specific weights, and for times when the tank is initially filled and at the end of 30 minutes after fill began:

Insulation thickness		Insulation specific weight		Boiloff fraction, W_{bo}/W_f	
in.	cm	lb/ft^3	kg/m^3	End of tank fill	30 Minutes after tank fill began
1/2	1.27	2	32	0.00938	0.0138
1	2.54	2	32	.00774	.0107
2	5.08	2	32	.00719	.00938
1	2.54	4	64	.00867	.0120

From this table it can be seen that only a small portion of the fuel loaded into the tanks is boiled off. The maximum value shown in the table is less than $1\frac{1}{2}$ percent of the fuel loaded into the tank. The values would be somewhat higher for heated tanks upon return from a supersonic flight if the tanks were dry during part of the flight. This boiloff gas can be captured and reliquefied so that it is not lost.

The preceding table also shows that, for constant insulation specific weight, the total boiloff fraction decreases at the end of fill and at the end of an additional 10 minutes of ground hold as insulation thickness increases. This trend is opposite to the effect that would occur if only the sensible heat in the insulation were causing the boiloff. Therefore heat conduction from the wing surface is influencing boiloff within the relatively short time period of 20 minutes. Comparing the insulations with two different specific weights but with the same thickness of 1 inch (2.54 cm) shows that, as would be expected, the boiloff is somewhat higher with the higher specific weight. In the analysis, the insulation thermal conductivity was assumed not to vary with specific weight since the data shown in reference 7 did not show any definite relation between specific weight and thermal conductivity for a large sampling of polyurethane foams.

Figure 5(b) also shows the temperature history of the upper and lower surfaces of the wing during fuel loading on a 70° F (294 K) day with the sun shining and little or no wind. It can be seen that on the upper surface, for insulation thicknesses from 0.5 to 2 inches (1.27 to 5.08 cm), the surface temperature reduction is 30° to 16° F (17 to 9 K), respectively, during the 30-minute fill and ground hold. Due to less heat transfer by radiation to the lower wing surface, the lower surface temperature reduction is 52° to 22° F (29 to 12 K) for the same range of insulation thicknesses. These temperature reductions are enough to cause problems in moisture freezing or frost on the wing surfaces under many fueling conditions.

Regardless of the amount of internal insulation between the wing surface and the liquid methane (within reasonable limits), the wing surface temperature is going to be depressed by the liquid methane within the tanks (fig. 5(b)). Under some weather conditions, this depressed temperature will cause freezing or frost problems. As a result, some other means besides insulation are required to protect wing surfaces during adverse weather conditions. There are many possible solutions - all of which result in complications and/or cost. Some of the possibilities include (1) water spray during moderate weather to keep surface above freezing; (2) water-glycol spray during colder weather to depress freezing; (3) insulating or possibly heated blankets to cover the wing surfaces; (4) radiant heaters or hot-air blowers rolled in place when the airplane is on the ground to heat wing surfaces; (5) internal wing deicing devices, which could include (a) electrical heating, (b) hot-gas heating, or (c) circulating liquid heating. These devices are mentioned only to indicate the problem; their evaluation is not a part of the investigation covered in this report.

Boiloff From Tank Pressure Reduction

A cryogenic fluid such as liquid methane stored in an insulated container will reach a boiling quasi-equilibrium condition. At this condition the methane vapor pressure matches the pressure in the container. At 1 atmosphere of pressure the boiling temperature is approximately -259° F (111 K). If the pressure in the container is lowered, as would be the case in a vented fuel tank in an airplane as the altitude is increased, rapid boiling will take place in the liquid methane. During this boiling the heat of vaporization cools the remaining liquid methane, and its temperature is reduced. This temperature reduction, resulting from boiling, will continue until the vapor pressure of the methane again matches the pressure in the container. Figure 6 shows the amount of boiloff that must occur as altitude is increased in order for the methane vapor pressure to match the tank pressure if the methane is initially loaded into the tank at a temperature corresponding to 1 atmosphere of pressure absolute. Two cases are shown: (1) tank pressure equal to ambient pressure; and (2) the pressure in the tank maintained at a value of 4 psi (2.8 N/cm^2) above ambient. (For altitudes where the pressure is greater than 10.7 psia (7.4 N/cm^2), the tank pressure would be 14.7 psia (10.1 N/cm^2).) This gage pressure of 4 psi (2.8 N/cm^2) is a value that might be considered feasible for pressurization of integral wing tanks in an aircraft. Figure 6 also shows the temperature that the liquid methane would assume as the pressure in the tank is reduced.

Figure 1 shows that supersonic cruise at a Mach number of 2.7 begins at an altitude of about 63 000 feet (19 200 m). Figure 6 shows that almost 8 percent of the fuel stored in a tank would be boiled away during this climb to altitude if the maximum permissible tank pressurization were 4 psi (2.8 N/cm^2) above ambient. If the tank pressure was main-

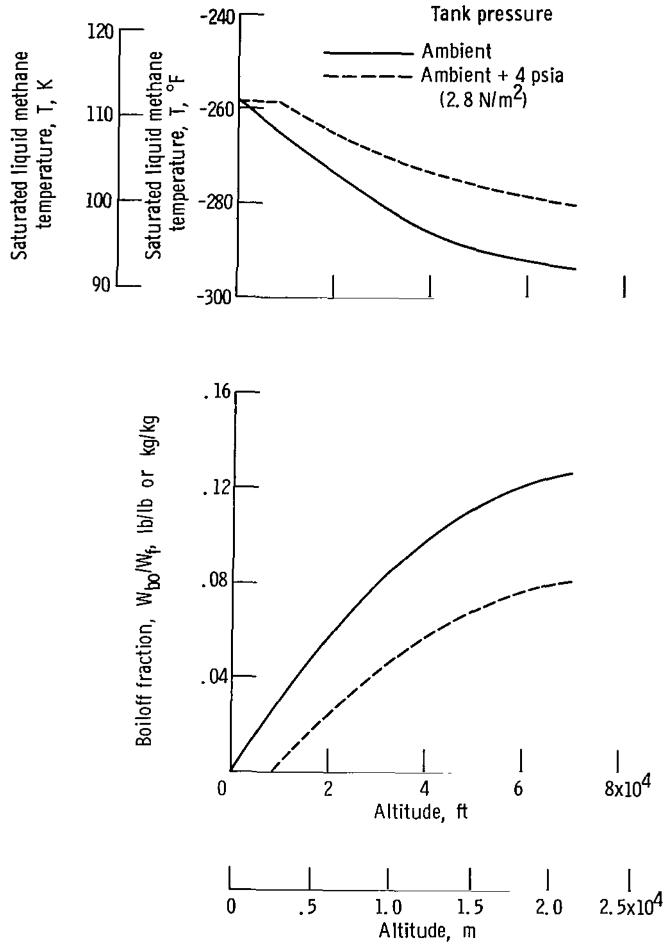


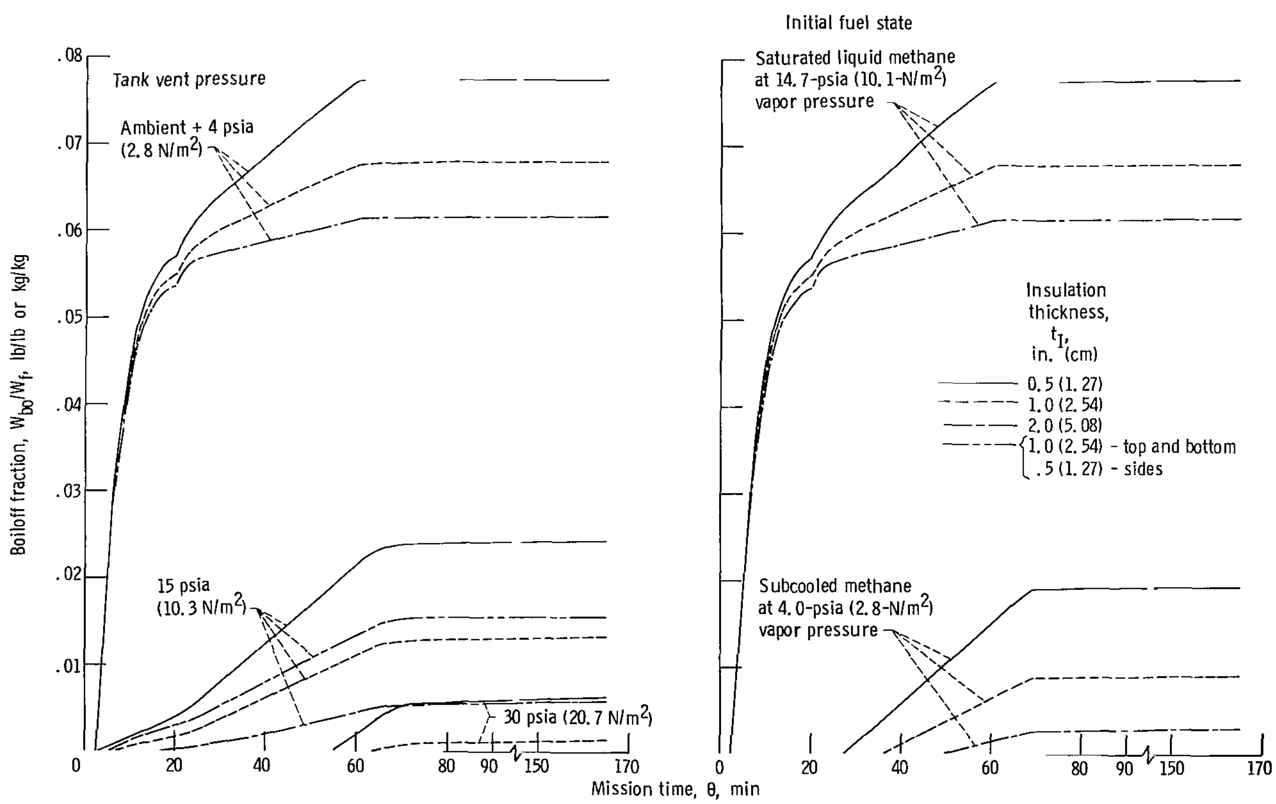
Figure 6. - Methane boiloff fraction resulting from climb for vent pressure setting of ambient and ambient plus 4 psia (2.8 N/m^2). No fuel usage during climb; initial tank pressure, 1 atmosphere.

tained at ambient pressure conditions, over 12 percent of the fuel would be boiled away during climb. These boiloffs of 8 and 12 percent would reduce the fuel temperature from -259° F (111 K) at sea level (14.7 psia, 10.1 N/cm^2) to -279° F (100 K) with ambient-plus-4-psi (2.8-N/cm^2) tank pressure and -293° F (92 K) for ambient pressure in the tank, respectively.

The boiloff values shown in figure 6 are for the case where there is no fuel usage from the tank during climb. If some of the fuel were to be used in the engines, the percentage of initial fuel in the tank that would be boiled off during climb would be somewhat reduced since there would be less bulk fuel to cool at the higher altitudes. Two methods of overcoming this boiloff loss are discussed in more detail later. These methods are (1) pressurize the tanks to at least 1 atmosphere, or (2) initially subcool the methane to a temperature as low or lower than the equilibrium temperature at altitude, as shown in figure 6. Some of the problems and approaches that could be used for both of these cases are discussed in reference 4.

Boiloff for Typical SST Mission

Insulation thickness and tank pressure effects. - Figure 7 shows the calculated boiloff as a fraction of the initial fuel weight in the tank for wing tanks in a typical SST mission having a cruise Mach number of 2.7. For these calculations it was assumed that the wing tanks contained about one half of the total fuel carried in the aircraft, and that this wing tank fuel was burned during the initial portion of the flight at an equal rate from all wing tanks. As a result, the wing tanks will go dry between 60 and 74 minutes after takeoff. The boiloff weight fractions shown result from both altitude change (where vent pressure is less than 1 atm and there is no initial methane subcooling) and aerodynamic heating. Figure 7 shows that, for the case where the tank vent pressure is 4 psi (2.8 N/cm^2)



(a) Effect of tank vent pressure and insulation thickness for saturated liquid methane at 14.7-psia (10.1-N/m²) vapor pressure.

(b) Effect of initial fuel state on boiloff for tank vent pressure of ambient plus 4 psia (2.8 N/m²).

Figure 7. - Fuel weight fraction of methane boiloff during Mach 2.7 mission.

above ambient, the boiloff losses are extremely high, as expected from the discussion of figure 6. Note that supersonic cruise altitude is reached after 25 minutes mission time and that the boiloff losses in figure 7 for all three insulation thicknesses considered are less than those shown in figure 6 for an altitude of 63 000 feet (initial supersonic cruise altitude). As previously explained, this difference results from engine fuel usage during climb. After approximately 60 minutes there is no increase in the boiloff weight fraction for the wing tanks vented at 4 psi (2.8 N/cm^2) above ambient. At this point in the mission there is no liquid fuel left in the tanks - only vapor from boiloff.

The curves shown for a tank vent pressure of 15 psia (10.3 N/cm^2) indicate the boiloff losses that occur from aerodynamic heating only. As noted in figure 4(a), the upper and lower wing surface boundary layer temperatures are about 435° F (497 K) during supersonic cruise. Therefore, the temperature gradients through the insulation are very large. Even with these high temperature differences between the wing surfaces and the liquid methane, figure 7(a) shows that 1 inch (2.54 cm) of insulation with a thermal conductivity equivalent to polyurethane foam will result in a wing tank fuel boiloff of only $1\frac{1}{4}$ percent of the initial fuel loaded into the tank.

If the pressure in the fuel tank were allowed to increase to 30 psia (20.7 N/cm^2) before venting, the bulk methane temperature could increase from the loading temperature of -259° F (111 K) to -242° F (121 K). The heat absorbed in this fuel as a result of the increase in temperature (and enthalpy) further reduces the amount of boiloff that would be vented overboard. Figure 7(a) shows that at 30-psia (20.1-N/cm^2) tank pressure an insulation thickness slightly greater than 1 inch (2.54 cm) would completely eliminate boiloff from wing tanks. As shown in reference 3 the increase in tank weight for nonintegral pressurized wing tanks is often small, due to minimum gage considerations, when designing the tanks for a 30-psia (20.7-N/cm^2) vent pressure instead of 15-psia (10.3-N/cm^2) vent pressure. As a result it may be possible to design supersonic cruise aircraft fueled with liquid methane so that there will be little or no vent losses during the aircraft mission.

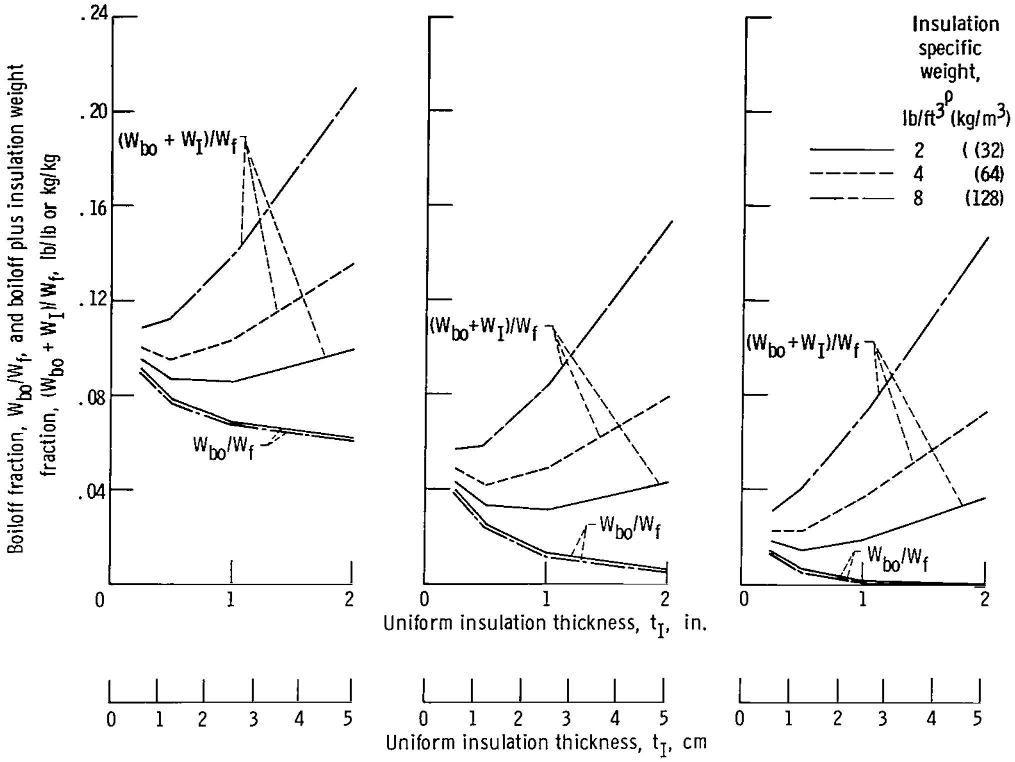
Figure 7(b) shows how boiloff losses can be reduced by loading fuel that is initially subcooled into the wing tanks. In the case shown the fuel was subcooled to the point where its vapor pressure was 4 psia (2.8 N/cm^2). This vapor pressure corresponds to a temperature of -284° F (98 K) or 25° F (14 K) of subcooling. To use subcooled liquid methane, either a noncondensable gas of low solubility must be provided in the ullage volume or the tank must be completely filled with fuel. Details of storage systems using subcooled liquid methane are developed in reference 4.

By comparing figures 7(a) and (b) it can be seen that, for the standpoint of boiloff losses, 25° F (14 K) of subcooling is approximately equivalent to pressurizing the tank to 15 psia (10.3 N/cm^2). Actually, the subcooling illustrated is superior to 15 psia (10.3 N/cm^2) pressurization for two reasons: (1) there would be over a 3° F (2 K) bulk fuel temperature rise before venting would occur at cruise altitude (63 000 ft, or 19 200 m) for the subcooled case, whereas only about $1/2^{\circ}$ F (1/4 K) temperature rise would be permitted for the pressurized tank, and (2) for the subcooled case it is possible that during climb, but before reaching cruise altitude, the bulk fuel temperature can exceed the temperature it will have at cruise altitude since the tank pressure will be higher during climb than at cruise altitude. Since part of this "heated" fuel will be burned in the engines during climb, it will not be necessary to later cool this fuel to the equilibrium temperature at cruise altitude by boiling. As a result of these effects, the boiloff for 1 inch (2.54 cm) of insulation with initially subcooled methane would be about 0.9 percent, as compared to 1.25 percent for tanks pressurized to 15 psia (10.3 N/cm^2). In either case the boiloff values are very low.

For either subcooled methane or for tanks allowed to vent at 15 psia (10.3 N/cm^2), the effect of insulation thickness on boiloff is large on a relative percentage basis of fuel lost by boiloff, but the variation in boiloff, as a percentage of initial fuel weight in the tank, is only about ±1 percent as the insulation thickness is doubled or halved from a value of 1 inch (2.54 cm). The discussion in the following section shows that the disadvantage of the weight increase resulting from thicker insulation may be greater than the advantages gained through fuel weight savings from thicker insulation.

Total insulation and boiloff weight penalties. - Figure 8 shows the combined weight penalties of insulation weight plus boiloff weight, as well as the boiloff-only values beginning with takeoff, for the three vent pressure cases shown in figure 7(a). These penalties are shown for insulation specific weights of 2, 4, and 8 pounds per cubic foot (32, 64, and 128 kg/m^3). As shown in reference 7, specific weight does not have a consistent effect on the thermal conductivity of polyurethane foam; therefore, the calculations for figure 8 make no allowance for changes in thermal conductivity with insulation specific weight. Specific weight does, however, affect the heat absorbed by the insulation due to its larger mass as specific weight increases. This last effect is of secondary importance on boiloff, as evidenced by the narrow band of boiloffs that result from insulations with different specific weights.

From the results shown in figure 8 it can be seen that for the cases with pressurized tanks (to eliminate boiloff due to altitude change) the insulation weight is usually far in excess of the boiloff weight. Since the weight of the insulation must be carried on the entire aircraft mission, while the excess wing tank fuel that is expended by boiloff is carried for only a portion of the mission, the payload penalty for insulation weight is far in excess of that for boiloff. The effect on direct operating cost is beyond the scope of the present investigation, therefore, no conclusions are drawn as to the optimum insulation thickness. It is obvious, however, that every attempt should be made to provide as low specific weight insulation as possible. Suitable insulation for methane tanks in aircraft have not, as yet, been developed. Preliminary investigations of internal and external in-



(a) Tank vent pressure, ambient plus 4 psia (2.8 N/m^2).

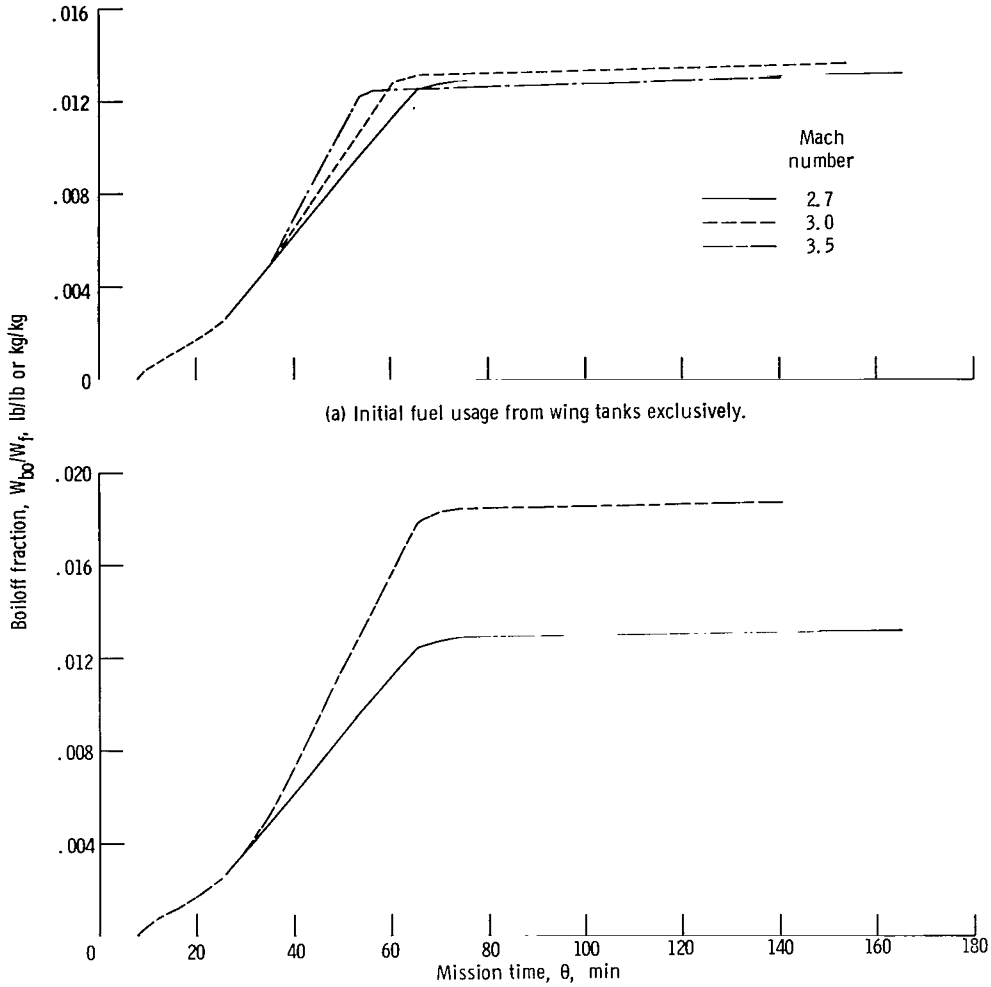
(b) Tank vent pressure, 15 psia (10.3 N/m^2).

(c) Tank vent pressure, 30 psia (20.7 N/m^2).

Figure 8. - Fuel weight fraction of insulation weight and methane boiloff for ranges of tank pressures, insulation thickness, and specific weight during Mach 2.7 missions.

sulations systems for methane tanks with an upper temperature limit of at least 700° F (644 K) have indicated a possible range of insulation weights from less than 2 to about 4 pounds per cubic foot (32 to 64 kg/m^3). Figure 8 shows a small decrease in total weight penalty (boiloff plus insulation weight) in going from 1/2 inch (1.27 cm) to 1 inch (2.54 cm) for a specific weight of 2 pounds per cubic foot (32 kg/m^3) and a somewhat greater saving in fuel. It therefore appears that as a rough approximation, an insulation thickness of the order of 1 inch (2.54 cm) or less would appear reasonable. Due to the very significant effect of insulation specific weight on the overall weight penalty, research should be conducted to minimize insulation specific weight as much as possible.

Cruise Mach number effects. - The majority of this analysis was conducted for a cruise Mach number of 2.7 because information was available on possible aircraft configurations and mission requirements from investigations such as references 1 and 2. Since propulsion efficiency improves as cruise Mach number is increased, advanced future commercial transports will probably have Mach numbers up to 3.5 using conventional turbine propulsion systems. Figure 9 illustrates how increased cruise Mach numbers could affect methane boiloff. For the purposes of this investigation it was assumed that the



(a) Initial fuel usage from wing tanks exclusively.

(b) Fuel used at same rate for both flight Mach numbers.

Figure 9. - Effect of increased cruise Mach number on fuel weight fraction of methane boiloff. Tank vent pressure, 15 psia (10.3 N/m^2); insulation thickness, 1.0 inch (2.54 cm).

gross aircraft configuration and volume of wing tanks did not vary as cruise Mach number was increased. The cruise altitude was increased with Mach number to obtain approximately optimum lift-drag ratio.

The boiloff results shown in figure 9(a) for tanks pressurized to vent at 15 psia (10.3 N/cm^2) and with an insulation thickness of 1 inch (2.54 cm) were based on fuel being used from the wing tanks at the rate required for climb and cruise. At the higher cruise Mach numbers, more fuel was used during the climb portion of the mission, since the cruise altitudes were higher and longer acceleration times were required. As a result of this higher fuel usage rate during the early part of the mission, the wing tanks went dry earlier for the higher Mach number missions. Figure 9(a) shows that for mission times from about 35 minutes to 53 or 60 minutes (depending upon cruise Mach number) the slope of the boiloff curves increases with increasing cruise Mach number as would be expected. But at the highest cruise Mach number (3.5) the fuel in the wing tanks was expended before the total amount of fuel boiled off could exceed the boiloff for lower flight Mach numbers. As a result, the fuel boiled off and vented from wing tanks was not significantly affected by flight Mach number.

The results as presented in figure 9(a) are highly dependent on the proportion of the total fuel load that would be stored in the wing tanks. With a different aircraft configuration the results might have been different. In figure 9(b) fuel boiloff values were calculated for flight Mach numbers of 2.7 and 3.5 for a different set of assumptions on fuel usage rates from the wing tanks. For this figure, it was assumed that fuel was being burned from the wing tanks at exactly the same rate for both flight Mach numbers (for the assumptions used in this analysis, it was assumed that for a cruise Mach number of 3.5 that fuel was being used from both the wing tanks and the fuselage tanks for approximately the first 74 minutes of the mission). Figure 9(b) shows that for the same fuel dwell-time in the wing tanks the boiloff values for cruise at Mach 3.5 are higher than for Mach 2.7 as expected. It is interesting to note, however, that even at the higher cruise Mach number, which results in a boundary layer temperature on the wing of 775° F (686 K), or 340° F (189 K) higher than for cruise at Mach 2.7, the amount of fuel boiled off from the wing tanks is still less than 2 percent of the initial wing tank fuel weight for 1 inch (2.54 cm) of insulation.

The results presented herein are for wing tanks only. Fuel would have to be carried in the fuselage for the entire supersonic cruise period and would be subject to much longer heating times. The environment for the fuselage tanks is much more favorable than for wing tanks, however. Fuselage tanks have a much lower surface to volume ratio; therefore, proportionately less heat would be transferred to the fuel. Based on the results of this investigation on thermal projection for wing tanks and their resulting low boiloff values, it would appear that pressurized fuselage tanks could be designed and insulated in a manner that would almost, if not completely, eliminate boiloff.

Reserve fuel that would be carried in fuselage tanks would be heated so that there would be a pressure rise during the flight. Upon landing, this pressure would have to be vented and boiling allowed to again reduce the bulk fuel temperature. This vented gas could be captured on the ground and recycled through a liquefaction plant so that there need not be a fuel loss due to heating of the reserve fuel.

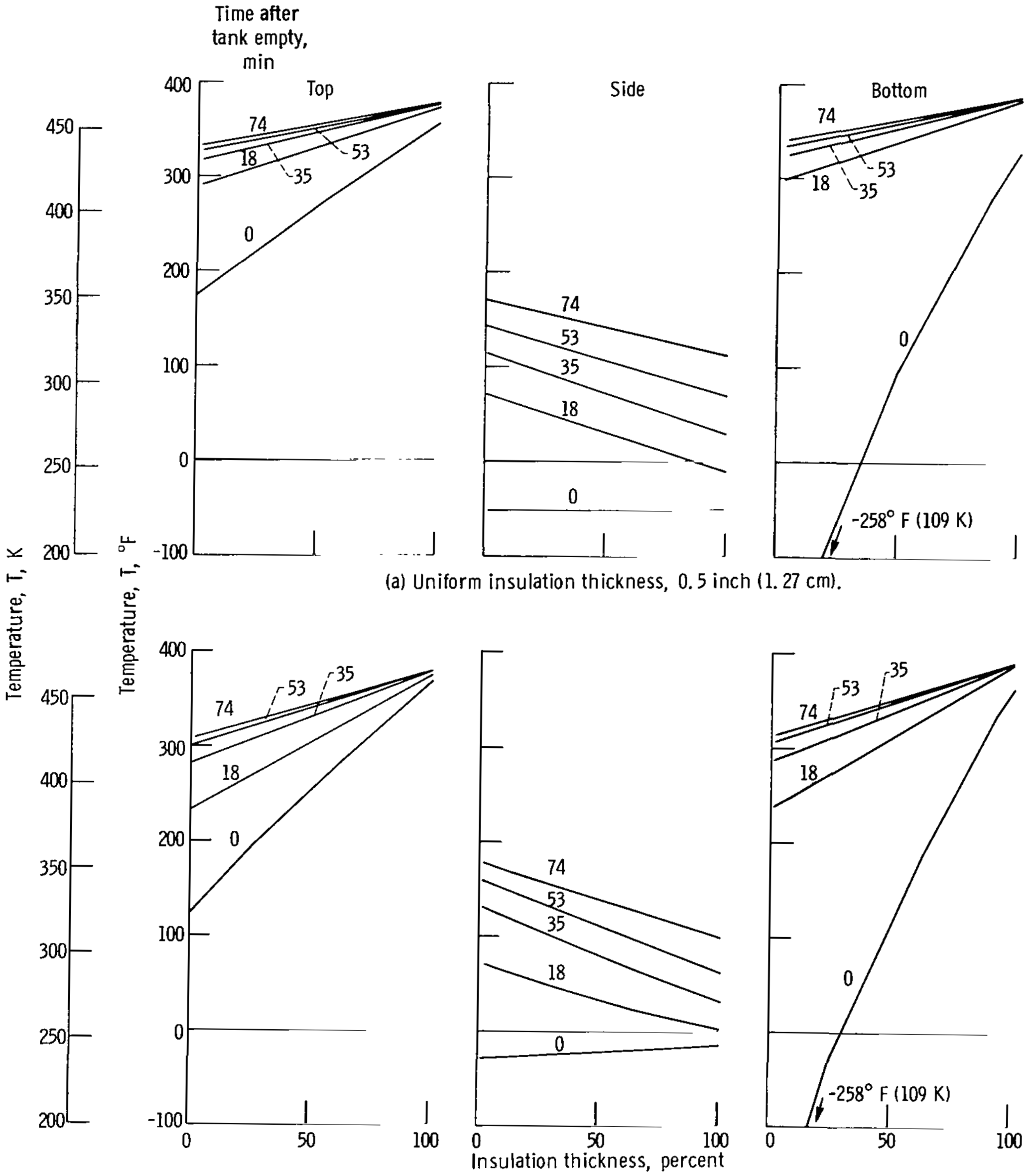
Effect of airgap in insulation. - In the majority of the calculations made in this analysis, it was assumed that there was an 1/8-inch (1/3-cm) airgap between the aircraft structure and the outer surface of the insulation. The mode of heat transfer through this airgap was by radiation and conduction. If the insulation were in direct contact with the aircraft structure, the outer surface of the insulation temperature would be increased to approximately the same value as that of the structure, and the heat transfer into the tank would be somewhat increased. In order to determine the effect of this airgap, calculations were made of the boiloff that would be obtained with 1 inch (2.54 cm) of insulation with and without the airgap being present for a mission with a cruise Mach number of 2.7. Elimination of the airgap resulted in an increase in boiloff from the wing tanks of less than 2 percent of the boiloff with the airgap. These results show that if the insulation contacts the structure, the penalty in boiloff is very small. For instance, with a tank pressurized to 15 psia (10.3 N/cm^2), the total wing tank boiloff fraction W_{bo}/W_f would increase from 0.0132 to only 0.0134. If an airgap is built into the insulation system, it should be kept as small as possible in order to utilize the maximum possible volume within the wing structure for fuel tanks.

It is possible to calculate the optimum airgap to save insulation weight. This is the gap that results in the same heat transfer as if the space were filled with insulation. This gap is so small that it probably is not within fabrication limits for installing insulation. The optimum gap varies from about 0.045 to 0.023 inch (0.114 to 0.058 cm) for structure temperatures from 400° to 700° F (477 to 644 K), respectively. The volume required to ensure an airgap in a volume-limited airplane probably far overshadows any benefits gained.

Insulation Temperature

During the time that there is liquid fuel in the tanks, the fuel acts as a very significant heat sink. In the portion of the tank where the walls are wetted, that portion of the wall and the inner insulation temperature very closely approaches the bulk methane temperature. This analysis assumed that there was no violent sloshing during the mission, but that moderate sloshing wetted the tank walls approximately 1 inch (2.54 cm) above the liquid level. In the portions of the tank that are in contact with the methane vapor, the walls become much warmer than the wetted region due to both the lower heat transfer coefficients between fuel vapor and wall and the vapor convection with vapor heated by the warmer top of the tank. As long as fuel remains in the tank and boiling occurs, the vapor is cooled by the boiloff vapor. As soon as the tank goes dry, however, this heat sink due to boiling disappears and both the vapor and walls heat up. These heated walls will require cooling during refueling after landing. As a result, boiloff will occur during refueling operations that must be captured and reliquefied, as discussed in connection with figure 5. It takes energy for this reliquefaction and it also takes time for the tank and insulation temperatures to again reach equilibrium after refilling. The temperatures that the insulation attains are, therefore, of interest. In addition, these maximum temperatures provide some limitations on the choice of materials that can be used for the insulation.

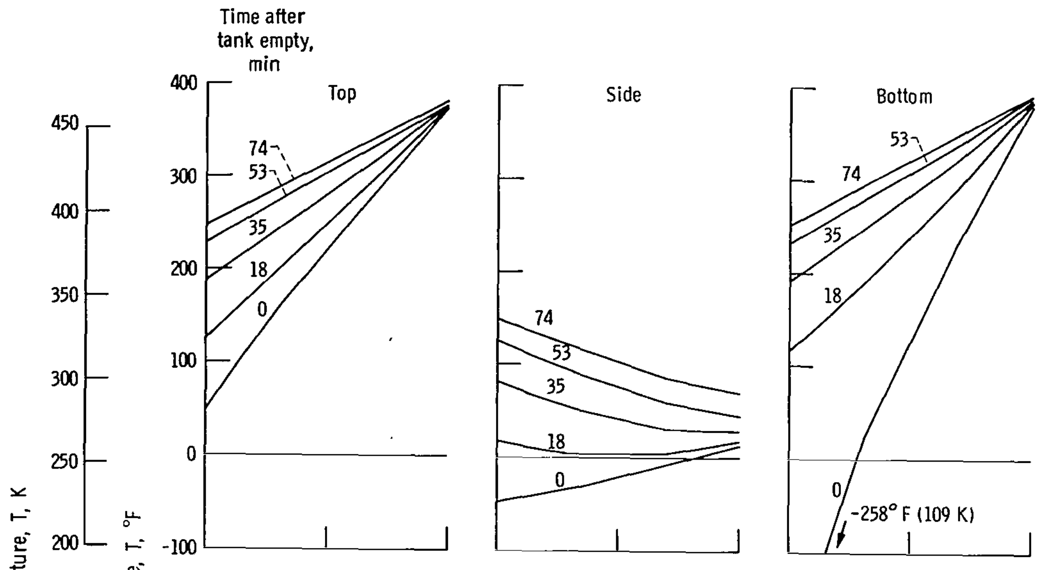
Figure 10 shows the insulation temperatures at the tank top, side (midheight), and bottom of the tank at the instant when the tank goes dry and at specific time periods after the tank has gone dry. These time periods approach 20-minute increments, but for convenience are recorded on the figure at times that could be read from the computer output. The curves for all combinations of insulation thickness show maximum internal insulation temperatures (at some location around the tank periphery) in excess of 250° F (394 K)



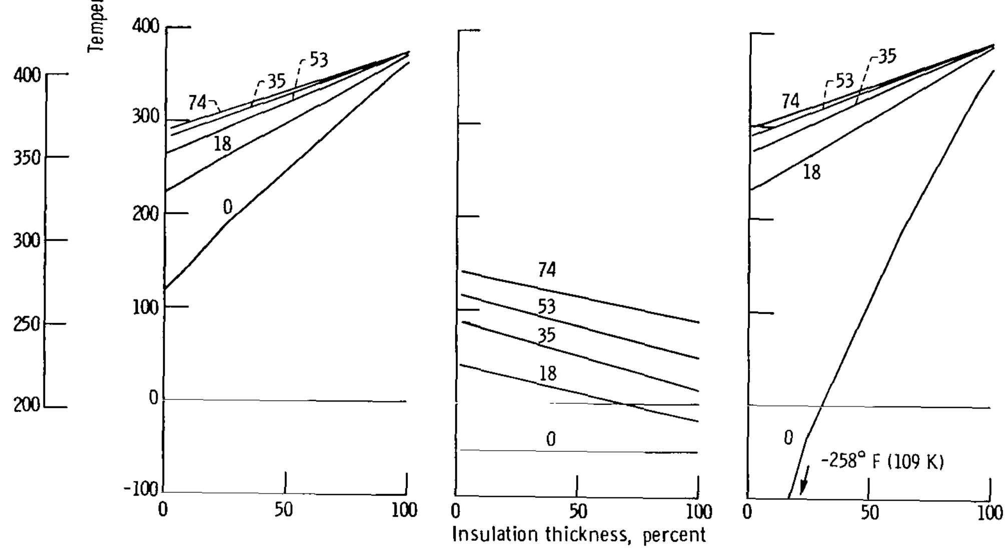
(a) Uniform insulation thickness, 0.5 inch (1.27 cm).

(b) Uniform insulation thickness, 1 inch (2.54 cm).

Figure 10. - Transient temperature history through tank insulation for various times after tanks empty of fuel. Cruise Mach number, 2.7; tank vent pressure, 15 psia (10.3 N/m²); insulation specific weight, 2 pounds per cubic foot (32 kg/m³).



(c) Uniform insulation thickness, 2 inches (5.08 cm).



(d) Insulation thickness, top and bottom, 1 inch (2.54 cm); insulation thickness, sides, 0.5 inch (1.27 cm).

Figure 10. - Concluded.

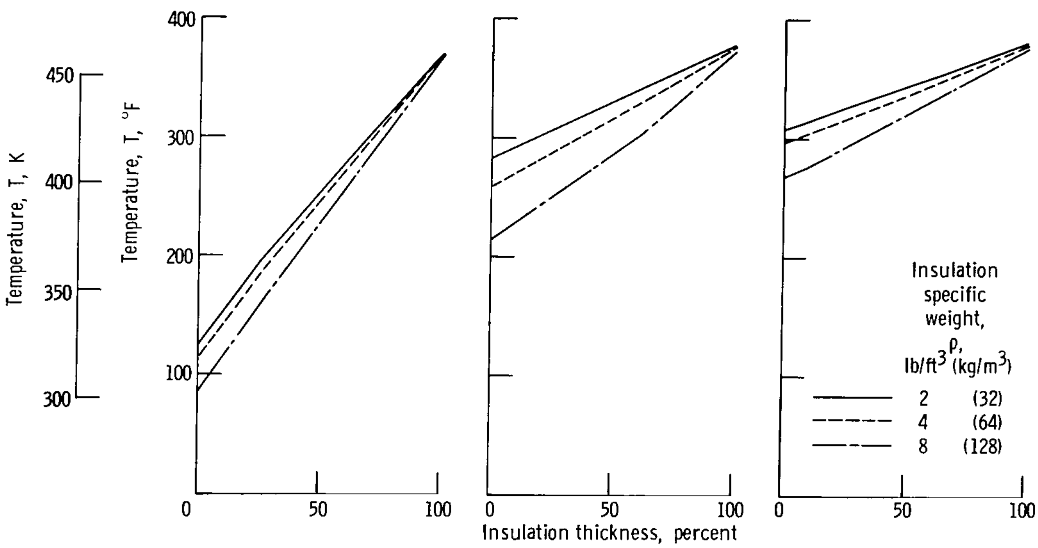
near the end of the mission (74 min) after tank is emptied). The most rapid temperature rise occurs on the tank bottom after the tank is emptied and the liquid methane heat sink is removed. Within 18 minutes, the insulation temperature at the tank bottom very closely approaches the temperature at the tank top, which has not been wetted by liquid methane for almost the entire mission. These results show that the insulation is a poor heat sink.

The temperature levels of the insulation at the top and bottom of the tank are too high to permit use of the common, but very effective insulation, polyurethane foam. This foam degrades at temperature levels approaching 200° F (366 K). The results shown in figure 10 would indicate, however, that polyurethane foam could be used for insulating the sides of the tank since these temperatures never approach 200° F (366 K). The temperatures shown are in the midheight region, however. Data from the computer output show that only the central three-fifths of the tank has temperature levels low enough to use polyurethane foam.

Although the calculations of this analysis were based on the properties of polyurethane foam, it is believed that other insulation systems could be developed that would have a higher temperature capability and similar thermal properties. One possibility under investigation under a NASA contract is a dry-gas-purged multireflective foil insulation with fiber glass separators.

The slope of the temperature curves for the side wall in figure 10 is opposite to that for the top and bottom because the heat flow into the insulation is in the opposite direction. The top and bottom of the tanks are heated primarily by conduction from the outer surfaces of the wing. The conduction path from the outer surfaces through the wing beam separating the wing tanks (see fig. 2) is long. As a result, the primary mode of heating the insulation on the side walls is by convection between the methane vapor in the tank and the side walls.

Figure 11 shows the effect insulation specific weight has on the temperature distribution in the insulation after the fuel tank goes dry. As would be expected, the heavier in-



(a) Time after tank empties, 0 minutes.

(b) Time after tank empties, 35 minutes.

(c) Time after tank empties, 74 minutes.

Figure 11. - Effect of insulation specific weight on transient temperature history through top-of-tank insulation for various times after tanks empty of fuel. Cruise Mach number, 2.7; tank insulation thickness, 1 inch (2.54 cm); tank vent pressure, 15 psia (10.3 N/m²).

sulation would heat up more slowly, but the temperature differences are small. These results do not alter the conclusion that the designer should strive for the lowest specific weight insulation possible.

Consideration is sometimes given to the possibility of not allowing fuel tanks to go dry in order to maintain a heat sink for keeping insulation temperatures at low enough values that materials such as polyurethane foam (with an upper temperature limit of about 200° F (366 K)) could be used for insulation. Figure 12 shows the temperatures through

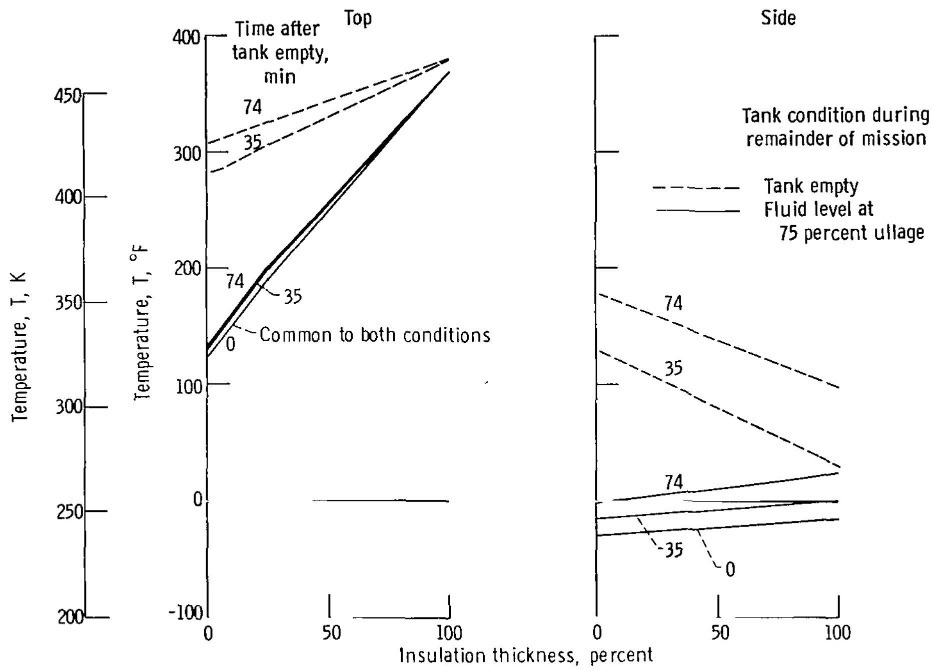


Figure 12. - Effect of residual fuel left in tank on transient temperature history through tank insulation thickness. Cruise Mach number, 2.7; tank vent pressure, 15 psia (10.3 N/m^2); insulation density, 2 pounds per cubic foot (32 kg/m^3; tank insulation thickness, 1 inch (2.54 cm).

the insulation thickness for the top and side wall for the case where 25 percent of the fuel remains in the tank throughout supersonic cruise. These results show that the side walls could be insulated with polyurethane foam for either case (tank allowed to go dry or 75 percent ullage). On the top of the tank about one-fourth of the insulation thickness would be kept below the 200° F (366 K) temperature limit for polyurethane foam. The temperature on the bottom of the tank would be the same as that shown in figure 10(b) for zero minutes after tank was emptied. It can be seen that more than one half of the insulation thickness is at a temperature less than 200° F (366 K).

CONCLUDING REMARKS

From this analytical investigation of insulated wing tanks for liquid methane fuel in supersonic-transport-type aircraft, the following conclusions can be drawn:

1. Even though liquid methane is a cryogenic fuel with a normal boiling point of -259° F (111 K) at 1 atmosphere of pressure, it could be stored in wing tanks of the aircraft and the boiloff losses could be kept to less than $1\frac{1}{2}$ percent or lower for cruise Mach numbers up to 3.5 for an insulation thickness of 1 inch (2.54 cm) if the internal tank pressure could be maintained at 1 atmosphere or above, or if the fuel were initially subcooled approximately 25° F (14 K).

2. Increasing the cruise Mach number does not necessarily result in increased fuel loss due to boiloff in wing tanks. If the fuel from the wing tanks is burned in the engines before fuel is used from the fuselage tanks, it was found for the aircraft configuration investigated the wing tank fuel was used in a shorter time period for cruise Mach numbers of 3.0 and 3.5 than for 2.7, and as a result the venting time was decreased. The resulting boiloffs were approximately the same for all three cruise Mach numbers for an insulation thickness of 1 inch (2.54 cm).

3. Boiloff will occur during fueling and ground hold as a result of both tank chilling and heat transfer into the structure. This boiloff, including a 20-minute fill and an additional 10 minutes of ground hold, can be expected to be less than $1\frac{1}{2}$ percent of the fuel stored in wing tanks and the maximum boiloff rate during filling will probably be less than one thirty-fifth of the fill rate.

4. Wing surface temperature depression during ground hold can cause moisture freezing or frosting problems under some atmospheric conditions. This situation cannot be avoided by adding extra insulation. A method of wing surface heating or adding a deicing fluid will be required.

5. After fuel is expended from wing tanks, the insulation temperature rises rapidly. It does not appear feasible to use common insulations, such as polyurethane foams, because of excessive tank temperatures, with the possible exception of side walls where conduction paths are long and insulation temperatures remain low during the heat soak. Allowing fuel to remain in the tanks would permit about one fourth of the insulation thickness on the top of the tank and about one half of the insulation thickness on the bottom of the tank to be polyurethane foam for a cruise Mach number of 2.7, but fuel losses due to boiloff of this remaining fuel would probably be unacceptable.

6. An airgap between the wing structure and the insulation results in a slight decrease in the heat transferred to the tanks, but the decrease is negligible. The volume

required to ensure an airgap in a volume-limited aircraft probably far overshadows any benefits gained.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 22, 1969,
720-03.

APPENDIX A

SYMBOLS

A	area, ft^2; m^2
C	heat capacity of node, $C_p \rho V$, Btu/^{o}F; W-hr/K
C_p	material specific heat, Btu/(lb)(^{o}F); W-hr/(kg)(K)
H	enthalpy, Btu/lb; W-hr/kg
h	heat transfer coefficient, Btu/(hr)(ft^2)(^{o}F); W/(m^2)(K)
J	mechanical equivalent of heat, ft-lb/Btu; N-m/W-hr
k	conductivity, Btu-ft/(hr)(ft^2)(^{o}F); W-m/(m^2)(K)
P	power factor at time θ
p	pressure, psi; N/m^2
Q	heat added, Btu; W-hr
q	irradiation rate, $q^*VP(\theta)$, Btu/(hr)(ft^2); W/m^2
q^*	base irradiation rate, Btu/(hr)(ft^2); W/m^2
R	gas constant, lb-ft/(^{o}R)(lb); N-m/(K)(kg)
T	temperature, ^{o}F; K
t	thickness, ft; m
u	temperature function of time, ^{o}F; K
V	volume, ft^3; m^3
W	weight of fluid, lb; kg
$W_{evap,f}$	fuel evaporated due to flashing, lb; kg
$W_{evap,q}$	fuel evaporated due to heat added, lb; kg
$\dot{W}$	fuel fill rate, lb/min; kg/min
x	coordinate
Y	admittance, Btu/(hr)(^{o}F); W/K
y	coordinate
Z	compressibility factor
z	coordinate
Δ	incremental
θ	time, hr
ρ	specific weight, lb/ft^3; kg/m^3

Subscripts:

bo	boiloff
evap	total fuel evaporated across interface
f	total wing fuel weight
g	gas
I	insulation
i,j,k	index
l	liquid
lh	latent heat
max	maximum
min	minimum

ref	reference
s	local
sat	saturated
used	fuel used
v	vapor
vt	vent
θ	time index
1,2	initial and final states of fluid, respectively
∞	free stream

APPENDIX B

TRANSIENT HEAT TRANSFER METHOD

The temperature calculation code TØSS is based on a calculational procedure developed in reference 14. The calculations consist of stepping through time in increments of $\Delta\theta$ and solving the explicit form of the first forward finite-difference expression for a general form of the heat-diffusion equation without internal heat generation applied in three dimensions (x, y, and z) for each node

$$\frac{\partial}{\partial x}\left[k(T)\frac{\partial u}{\partial x}\right] + \frac{\partial}{\partial y}\left[k(T)\frac{\partial u}{\partial y}\right] + \frac{\partial}{\partial z}\left[k(T)\frac{\partial u}{\partial z}\right] = \rho C_p(T)\frac{\partial u}{\partial \theta} \tag{B1}$$

where

$$u = T(\theta)$$

The insulation and wing structure shown in figure 2 is divided into a number of cells and each cell is associated with one of its interior points and is called an internal node. Each node is considered to be a parallel piped and is specified by an index number j, physical dimensions of length, width and depth, and thermal properties of the cell material. Surfaces of cells which lie on a boundary are associated with its surface points and are called surface nodes. The surface node is specified by a surface area and a film coefficient. The model is then described or represented by a three-dimensional mesh of these cells or nodes. The number of nodes to describe the wing tank models varied from 165 to 270 internal nodes and 139 to 160 surface nodes for insulation thicknesses of 0.5 to 2 inches (1.27 to 5.08 cm), respectively.

Assumptions. - The basic assumptions used in deriving the explicit finite-difference form of the thermal equation are as follows:

(1) In calculating the change of temperature of any node for a small time interval, only that node and its adjacent nodes are considered.

(2) The temperature at any node is the average temperature over its own increment.

(3) The initial rate of temperature change for any time interval is constant over the whole interval.

Heat transfer calculations. - The explicit finite-difference form of equation (B1) with irradiation is

$$\frac{\Delta\theta}{C_j}\left[\frac{q_j}{t_j} + \sum_i T_i(\theta)Y_{ij}\right] = \Delta T_j \tag{B2}$$

where i denotes all neighboring nodes of internal node j and j itself, and Y_{ij} represents the reciprocal of the heat transfer resistance between either adjacent internal nodes or surface-to-internal nodes. The boundary effect is transmitted to the internal node by virtue of an appropriate heat transfer coefficient between boundary and surface nodes.

Equation (B2) is written for each internal node j and is solved explicitly for ΔT_j, and subsequently,

$$T_{j,\theta+\Delta\theta} = T_{j,\theta} + \Delta T_j \tag{B3}$$

The updated temperature of node j is then used for the next time increment.

This procedure is continued until the end of a specified time interval is reached, which in this report is a 1-inch (2.54-cm) level drop in the tank, at which time new fluid states are computed.

Stability. - The explicit solution of the set of equations is stable under certain conditions on $\Delta\theta$ for all internal nodes j. The absolute stability relation from reference 14 is

$$\Delta\theta_{max} = \left(-\frac{C_j}{Y_{jj}}\right)_{min} \tag{B4}$$

Test runs with $\Delta\theta$ multiplied by factors greater than 1 showed insignificant changes in final results and therefore factors of 2 were used to conserve computing time.

APPENDIX C

THERMODYNAMICS

Instantaneous average temperatures of the gaseous and liquid methane remaining in the tank are the constant boundary temperatures used for transient heat transfer computations during a succeeding computing time interval. An iterative algorithm applied to the heat balance equations given in this appendix yields the gas state point and liquid state point as a function of heat added, weight of liquid used, and weight of gas vented as obtained from a preceding computing time interval. The time interval between thermodynamic computations is arbitrarily set to ensure overall stable computations.

Initial input data. - The following data are required initial input data:

(1) Fluid properties: saturated methane properties, superheated methane properties, and compressibility factors

(2) Wing tanks fuel usage schedule

(3) Vent pressure schedule

(4) Geometry data: surface areas in contact with fluid; tank dimensions (cross section and length)

Assumptions. - The following assumptions affect the computation of gaseous and liquid methane state points:

(1) No heat transfer across the interface between gas and liquid; no radiation heat transfer to liquid from tank walls

(2) No condensation

(3) Liquid in saturated condition with $p_v \leq p_{vt}$

(4) Gas pressure between p_v and p_{vt}

(5) Gas temperature less than maximum temperature of adjacent insulation

(6) Complete mixing of gas in ullage space

(7) No stratification in liquid regions

Heat balance equations. - The pressure, temperature, and enthalpy values of gaseous and liquid methane remaining in the tank are obtained by solving heat balance equations after each transient heat transfer computing time interval.

Gaseous methane in ullage space: The primary heat balance equation defining the gas state in the ullage space for moderate amounts of liquid evaporation and gas vented is

$$W_{g,2}H_{g,2} = W_{g,1}H_{g,1} + Q_g - \frac{1}{J}\int p\,dV + W_{evap}H_{g,sat} - W_{bo}\left(\frac{H_{g,1} + H_{g,2}}{2}\right) \qquad \text{(C1)}$$

Initial conditions of various terms and their source are discussed below.

Liquid methane remaining: The heat balance equation defining the liquid state of the remaining liquid fuel in the tank is

$$W_{l,2}H_{l,2} = W_{l,1}H_{l,1} - W_{evap}H_{lh} + Q_l - W_{used}H_{l,1} \tag{C2}$$

where

$$W_{used} = W_{l,1} - W_{l,2}$$

and the enthalpies used are at saturated liquid condition.

Initial conditions for each computation. - The iterative algorithm requires the use of starting values and updated values of unknowns on subsequent computations to solve the preceding heat balance equations.

Starting values: The previously computed gas state variables $W_{g,1}$ and $p_{g,1}$ are substituted for $W_{g,2}$ and $p_{g,2}$, respectively, with $W_{evap} = W_{bo} = 0$. Heat added to the gas in the ullage space is obtained from the heat transfer analysis data using the incremental equation

$$Q_g = \left(\sum_i k_i A_i \frac{\Delta T_i}{\Delta x}\right)\Delta\theta \tag{C3}$$

where i ranges over the insulation material nodes adjacent to the gas, $\Delta\theta$ is the previous heat transfer computation time period, and ΔT_i is the temperature difference across Δx insulation adjacent to the ullage space. Since ΔT_i is a function of a changing gas temperature, Q_g is updated for every iteration cycle.

For the liquid, $W_{l,2} = W_{l,1} - W_{used}$ and $W_{evap} = 0$ are substituted in equation (C2). Heat added to the remaining liquid is computed similar to equation (C3)

$$Q_l = \left(\sum_i k_i A_i \frac{\Delta T_i}{\Delta x}\right)\Delta\theta$$

where i ranges over the insulation material adjacent to the liquid and includes effects of sloshing and liquid evaporation off of wetted surfaces exposed by fuel used.

Updated values: The following equations are used to obtain updated values during each iteration cycle.

For the gas,

$$T_{g,2} = f\left[\left(p_{g,2}\right)_k, \left(H_{g,2}\right)_{k+1}\right] \qquad T_{g,2} \leq T_{I_{max}}$$

$$\left(p_{g,2}\right)_{k+1} = \frac{Z\left(W_{g,2}\right)_k RT_{g,2}}{V_{g,2}} \qquad p_{l,2} \leq p_{g,2} \leq p_{vt}$$

$$\left(W_{g,2}\right)_{k+1} = \frac{\left(p_{g,2}\right)_{k+1} V_{g,2}}{ZRT_{g,2}}$$

with

$$W_{evap,q} = \frac{W_{l,2}\left(H_{l,1} - H_{l,2}\right) + Q_l}{H_{lh}}$$

$$W_{bo} = W_{g,1} + W_{evap,q} - W_{g,2}$$

A change of 1° F (0.55 K) in $T_{g,2}$ between consecutive computations ends the iteration.

For the case where $p_{g,2} < p_{l,2}$, additional mass transfer across the interface due to flashing occurs

$$W_{evap,f} = W_{g,2} - W_{g,1} - W_{evap,q}$$

Total mass transfer W_{evap} used in equations (C1) and (C2) is computed from

$$W_{evap} = W_{evap,q} + W_{evap,f}$$

For the liquid,

$$W_{l,2} = W_{l,1} - W_{used} - W_{evap} \tag{C4}$$

Conservation of weight. - During the iterative computations, the properties of the fluids vary as a function of the temperatures and pressures, which affects the weight of the various volumes being computed. Equation (C4) and the following equation represent a consistent set of conditions which all the portions of the total weight of fluid must satisfy:

$$W_{g,2} = W_{g,1} + W_{evap} - W_{bo}$$

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NASA-Langley, 1970 —— 28 E-5258

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