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HELIUM PRESSURIZATION SYSTEMS FOR LIQUID-METHANE FUEL IN SUPERSONIC TRANSPORTS

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16. Abstract

Using liquid-methane fuel in place of JP fuel promises economic improvements. However, with fuel loaded in a saturated condition, much will flash off as tank pressure lowers during climb. Subcooled fuel solves this problem but requires the use of scarce pressurants, the loss of which must be prevented. Three systems for using helium for pressurization are studied: One holding the helium within the fuel tanks; one returning the helium to its high-pressure bottle; and one allowing, but minimizing, helium loss. Results indicate that these systems offer potential solutions to the tankage problem but are exceedingly complex.

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SUMMARY

Because liquid methane has a greater heating value and heat-sink capacity than JP fuel, use of liquid methane in supersonic transports promises economic improvements. However, the cryogenic nature of liquid methane results in aircraft fuel tankage problems.

Chief among these problems is that resulting from the decrease in ambient pressure as the aircraft climbs. If the fuel is loaded as a saturated liquid at 201° R (112 K), much fuel will evaporate during climb as the tank pressure is reduced with increasing altitude. One method for solving this problem is to load the fuel in a subcooled state with a resulting lower vapor pressure. However, with subcooled fuel a pressurizing gas is required.

The pressurizing gas must be safe and have a low solubility in methane. Only scarce gases such as helium and neon meet these criteria. If these gases are used, methods to minimize or eliminate their loss must be employed. This report examines three helium pressurization systems in order to determine their feasibility. The first is a helium circulation system, where the helium gas is held within the fuel tanks. The second system is a helium rebottled system, where the helium gas is returned to its high-pressure bottle. And the third system is a minimum helium loss system, where the magnitude of the helium loss is balanced against the loss in aircraft performance due to fuel boiloff.

It was found that all three systems allow gains in payload of more than 20 percent when compared with JP-fueled supersonic transports, retaining most of the 28-percent potential payload increase offered by methane. However, the present study is not sufficiently detailed to make a certain, definitive judgment as to which system is best. All three of these systems are very complex. Thus, eventually, detailed design studies must be made to evaluate them along with other proposed pressurization systems, including the more simple approach of high-pressure tanks, to determine which system to use.

INTRODUCTION

The heating value and the cooling capacity of liquid methane are both greater than those of kerosene or JP-type fuels. Because of these characteristics, methane has been suggested as a fuel for various types of transportation, ranging from trucks to supersonic transports (SST). Further, it is estimated in reference 1 that the cost of liquid methane on a unit weight basis could be 10 percent less than that of JP. Due to these attributes, improvements in aircraft performance and direct operating cost are possible by using methane.

Previous studies (refs. 2 and 3) show that by using liquid methane in a Mach 3, supersonic transport aircraft, there is a possible increase in passengers of about 30 percent over the load carried by a similar JP-fueled aircraft of equal gross weight flying the same distance. The direct operating costs are lowered by nearly the same amount. In determining these gains it was assumed that systems to prevent excessive fuel boiloff, or to utilize it, could be developed and would add very little in the way of fuel system weight penalties. Additional studies were suggested to assess development problems and fuel system weight penalties and their effect on airplane performance.

Fuel boiloff results from two conditions, that of heat influx and that of reduction in pressure during climb. The heat influx occurs because the normal boiling point of methane is 201° R (112 K), yet the external temperatures can vary from about 520° R (289 K) during ground and subsonic operations to the Mach 3 air-stagnation temperature of 1080° R (600 K) during cruise. This boiloff due to heating can be effectively limited by insulation. Unfortunately, the boiloff caused by a reduction in tank pressure as the aircraft rises from the ground to cruise altitude is not as amenable of solution.

The problem is this: As supersonic aircraft are now being designed, the fuel will be stored in integral tanks, mainly in the wing. In general, these tanks can hold a pressure differential of only 4 to 6 psi (28 to 41 kN/m^2). If these conventional JP-type tanks must be used for methane, and if the methane is loaded on the ground as a saturated liquid, boiling at 1 atmosphere of pressure, as the aircraft rises and ambient pressure drops the internal pressure must be reduced in order not to exceed the maximum tank differential pressure. The fuel will then boil off a sufficient amount to reduce its temperature to that of the new boiling point. If the maximum pressure differential is 4 psi (28 kN/m^2), 9 percent of the weight of fuel would be lost (ref. 3). In reference 4, still assuming a constant gross weight and a constant range, it is estimated that because of this loss in fuel the gain in passengers resulting from the use of methane would be only 7 percent. In reference 5 the same problem is studied; however, there the gross weight is allowed to vary and the number of passengers is held constant. The possible reduction in direct operating cost is still small, only 12 percent. Thus, pressure boiloff can cause the loss of a great part of the potential 30-percent liquid-methane payload improvements.

In reference 4 several methods are presented for alleviating this situation. The most straightforward method is that of using nonintegral high-pressure tanks, tanks designed so that they could withstand the maximum pressure differential that would occur in flight. Thus, the tanks need not be vented, and the evaporation caused by decreased tank pressure during climb is eliminated. A penalty in tank weight is incurred, however. Strengthening the structure to allow the use of the integral tanks at high pressures is another, and more basic, high-pressure tank approach. Unfortunately, the existence or magnitude of weight penalties that might be associated with this method can only be determined by an in-depth aircraft design. Such studies are not available in the current literature.

In references 2 and 3 another approach which avoids the tank weight penalty is proposed. Here the climb boiloff is completely eliminated by loading the fuel subcooled, corresponding to a vapor pressure lower than the lowest tank pressure to occur in flight. With this method, however, a problem exists at takeoff and low altitudes because the vapor pressure is now lower than atmospheric. The difficulty is this: The fuel tanks cannot support negative pressure and, thus, if the tanks are sealed and any void spaces exist, a gas is required to fill these voids in order to prevent tank collapse.

For JP fuel the pressurant could be a gas such as air or nitrogen. As pointed out in reference 6, nitrogen and oxygen are very soluble in methane, about 10 percent by weight in methane subcooled 25° R (14 K). Reference 3 estimates that due to this solubility of nitrogen, all gains are lost by using it; and the assumption was made, therefore, that nitrogen could not be used as a pressurant. In reference 5, however, it is shown that if gross weight rather than number of passengers is allowed to vary, and if the nitrogen comes out of solution during climb, then some gains in direct operating costs can still be achieved. Nevertheless, using air or nitrogen could result in sizable decrements from the potential advantages of liquid methane, and thus it would be desirable to avoid their use as pressurants for the liquid-methane fuel.

One method of avoiding the use of soluble pressurants when using subcooled fuel is to fill the tanks, or the great majority of the tanks, in such a manner that no void spaces exist, thus avoiding the necessity of using any pressurant gas at all in them (refs. 4 and 5). If ullage spaces cannot be eliminated, another approach is to use some relatively insoluble gas rather than the more common soluble gases.

Reference 6 indicates that hydrogen, helium, and neon are the only candidate gases. It is unlikely that hydrogen would be considered since it is highly flammable. This leaves neon and helium as the only relatively insoluble gases practical for pressurizing subcooled methane. However, both of these gases are relatively scarce, and if they are to be used as pressurants, methods to eliminate or severely limit the loss of gas must be employed.

The situation with neon and that with helium are somewhat different. Neon, although scarce, is obtained from the atmosphere. The supply is thus essentially limitless, but the cost of obtaining it is very high. The resulting price of neon is about \$14 per pound

($31/kg). Therefore, neon must be conserved because of cost.

Helium is not only scarce, but it also exists in obtainable quantities only in natural deposits within the earth's crust. Thus, helium is limited in total quantity. Further, helium is also a vital industrial commodity, and it is therefore protected by the United States Government as a limited natural resource. The short supply of helium can be illustrated by the fact that if helium were used to pressurize the projected number of SST's, and if current techniques of pressurization were used (where the pressurant gas is used for fuel expulsion and is not salvaged), the current total world production of helium would be required for this purpose (ref. 4). Thus, even without considering cost, helium must be conserved.

This report is devoted entirely to pressurization with helium in systems which either minimize or eliminate helium loss. An examination is made of three systems in order to determine their feasibility. The first system is a helium circulation system in which the excess helium in any one fuel tank is transferred to other emptying fuel tanks and thus kept within the fuel tank system. The second system is a rebottled helium system in which excess helium in any fuel tank is returned to the high-pressure helium bottle from which it was originally released. The third system is a minimum helium loss system in which some fuel is loaded subcooled and pressurized with helium, and some fuel is loaded in a saturated liquid state. With this third system no attempt is made to recover excess helium from any tank and there results a tradeoff between helium loss and loss of fuel from boiloff.

Penalties to aircraft performance are estimated for each system. These penalties are used to determine the effect on number of passengers for a Mach 3 supersonic transport having a takeoff gross weight of 460 000 pounds (208 652 kg) and flying a range of 3500 nautical miles (6482 km).

DESCRIPTIONS AND RESULTS

General Descriptions

Benefits of methane. - The comparative characteristics of methane and JP fuels that are important to this study are presented in table I. The heat of combustion of methane is 13 percent higher than that of JP. Thus, fuel consumption will be lower. The liquid specific heat and the heat of vaporization of methane are both much higher than those of JP, the actual heat-sink capacity of methane being more than four times that of JP. This greater heat-sink capacity allows more turbine-blade cooling than is possible with JP, since the air that is used to remove heat from the turbine blades can be greatly cooled by the cryogenic methane prior to coming in contact with the blades. This then

TABLE I. - FUEL PROPERTIES

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

permits a higher turbine-inlet gas temperature, which in turn results in smaller, and thus lighter, engines.

In addition to these fuel characteristics that improve overall aircraft performance, methane also offers another important advantage. The high thermal stability of methane virtually eliminates coking, a problem that is becoming more serious as ever higher environmental and engine cycle temperatures are being encountered (ref. 7).

Aircraft used. - The aircraft that is used in this report to evaluate the benefits afforded by the use of methane is the SCAT-15F, a hypothetical, Mach 3, arrow-wing, four-engine supersonic transport. This aircraft was originated by the NASA Langley

TABLE II. - AIRCRAFT CHARACTERISTICS

Takeoff gross weight, lb; kg	460 000; 208 652
Range, n mi; km	3500; 6482
Engine	Afterburning turbojet
Engine turbine-inlet temperature, $^{\circ}$R; K:	
JP-fueled	2660; 1478
Methane-fueled	3260; 1811
Basic fuel system fraction, percent $\left(\frac{\text{Weight of fuel system}}{\text{Weight of fuel}} \times 100\right)$	2.09
Deicer fraction, percent $\left(\frac{\text{Weight of deicers}}{\text{Weight of fuel}} \times 100\right)$	0.16

Research Center. The pertinent aircraft data are presented in table II. The basic fuel system fraction consists of the weight of plumbing and controls that would be required for whatever fuel is used. The deicer fraction represents a system to prevent ice formation on the surface of the cryogenic-filled aircraft during groundhold and low-speed operation. More detailed information concerning this aircraft can be found in reference 3.

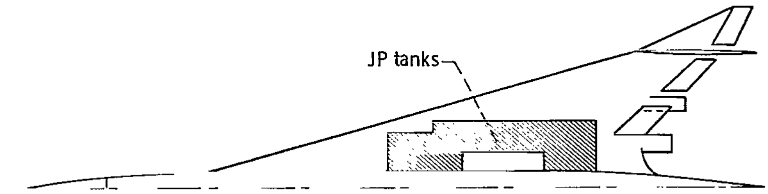
The fuel tanks for the SCAT-15F are shown in figure 1. This figure indicates the volume problem that results from the lower density of methane. When JP is the fuel, only part of the void space in the wing is required for fuel storage. If lower-density methane (table I) is used, however, most of the available volume in the wing and fuselage must be used. Seventy percent of the fuel is still stored in the wing. Of the various aircraft configurations derived by NASA and industry during the SST design effort, the SCAT-15F had the largest volume available for fuel storage. Other aircraft configurations might possess less volume for fuel storage and would have to be stretched in some fashion, with a consequent weight and drag penalty.

Environmental conditions. - The magnitudes of the tankage problems with methane fuel are a function of the severity of the external environment that the aircraft encounters during the flight. The heat flow into the fuel results from the difference between the temperature of the fuel, boiling at only 201° R (112 K) at 1 atmosphere (table I), and that of the air adjacent to the skin of the aircraft. This air temperature can possibly be as high as the stagnation temperature depending on the location on the aircraft and the time into the flight.

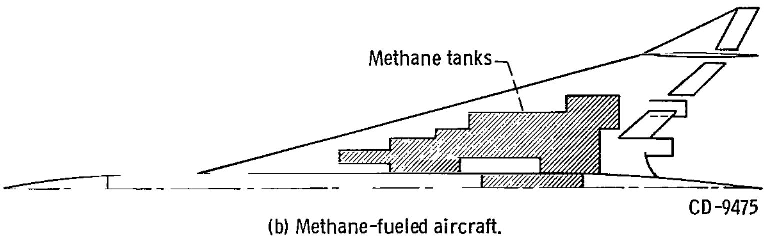
Figure 2(a) presents Mach number as a function of time into the flight. The great majority of the flight is flown at velocities greater than Mach 1, with cruise velocity at Mach 3. It is these high velocities that cause the high stagnation temperatures shown in figure 2(b). The temperature difference is greatest during the supersonic cruise, when the stagnation temperature is nearly 1100° R (611 K). However, high thermal gradients exist at all times in the flight, even during ground operations.

Figure 2(c) presents the aircraft altitude as a function of time into the flight. The climb is very rapid, with cruise altitude being above 70 000 feet (21 336 m). The resulting ambient pressures are shown in figure 2(d). They start at 14.7 psi (101.4 kN/m^2) at sea level and drop to about 0.5 psi (3.4 kN/m^2) at cruise altitude, a 97-percent pressure decrease. Thus, if the fuel were kept at 1 atmosphere, for example, at cruise the tank walls would have to have the strength to contain very nearly all of the internal pressure.

Pressurization requirements and heating. - The problems that must be overcome in order that this system function are made obvious by an examination of the pressurization requirements of the aircraft fuel and the heat input into the pressurant gas. Figures 2(c) and (d) show that during groundhold the pressurant simply fills the void spaces in the

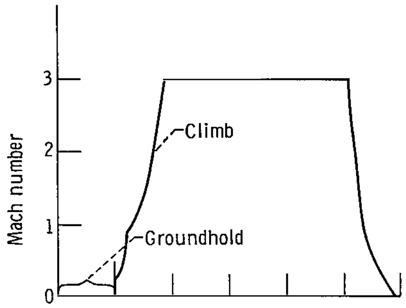


(a) JP-fueled aircraft.

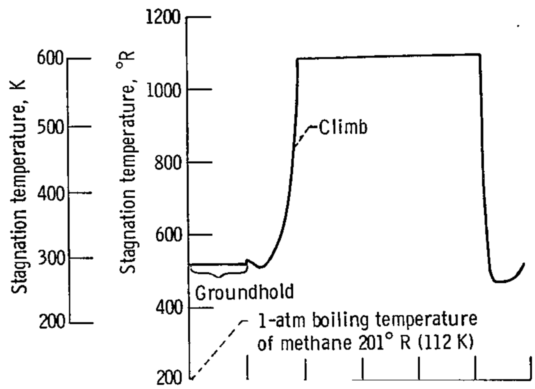


(b) Methane-fueled aircraft.

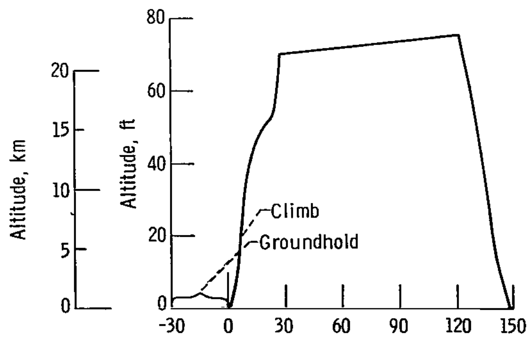
Figure 1. - Aircraft fuel tanks.



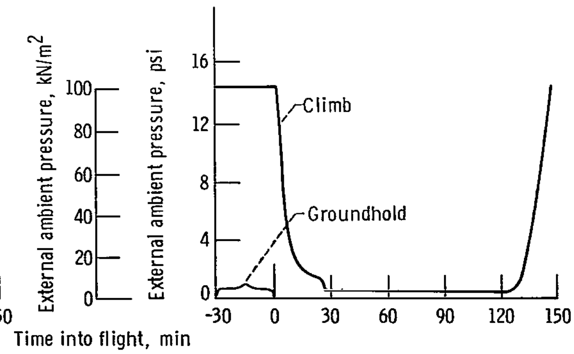
(a) Mach number.



(b) Temperature.



(c) Altitude.



(d) Pressure.

Figure 2. - Airplane environment.

tanks to prevent tank collapse and to allow the fuel to be pumped. As the aircraft takes off and then rises in the early part of its climb, the external pressure remains close to 1 atmosphere, and helium is added from the high-pressure bottle into the emptying fuel tanks in order that internal pressure matches external.

As the aircraft climbs higher, the drop in ambient pressure makes it unnecessary to add more helium to the system in order to keep the internal pressure equal to the external. Pressurization of the fuel tanks can then be accomplished merely by allowing the helium already in the tanks to expand into the spaces resulting from fuel usage. Eventually, as the aircraft continues to gain altitude, the ambient pressure falls at a more rapid rate than can be achieved internally by allowing this expansion of the pressurant gas into those spaces being emptied of fuel. At this point, a pressure differential across the tank wall must be tolerated if no helium is to be vented. If this differential pressure is in the range of 4 to 6 psi (28 to 41 kN/m^2), a pressure which integral wing tanks can contain, it can be allowed and no helium need be lost.

This situation is overly simplified, however, for no mention has been made of possible temperature increases of the helium pressurant. Actually, once a tank empties and no longer contains low-temperature methane, the temperature of the gas tends to rise rapidly and cause a correspondingly rapid rise in pressure. Even in tanks containing methane the helium temperature will rise slightly because the external skin temperature rises as the aircraft speed increases.

Methods and equipment weights. - There are several factors affecting the performance and weights of all three pressurization systems. These factors are discussed here.

Heat into fuel: The actual amount of heat into the fuel is a function of the temperature of the aircraft skin, since the skin is used as the tank wall in this study, and the degree of isolation of the fuel from this heat source. The methods for determining the skin temperatures are presented in appendix A.

When the skin temperatures during the flight are known, the heat protection required can be computed. The insulation characteristics used for computations in this study are those of a form of MIN K. The properties of this insulation were given in reference 3 and are presented here in table III. Reference 8 discusses the composition of MIN K insulation.

TABLE III. - PROPERTIES OF MIN K INSULATION

Density, ρ, lb/ft^3; kg/m^3	10; 160
Thermal conductivity, k, Btu-ft/(ft^2)(hr)(^oR); J-m/(m^2)(hr)(K)	0.0108; 67.35
$k\rho$, Btu-lb/(ft^4)(hr)(^oR); J-kg/(m^4)(hr)(K)	0.108; 10 776

The manner in which the insulation is applied and the computation of its thickness are discussed in detail in appendix A. The thickness of insulation on each tank and thus the total weight of insulation is the same for all three systems presented in this report.

Subsystem weights: Associated with the three fuel systems presented in this report are several subsystems which have a sufficiently large weight that they noticeably affect the number of passengers that can be carried aboard the aircraft. These subsytems are described briefly in this section.

Common to all three pressurization systems is the high-pressure, spherical bottle of helium gas. The weight of the helium and the size and weight of the bottle required to contain it are the same for all the systems. The gas is kept at liquid-methane temperatures by submerging the bottle of helium in the reserve fuel during all normal operations. To allow this submergence a bottle diameter of 5 feet (1.52 m) is chosen.

The helium circulation and helium rebottled pressurization systems both require compressors for pressurizing the vapors, as well as ducting to transport, and heat exchangers to cool, the helium-methane vapor mixture.

A complete discussion of all these subsystems and the equations used in computing their weights is presented in appendix A.

General Results

Table IV presents a summary of weights that are common to all three systems. The basic system fraction and deicer weights are both from reference 3. The total weight of mission fuel for the three systems studied remains very close to the 185 000 pounds (83 990 kg) noted. All weight penalty fractions are assumed to remain constant for all cases. Thus, the sum of these weight penalty fractions, 5.41 percent, is used for any of

TABLE IV. - SUMMARY OF GENERAL WEIGHTS

	Weight		Fraction of total fuel, percent
	lb	kg	
Total fuel	185 000	83 990	100.00
Basic fuel system fraction	3867	1756	2.09
Deicer system	300	136	.16
Pressurant and bottle	740	336	.40
Insulation	5106	2318	2.76

the cases investigated in this report. In addition to these, each system has other weight penalties which are presented where the particular system is discussed.

The pressure in the high-pressure helium bottle is not listed in table IV since it does not affect the weight of the bottle. The weight of the helium carried is 192 pounds (87.1 kg), which is sufficient to pressurize 90 percent of the total tank volume of the aircraft to 1 atmosphere. This is also sufficient helium such that the methane fuel could be pressurized in the more conventional manner of using helium for all pressure control and dumping the excess overboard with no attempt at either minimization of use or salvage. In order to keep the 5-foot (1.52-m) bottle diameter, a pressure of 1500 psi (10 343 kN/m^2) is required. The magnitude of this pressure has a major effect on the operation of the helium rebottled system. This effect is discussed later.

Helium Circulation System Description

The helium circulation system (HC) is one possible technique for using helium-pressurized, subcooled methane which includes special provisions to avoid any loss of helium during the flight. The basic idea in the HC system is to keep all the helium gas that is released from the pressurant bottle confined within the fuel tanks so that at the end of the flight this gas may be salvaged.

The system. - In the section Pressurization requirements and heating, it was pointed out that the chief cause of loss of the helium pressurant was the heating of this gas. Therefore, a method for constantly compressing, cooling, and reexpanding the helium gas back into the fuel tanks is used to maintain a constant, low, gas temperature. The complete system is shown schematically in figure 3. The helium gas is initially released from its high-pressure bottle into the fuel-tank ullage space. The average temperature of the fuel is assumed to be 172° R (96 K), with a resulting average vapor pressure of 2.7 psi (18.6 kN/m^2) (ref. 9). The helium becomes mixed with methane vapors. As this gas mixture warms up, it is removed from the fuel tank, compressed, and passed through the heat exchanger. It is cooled by transferring its heat to some of the fuel going to the engines, changing this fuel from the liquid to the gaseous state - that is, boiling it. The mixture is then expanded through a turbine and reintroduced into the fuel tank in this cooled state. This turbine supplies most of the work for the compressor, thus reducing the amount of pump work the engines must supply.

Choice of allowable temperature rise in gas. - When the pressurant enters a tank, it immediately begins to absorb heat, and the temperature rises. This continues until the gas leaves the tank to be recooled. Since the tank geometry, tank insulation, and external environment are fixed, the only way that the allowable temperature rise δT can be changed is by a change in the flow rate of the gas $\dot{W}_g$ through the tank. An increase

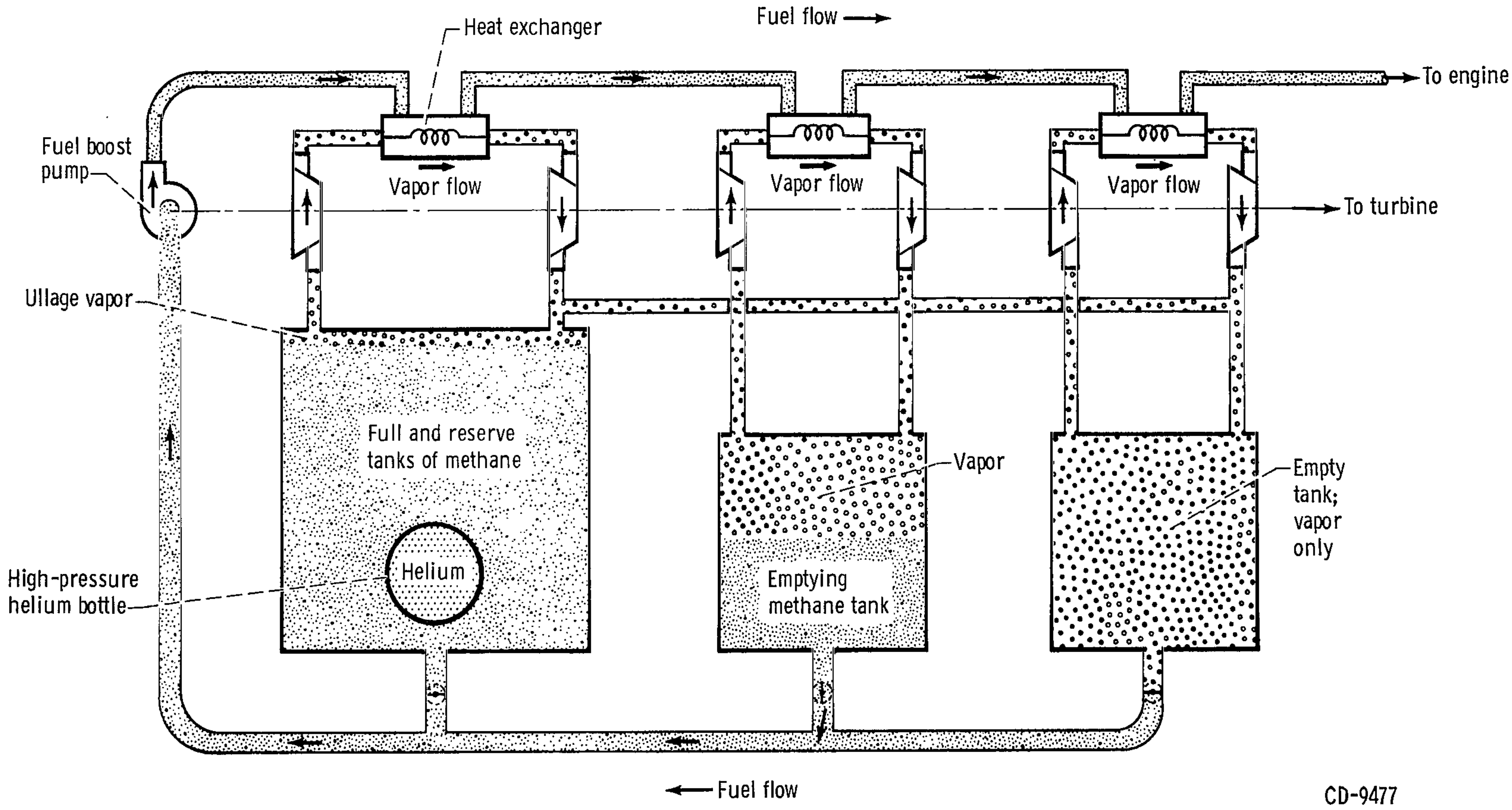


Figure 3. - Helium circulation system.

in $\dot{W}_g$ results in a reduction in δT. A compromise between a large δT and a high $\dot{W}_g$ is made. A discussion of the reasoning used in determining δT is presented in appendix A. All symbols used in this and the following sections are defined in appendix B.

Ducting and pressure ratio. - When the gas weight flow $\dot{W}_g$ and the temperatures of the pressurant at tank entrance and tank exit are known, the ducting can be designed. A ducting layout is assumed that could allow the circulation of vapors from and to all parts of the 100-foot- (30-m-) long tankage area. This system consists of 24 feeder pipes, 12 lines carrying the warm gas toward the heat exchangers and 12 return lines. These feeder lines lead into, or from, four larger main pipes. The average feeder pipe length is 20 feet (6.1 m). Since each feeder line services more than one tank, the average flow distance is somewhat less than the pipe length, averaging 12 feet (3.7 m). The main pipes are 80 feet long (24.4 m).

A maximum diameter for the main pipes is assumed to be 0.75 feet (0.23 m), with a maximum flow Mach number of 0.25. With the diameter set and the rate of weight flow and the physical characteristics of the vapors known, the allowable volume flow, and thus the pressure ratio for compressing the gas, can be determined. Since both the pressure and total weight flow of the pressurant gas are now determined, the diameter of the feeder ducts and the Mach number through them is also determined. The weight of the ducts is computed by assuming that they are constructed of titanium.

Power required to compress pressurant gas. - The compression of the pressurant vapors requires a significant amount of power from the engines. A complete discussion of the assumptions used in calculating the power and the fuel usage is presented in appendix A.

Weight of compressor and expansion turbine. - At this point the weight of pressurant flow, the pressure ratios, and the power of both the compressor and the expansion turbine are available. Thus, the empirical equations presented in appendix A can be used to calculate compressor and expansion turbine weights.

Cooling requirement for pressurant. - When the pressurant vapors leave the fuel tanks, they are already in need of cooling. They are then compressed, and thus the temperature is further increased. In the heat exchanger the vapor temperature is lowered sufficiently so that after the vapor expands again, through the expansion turbine into the tanks, the temperature is that required for entry into the fuel tanks.

It is necessary to determine both the temperature reduction required in the pressurant vapor and the heat-exchanger weight. The assumptions made and a more complete discussion are presented in appendix A.

Letdown. - During climb and cruise the rate of fuel flow to the engines is quite high. Thus, only a fraction of the heat-sink capacity of the fuel would be required to cool the pressurant gas (ref. 4). During descent, however, the engines would most probably be at idle, and thus almost no fuel heat sink would be available. A rapid descent using thrust reversal, rather than a low-power descent, might be possible. However, in this study a low-power descent is assumed. Therefore, some extra fuel must be used for cooling. After completing its cooling task, this fuel would then be dumped overboard as a vapor and lost.

An accurate determination of the temperature of the aircraft skin and structure during all periods of the letdown is beyond the scope of this study. Two boundary cases are chosen, however. In the first case, the skin and structure surrounding the fuel storage spaces are assumed to be at cruise temperature all the way down. Since there would certainly be some cooling of the aircraft as the Mach number drops, this assumption would be conservative. In the second case, it is assumed that in the skin and structure there is an instantaneous temperature drop to the adiabatic wall temperature T_{aw} associated with the reduced Mach number. This is a lower bound since there would actually be some lag in structural cooling.

With the approach just described the magnitude of the amount of extra fuel that must be used during descent only for pressurant cooling and the effect of such use upon aircraft performance can be computed.

Helium Circulation System Results

Tank differential pressure. - The initial situation examined in the HC system assumes no heating of the pressurant gas. This condition was presented in detailed descriptions in the section Pressurization requirements and heating. As noted there, in this case the excess pressure in climb is relieved by letting the gas fill the voids that are left as the fuel is consumed. Figure 4 shows the resulting pressure differential Δp_d across the tank wall as a function of time into the flight. Only the climb and cruise segments of the flight are presented. Note that if no heating of the vapors took place, the maximum Δp_d would be that at the end of climb, 5.6 psi (38.6 kN/m^2). Since it may be expected that conventional JP integral tanks can hold a differential pressure of from 4 to 6 psi (28 to 41 kN/m^2), this 5.6-psi (38.6-kN/m^2) Δp_d can be assumed to be acceptable. The central problem, then, is to keep the vapors cool.

Weight flow rate of vapors. - Figure 5 presents the weight flow rate of the pressurant vapors $\dot{W}_g$ as a function of the allowable temperature rise δT of these vapors as they pass through a tank. This curve is for the end of cruise when the maximum flow of pressurant gas occurs. The 1 percent rate of change of slope point is indicated on figure 5. This point, as explained in appendix A, is used to determine the weight flow and allowable rise in temperature to be used in this study. The δT that results is 60° R (33 K), with a sizable pressurant weight flow $\dot{W}_g$ of 20 pounds per second (9.1 kg/sec).

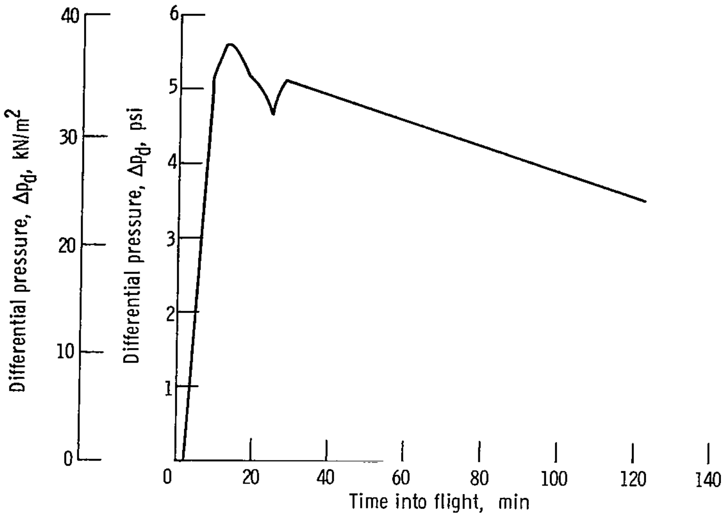


Figure 4. - Helium circulation system differential pressure across tank wall as function of time. Assumed average fuel temperature, 172° R (96 K); no heating of gas; methane vapor retained.

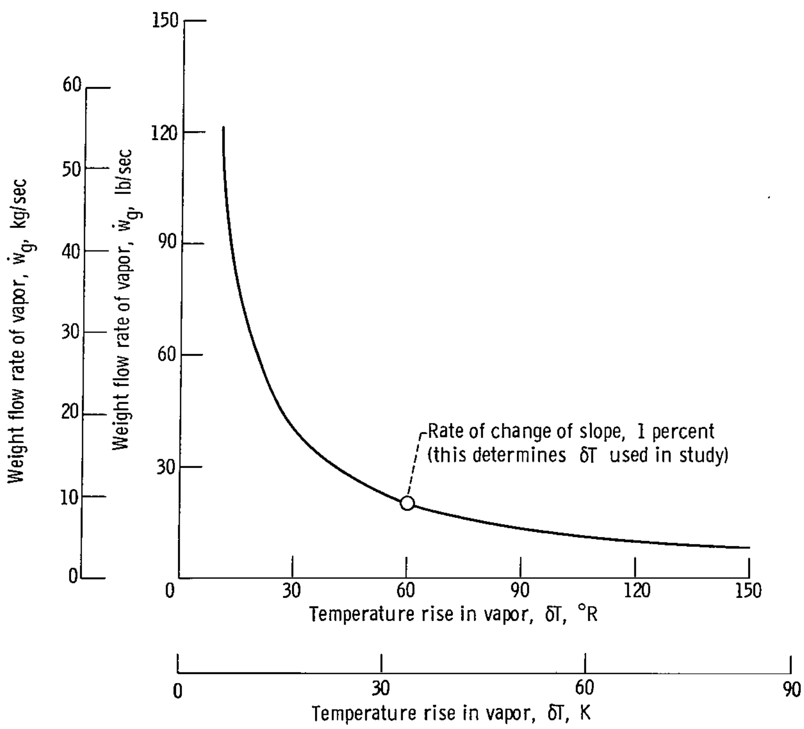


Figure 5. - Helium circulation system weight flow rate of vapor as function of temperature rise in gas. End of cruise.

Duct weight and pressure ratio. - When the maximum weight flow rate is known and the diameter of the main ducts is previously fixed, it is found that, at times, part of the gas leaving the tanks must be compressed with a pressure ratio of 5 before it enters the main ducts. The duct weights are determined by minimum gage. The resulting weight of the ducts is 494 pounds (225 kg), as is noted in table V.

Power supplied to compressors. - Figure 6 shows the power that must be supplied to compressors by the engines ΔP as a function of time into the flight. Note that whether the ullage fraction is 0 or 5 percent of the tank volume, the power at the end of cruise required is still very nearly the same, about 930 Btu per second (980 kW).

In determining this curve the assumptions are made that the rate of flow at the end of cruise, which sets the pressure ratio, is that chosen from figure 5; and at every point in the flight, the compressors are designed just for the flow and pressure ratios required at that point.

The preceding assumptions are made only for the computations used to determine the curves of figure 6. The following procedure is used to estimate fuel use caused by pressurant system operation. Actually, the compressors would have to be designed for the most difficult conditions, those at the end of cruise. In order to avoid computation of off-design compressor operation and yet be conservative in the computations of fuel required to run the compressors, it is assumed that the power required is always equal to that at the end of cruise.

Summary of HC system weights. - Table V presents a summary of helium circulation system results. It was assumed that, although only a 5.6-psi (38.6-kN/m^2) tank pressure differential was required, a rounded-off 6-psi (41-kN/m^2) tank pressure differential could be used as a maximum allowable. The maximum pressure of gas leaving the compressor is 21 psi (145 kN/m^2). This results from the fact that the maximum pressure ratio of 5 must be used when the pressure of the vapors in the tank is 4.2 psi (29.0 kN/m^2).

Note that the large weight penalties are the compressor weight, fuel used to run the compressors, and the letdown boiloff, the total of these three weights possibly running as high as 4687 pounds (2126 kg). The weights of the heat exchanger and ducting are much lower. Note, too, that less than one-half of the cooling capability available from the heat of vaporization of fuel headed for the engines is required during cruise.

All the weights presented herein must be divided by the weight of fuel, 185 000 pounds (83 990 kg), in order to get the weight penalty fractions which are required to determine aircraft payload capability, as is shown in the section Comparison of Systems.

Note that sufficient subcooling and insulation were provided to prevent any heat leak boiloff during the flight.

TABLE V. - HELIUM CIRCULATION SYSTEM RESULTS

Maximum tank wall differential pressure, Δp, psi; kN/m^2:	
Climb and cruise	5.60; 38.61
Letdown	6.00; 41.37
Maximum compression ratio	5
Maximum pressure, psi; kN/m^2	21; 145
Weight of ducts, lb; kg	494; 225
Weight of heat exchangers, lb; kg	93; 42
Weight of compressors, lb; kg	1440; 654
Fraction of heat of vaporization of cruise fuel required for cooling	0.483
Extra fuel to run compressors, lb; kg	1470; 667
Letdown boiloff, lb; kg	
At adiabatic wall temperature	502; 228
At wall temperature during cruise	1777; 807

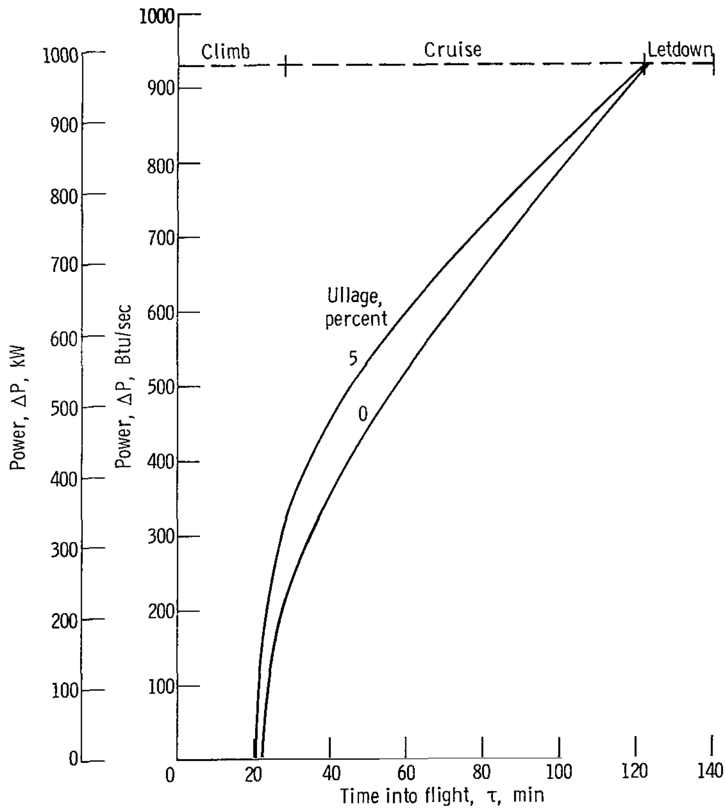


Figure 6. - Helium circulation system power required to compress vapors. Compressor always at design-point operation.

Helium Rebottled System Description

The helium rebottled system (HR) is another possible way in which helium can be used to pressurize subcooled methane while suffering no loss of helium during flight. As in the HC system excess vapors can result either from a low allowable differential pressure across the fuel-tank walls combined with a decrease in external pressure, or from an increase in pressurant temperature, as in a tank that is empty of fuel.

In this HR system all excess pressurant vapors, whether caused by pressure or heat, are vented from the fuel tanks. However, these vapors are not released into the atmosphere and lost. Rather, they are collected and compressed, and the helium is returned to the high-pressure bottle. Some helium will be in the fuel tanks at the end of the the flight. On landing, any helium the tanks contain can be salvaged.

The system. - This system is shown schematically in figure 7. The helium gas is initially released from its high-pressure bottle into the fuel-tank ullage space. The average temperature of the fuel is assumed to be 172° R (96 K) with a resulting average vapor pressure of 2.7 psi (18.6 kN/m^2) (ref. 9). Thus, the helium becomes mixed with methane vapors.

In the full tanks not being used during climb the decrease in ambient pressure, combined with the 4- to 6-psi (28- to 41-kN/m^2) allowable pressure differential across the tank wall, necessitates a reduction in the amount of helium within the ullage space. The gas being removed from these full tanks is assumed to have a 200° R (111 K) temperature, just a bit higher than that of the fuel. The emptying tanks from which fuel is being withdrawn during climb do not require vapor removal. Actually, helium may have to be added during the emptying of a tank. Just as a tank is emptied, however, vapor must again be vented off. In the empty tank the chief cause for gas loss is the rapid heating of the vapors when all heat sink is gone. This heating, in turn, causes a very rapid increase in vapor volume. Once an empty tank has again reached a stable temperature, the principal factor causing further vapor venting is, as in the full tank, the reduction in ambient pressure. However, the temperature of the gas in the empty tank will now be that of the skin temperature, several times higher than that in the ullage space of a full tank.

When any excess pressurant leaves a tank, it first passes through a heat exchanger. Here any gas having a temperature of over 300° R (167 K), such as the vapors in the long-empty tanks, is cooled to this 300° R (167 K) temperature. The gas is then compressed until a pressure equal to that of the high-pressure bottle is attained. It then passes through a second heat exchanger where it is cooled to a temperature close to that of the reserve fuel. All cooling in the heat exchangers is done by boiling a portion of the fuel headed to the engines. As the vapors cool, the methane drops out as a liquid and is

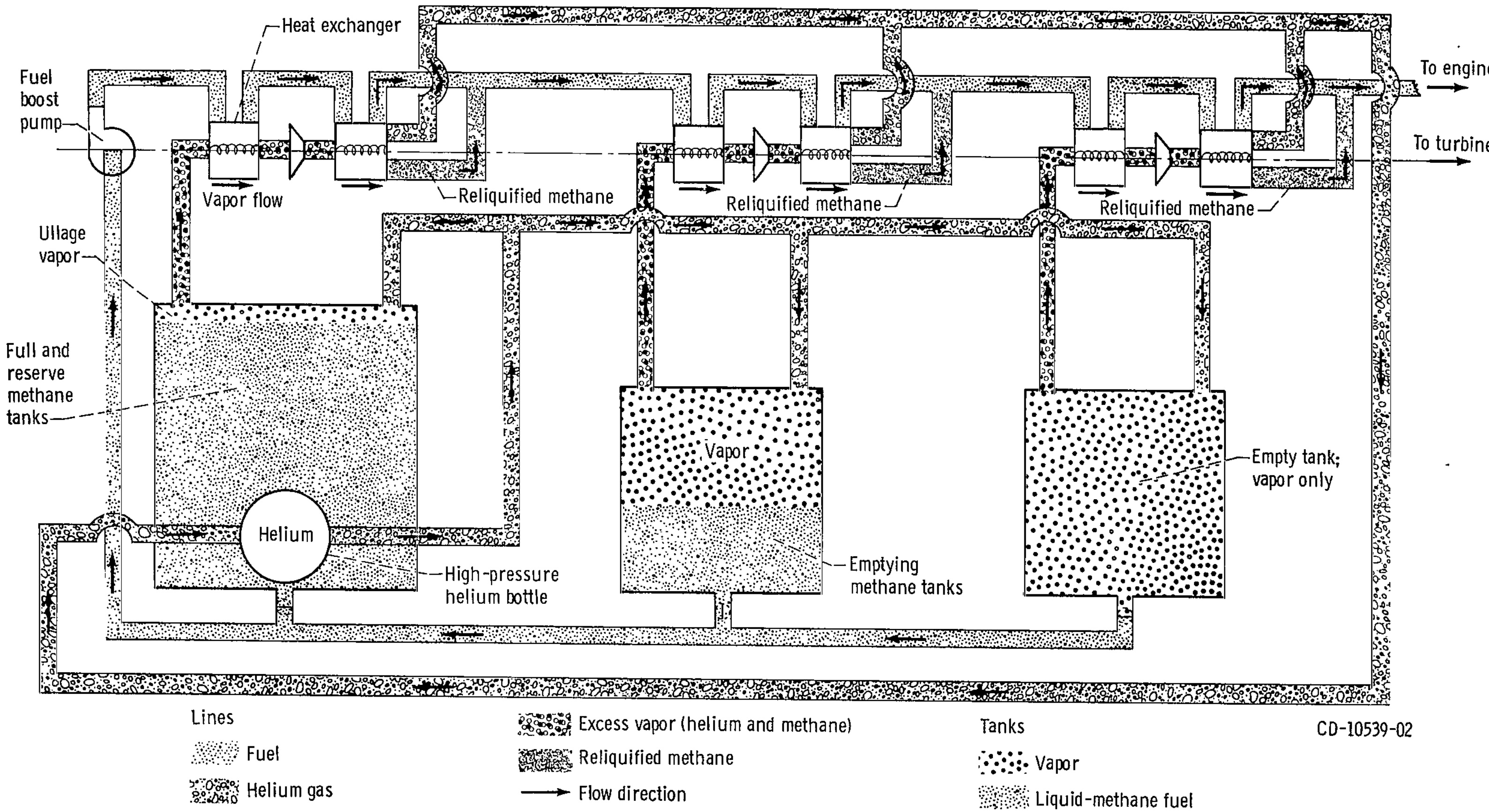


Figure 7. - Helium rebottled system.

piped to the engines. The remaining helium gas is returned to the high-pressure helium bottle.

Rate of gas removal. - The gas removal from the fuel tanks is done in such a manner that the internal pressure is never less than ambient and the maximum allowable differential pressure across the tank wall is never exceeded. In any tank the maximum rate of expulsion occurs immediately after the tank empties and the rapid heating of the gas begins. Therefore, as much pressurant vapor as possible is removed from a tank during the time that fuel is still contained within it. The maximum amount of pressurant that can be removed is determined by one of two minimum pressure requirements. First, as previously noted, the pressure in the tank must never be less than ambient, for structural reasons. Second, in order to totally prevent fuel boiloff due to heating, enough helium must be added to keep the tank pressure slightly higher than the vapor pressure of the methane fuel, even during fuel expulsion from the tank. If this is not done, a significant amount of heating boiloff will occur.

Following total fuel removal, the tank pressure is kept at ambient plus the maximum wall differential pressure, until the end of cruise.

During the descent, helium gas is added rather than removed, and the pressure is kept at just ambient. This helium in the tanks is salvaged at the end of the flight.

Design of ducting. - The ducts are designed in the same manner as in the helium circulation system case. However, here with the helium rebottled system the ducts are only required to take the vapors from the tanks to the compressors and heat exchangers; no return lines are necessary. Only very short distances are assumed from the final heat exchanger to the high-pressure bottle. Therefore, the weights of these small lengths are neglected.

Power required to compress pressurant gas. - The lowest pressure at which vapor exists in a tank is the expulsion vapor pressure of methane. Since this gas must eventually have a pressure equal to that in the high-pressure bottle, the required pressure ratio at any time can be determined. When the pressure ratio is known and the previously noted assumptions are used, the temperature rise through the compressor, the power required to compress the gas, and the additional fuel required can be computed.

Weight of compressor. - To complete the calculation of the pressurization system weight, the compressor weight must be known. At this point, the parameters necessary to make this calculation by using the empirical compressor weight equation are known.

Cooling requirements for pressurant. - In this HR system, as in the HC system, the tanks are emptied consecutively without fuel being transferred from tank to tank, fuel being moved only from tank to engine. Because of this the pressurant gases requiring cooling leave the tanks at two temperature levels. From empty tanks the vapor leaves at the high skin temperature. From tanks containing fuel the vapor leaves at a much lower temperature, about 200° R (111 K). The vapors from the empty tanks are cooled to 300° R (167 K) while still at low pressure. Then the 200° R (111 K) vapors and the 300° R (167 K) vapors mix together and are compressed to the same pressure as that of the high-pressure helium bottle. The temperature rise resulting from this compression is determined.

The compressed vapors must then be cooled to as close to the liquid-fuel temperature as possible in order to liquefy out the gaseous methane so that the helium gas can be placed back in the high-pressure bottle. When the weight flow rate, the specific heat, and the temperature drop required are known, the rate of heat removal can be computed. With this information and knowing the gas pressure, the heat-exchanger weight can then be determined.

Helium Rebottled System Results

Weight flow rate of vapors. - Figure 8 presents the weight flow rate of pressurant vapors, helium plus some methane vapor, as a function of time into the flight. The as-

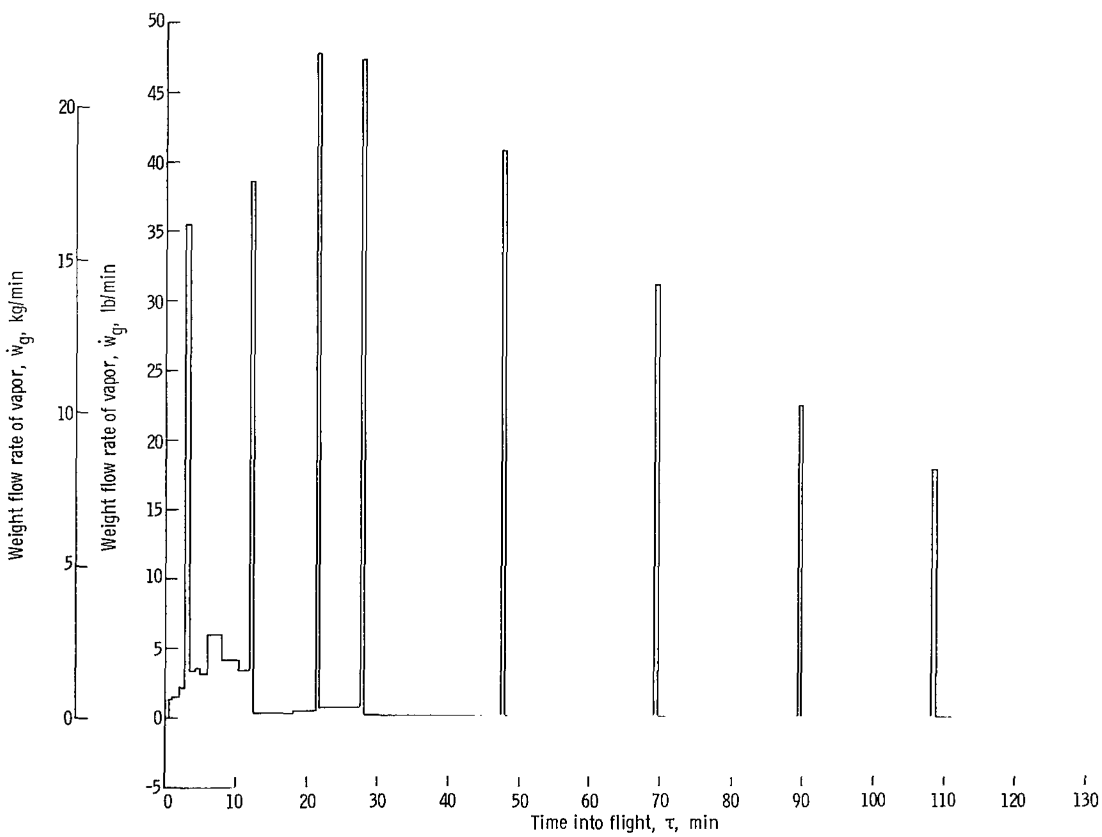


Figure 8. - Helium rebottled system weight flow of vapor to maintain pressure across tank wall of 4 psi (28 kN/m^2) or less.

sumption is made here that the maximum allowable differential pressure across the tank wall is 4 psi (28 kN/m^2). The high rates of flow occur immediately after tanks are empty of fuel, and the temperature of the gas within the tanks rises rapidly. The time durations for these periods of high weight flow indicated in figure 8 are those that would occur if the maximum rate of weight flow was constant. This is not the case. The rate drops off with time. However, in this study, all the systems are designed for maximum flow.

Power supplied to compressors. - Figure 9 presents the power P that must be supplied to the compressors as a function of time into the flight. The assumptions that are made in determining this curve are as follows:

(1) The weight rate of pressurant vapor flow at any time is that presented in figure 8.

(2) The pressure ratio at any point is that required to achieve the 1500-psi (10 343-kN/m^2) pressure of the helium bottle.

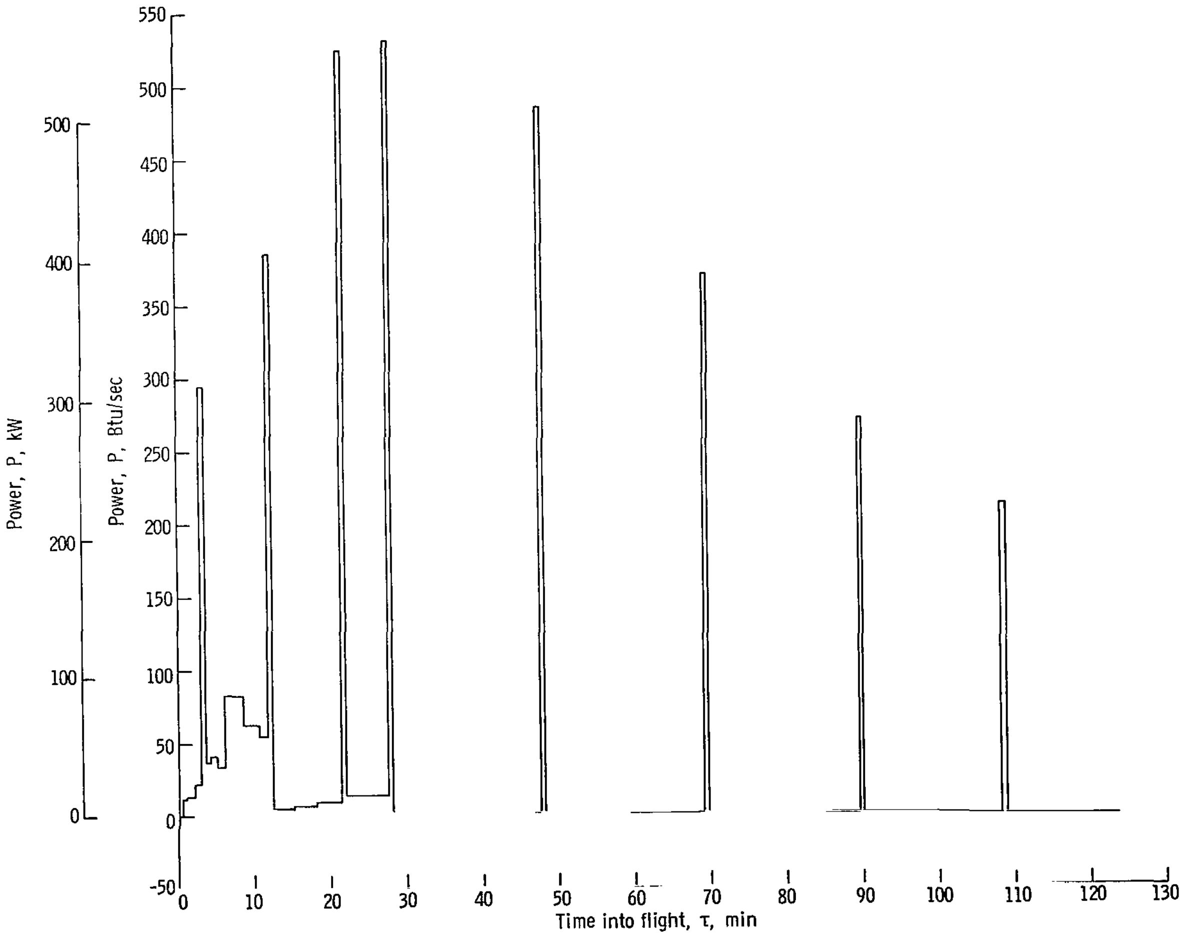


Figure 9. - Helium rebottled system power required to compress vapors for rebottling. Compressor always designed for given flow.

(3) At every point the compressors are designed just for the flow and pressure ratios required at that point.

Actually, the compressors must be designed for the maximum power requirement of 533 Btu per second (562 kW) which occurs in the early part of cruise. In computing extra fuel consumption to power the compressors, in order to avoid off-design compressor computations and yet remain conservative, it is assumed that this maximum power is required throughout the entire climb and cruise segments of the flight.

Summary of HR system weights. - Table VI contains a summary of the weights which result from using the HR system. These weights must be divided by the 185 000 pounds (83 990 kg) of fuel in order to get the weight penalty fractions which are required to determine aircraft payload capability, as is shown in the section Comparison of Systems.

TABLE VI. - HELIUM REBOTTLED SYSTEM RESULTS

Maximum tank wall differential pressure, Δp, psi; kN/m^2	4.00; 27.58
Maximum compression ratio	326
Maximum pressure, psi; kN/m^2	1500; 10 343
Weight of ducts, lb; kg	134; 61
Weight of heat exchangers, lb; kg	1384; 628
Weight of compressors, lb; kg	157; 71
Extra fuel to run compressors, lb; kg	706; 320

Minimum Helium Loss System Description

The minimum helium loss system (MHL) is another candidate system for using subcooled methane in a supersonic transport. It has three major differences from the other two systems discussed in this report. The MHL system uses saturated, as well as subcooled fuel. Some helium gas loss is allowed in the MHL system, while none is allowed in the others. Also, unlike the other systems, there is allowed some fuel boiloff caused by both the reduction in pressure during climb and the influx of heat into the tanks. The object with the MHL system is to attempt a compromise so that the weight of fuel boiloff from the saturated tanks will not seriously detract from the performance gains possible with methane, and yet the loss of the helium gas that is required to pressurize the subcooled fuel will be low enough that it will in no way threaten the estimated world helium supply. The guidelines as to actual helium usage for the United States are set by an agency of the Department of Interior. Since most of the helium supply is in the United States, this would have a dominant effect on world helium usage. However, the lower the fraction of the world supply used, the better the chance of such use being permitted.

The system. - The one great advantage of this system is simplicity. The high-pressure helium bottle is still required, since the fuel is partially subcooled. However, since helium is not salvaged, there is no requirement for the complex handling of the vented vapors with all of the resulting ducting, compressors, and heat exchangers.

The following guidelines are used in setting up this system:

(1) The ullage spaces should be minimized, thereby minimizing the amount of helium required.

(2) The saturated fuel is always used first in order to eliminate as much heating and pressure boiloff as possible.

(3) The fuel in a subcooled tank starts boiling just as the tank is about to begin expelling fuel. Thus, no additional helium is used for expulsion. As a result, however, all fuel suffers heating boiloff during expulsion.

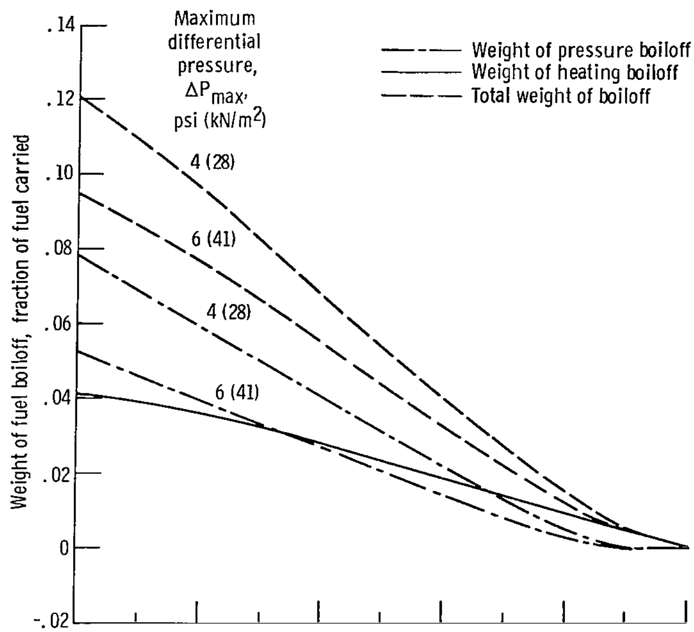
Computational limits. - Several limits are difficult to determine. The minimum fuel-tank ullage space that is practical for an operating aircraft is uncertain. The lowest improvement in payload that would still make this system appear attractive as compared with the JP system cannot be stated with certainty. And, as noted earlier, the permissible amount of annual helium usage must be determined by a government agency.

Because of these uncertain boundaries, computations are made with the fraction of total fuel that is helium pressurized varying from 0 to 100 percent. The ullage space varies from 0 to 6 percent of the tank volume. Maximum allowable pressure across the tank walls also has a considerable effect upon boiloff and helium usage. Therefore, calculations are made at both 4 and 6 psi (28 and 41 kN/m^2).

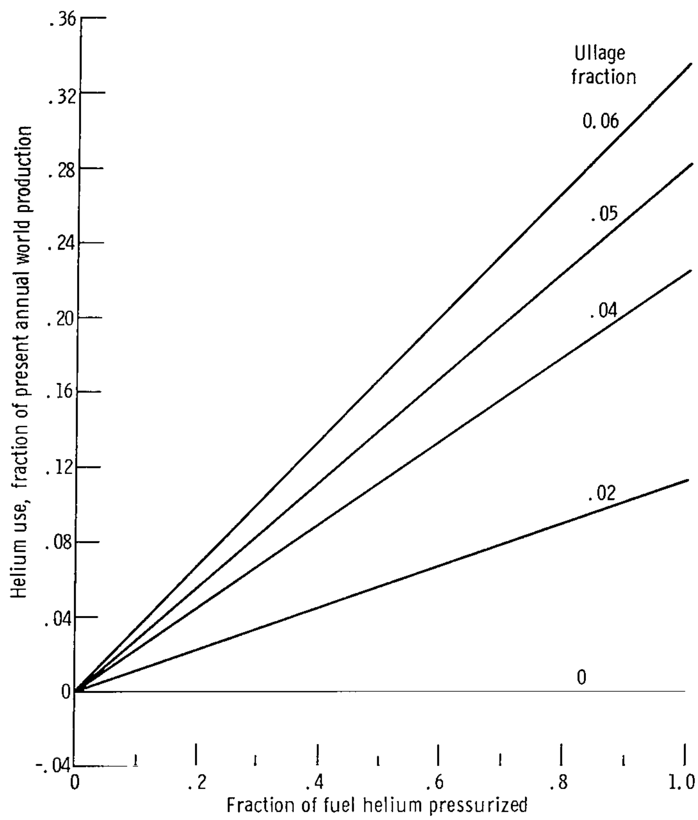
Minimum Helium Loss System Results

Figures 10(a) and (b) present the fraction of fuel boiled off and the fraction of the world supply of helium consumed, respectively, both plotted as functions of the fraction of the aircraft fuel that is helium pressurized. The effects of varying tank ullage space are also shown. The value used for the annual world supply of helium is 50.6 million pounds (22.95 million kg) based on figures presented in reference 10. The helium consumption is based on the assumption of a fleet of 1500 of the 460 000-pound (83 990-kg), supersonic aircraft flying three Mach 3, 3500-nautical-mile (6482-km) flights per day.

Note that if very little of the fuel is helium pressurized, there will be little helium loss; but the problem that must be alleviated, that of a great fraction of fuel boiling away, still is not solved. For example, if no helium is used, and all the fuel is boiling, the 10- to 12-percent boiloff loss appears once more. If, however, nearly all the fuel is helium pressurized, the boiloff is very low, but then a large fraction of the world helium supply would be consumed even with ullage fractions as low as 2 percent. For example,



(a) Weight of boiloff.



(b) Weight of helium use.

Figure 10. - Minimum helium loss system weight penalties as function of amount of fuel helium pressurized.

TABLE VII. - COMPARISON OF PAYLOAD GAINS

Aircraft and helium pressurization system	Weight penalty divided by weight of aircraft fuel										Helium loss fraction,[a] $\frac{W_{HeL}}{W_{AHeP}}$	Payload gain expressed as passenger fraction, $\frac{W_{ac}}{W_{JP}}$
	Basic fuel system fraction, $\frac{W_{bs}}{W_{f,t}}$	Pressurant and bottle fraction, $\frac{W_{pb}}{W_{f,t}}$	Insulation fraction, $\frac{W_{I}}{W_{f,t}}$	Boiloff fraction, $\frac{W_{bo}}{W_{f,t}}$	Heat exchanger fraction, $\frac{W_{hx}}{W_{f,t}}$	Compressor fraction, $\frac{W_{comp}}{W_{f,t}}$	Duct fraction, $\frac{W_{d}}{W_{f,t}}$	Deicer fraction, $\frac{W_{d,I}}{W_{f,t}}$	Extra fuel fraction, $\frac{W_{ef}}{W_{f,t}}$	Total system fraction, $\frac{W_{s}}{W_{f,t}}$		
JP-fueled aircraft	0.0209	0	0	0	0	0	0	0	0	0.0209	0	1.000
Methane-fueled aircraft:												
Basic case (assumed air can pressurize with no penalty)		0	.0276	0	0	0	0	.0016	0	.0501		1.283
Helium circulation system		.0040		[b]0.0096 0.0027	.005	.0078	.0027		.0079	[b]0.0826 0.0757		[b]1.217 1.237
Helium rebottled system				0	.0075	.0009	.0007		.0038	.0670		1.247
Minimum helium loss system:												
(1) Ullage, 5 percent; pressure differential, 4 psi (28 kN/m^2); fuel pressurized, 18 percent				.0990	0	0	0		0	.1531	.0500	1.066
(2) Ullage, 2 percent; pressure differential, 4 psi (28 kN/m^2); fuel pressurized, 89 percent				.0120	0	0	0		0	.0652	.1000	1.253
(3) Ullage, 0				0	0	0	0		0	.0541	0	1.278

[a]No leakage has been assumed.

[b]Higher value, temperature into fuel tank equals wall temperature at cruise for complete letdown; lower value, temperature into fuel tank equals adiabatic wall temperature at time in letdown.

with this 2-percent ullage space, if the tanks were all helium pressurized, more than 11 percent of the world supply would be consumed. This large helium loss occurs even though the helium is not used for expulsion of the fuel from the tank. Instead of using helium, the methane fuel is warmed sufficiently so that it will reach a vapor pressure at least equal to ambient (or to the required net positive suction pressure for the pumps if that should be higher) just as the fuel has to be expelled from the tank.

In view of all this, it is apparent that a practical ullage fraction must be chosen, and that then some compromise between helium loss and aircraft payload capability will have to be made. This determination is beyond the scope of this study; instead three example cases are presented in table VII to illustrate the diversity of possible situations.

Comparison of Systems

Relative payload capabilities. - Table VII presents a comparison of the gains in payload resulting from the use of methane fuel in conjunction with each of the three helium pressurization systems. The first 10 columns, going left to right, list the particular weight penalty divided by the weight of aircraft fuel. The eleventh column lists the helium loss per year divided by the present annual helium production. The last column presents the number of passengers, or weight of payload, on the given aircraft divided by that carried on the JP-fueled aircraft. The number of passengers in each case is determined from figure 11 (ref. 4), which presents number of passengers as a function of fuel system fraction. Figure 11 is entered with the sum of the total system fractions given in column 10 of table VII.

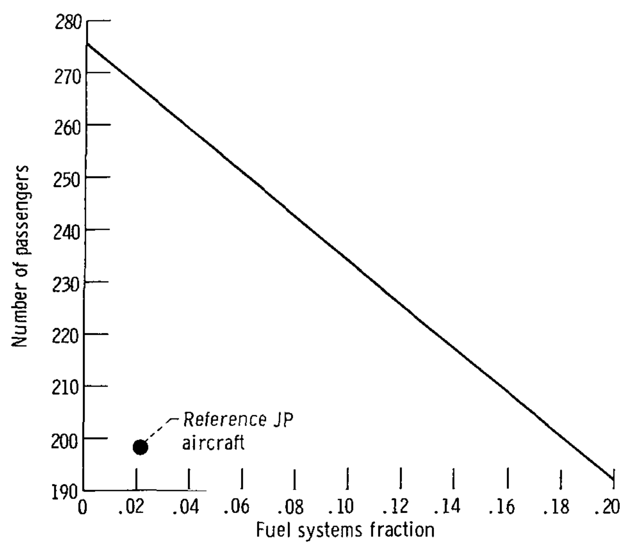


Figure 11. - Effect of fuel system weight on airplane payload.

The first line of table VII is concerned with the JP-fueled, Mach 3, supersonic transport. Here it is assumed that all fuel system penalties are included in the 0.0209 fraction. Since payload capability is based on that of the JP aircraft, the passenger fraction is equal to 1.

The remainder of the table presents the methane aircraft. The basic methane case is essentially that of reference 3 with MIN K substituted for silica aerogel as the insulation material. This case shows the maximum potential gain for this type of airframe and engines achieved by using liquid-methane fuel without weight penalties for boiloff or pressurization systems. The potential gains possible by using the three helium systems presented in this study are given in the remainder of table VII.

With the helium circulation system a good sized improvement in payload of over 20 percent above that of the JP-fueled aircraft appears possible. The difference between the two results given is a function of the assumed rate of cooldown of the tank walls during descent. The slower the cooldown, the greater will be the amount of fuel that must be used only for cooling.

The helium rebottled system offers an even more substantial increase. This possible 25-percent increase in payload must be considered relatively high since the very optimistic basic methane case offers only a 3-percent additional potential gain.

The greatest potential payload increase of any of the systems presented in this report is offered by the minimum helium loss system. However, to achieve this gain it is necessary to either have zero ullage in the tanks or else to accept a loss of helium. The first minimum helium loss case presented assumes an allowable pressure across the tank wall of 4 psi (28 kN/m^2), a 5-percent ullage, and that only 18 percent of the fuel, the reserves, is pressurized. The payload increase is very small and yet it is estimated that 5 percent of the world helium production would be consumed by the assumed supersonic transport fleet. If, with the same allowable pressure across the wall of 4 psi (28 kN/m^2), the ullage is reduced to 2 percent and all fuel affected by pressure boiloff is pressurized, the payload increase is over 25 percent. But now the fraction of world helium production consumed is up to 10 percent. If the ullage space can be eliminated, everything improves. There is no helium loss and no boiloff is dumped overboard. Since it is arranged that the methane reaches its boiling state just as it is about to be expelled from a tank, the helium is carried only for emergencies. The gains would be just about that of the basic case, about 28 percent.

Comparisons. - It is evident that all three of the pressurization systems allow gains of over 20 percent. Thus, any of these systems might be utilized in a methane-fueled supersonic transport. Unfortunately, the question as to which of these three systems is absolutely the best cannot yet be answered. A small difference in payload potential is not in itself a sufficient criterion to make such a definitive judgment.

Table VIII illustrates the difficulties that at present prevent this determination of a most preferable system. The table lists the systems, their advantages, their possible

TABLE VIII. - COMPARISON OF SYSTEMS

System	Advantages	Possible disadvantages	Questions requiring answers
Minimum helium loss	Very high payload increases possible	Requires low ullage	Can low ullages be achieved in everyday use?
	Simple plumbing	Some helium loss allowed	Will the requirement to conserve the world supply of helium allow any planned loss?
		Fuel temperature control important	Can fuel temperature control be achieved?
Helium rebottled	High payload increases possible	Very high compression ratios	Can leakage be kept low with very high pressure ratios and pressures?
		Very high pressures in heat exchangers	Can reliability against failure be kept high with very high pressure ratios and pressures?
Helium circulation	Good payload increases possible	High volume rate of circulated pressurant	Can leakage be kept low with very high circulation rates?
		Very complex plumbing	Can reliability against failure be kept high with such a complex system?
		Very complex pressure control	

disadvantages, and the questions that must be answered in order to make a choice between them. The questions concerning allowable helium use and system reliability present good examples.

The only purpose in going to these systems is to enjoy the gains offered by liquid-methane fuel, while consuming very little helium, an important and limited natural resource. However, how much is "very little" in actual quantitative terms? The answer to the question of how much, if any, helium consumption by these aircraft would be allowed depends on as yet unestablished guidelines which in turn must be based on the fact that helium is a vital resource.

Further, assuming that a certain fraction of the world helium production can be diverted to supersonic transport use, one question remains. Since when any of these systems has a serious malfunction large amounts of helium have to be used and lost overboard, can the systems be built with sufficiently high reliability to keep helium consumption within given bounds? Only very detailed design studies combined with operations tests can give answers to this reliability question or to any of the questions relating to the operation of the various systems. Thus, clearly, the acquisition of the information required to determine the best system is beyond the scope of this report.

CONCLUDING REMARKS

An analytical study has been made to determine the possibility of using helium pressurization systems to pressurize the fuel on a methane-fueled supersonic transport aircraft. Three systems have been proposed and investigated, all characterized by zero or minimum loss of helium. These systems are the helium circulation system (HC), the helium rebottled system (HR), and the minimum helium loss system (MHL). However, enough helium is carried aboard in each case so that the methane fuel could be pressurized in the more conventional manner of using helium for all pressure control and dumping the excess overboard with no attempt at either minimization of use or salvage. The effect on payload of these three systems has been determined analytically.

An increase in aircraft payload of more than 20 percent above that achieved by using JP fuel can be attained with methane fuel and any one of the three helium pressurization systems. Thus, most of the 28-percent potential payload increase offered by methane is retained. The MHL system offers the highest potential payload fraction, but it requires low ullages and allows some helium loss. The HR system allows high payloads, but it demands high pressures which could possibly cause leakage and reliability problems. The HC system offers good payload fractions, but the volume rate of helium flow is high and the system is complex. These factors, too, could cause leakage or reliability problems.

Thus, all three systems are possible methods for pressurizing methane on a supersonic transport. Also these approaches are not limited to the use of helium as the pressurizing gas. Neon, too, could be used, and it is expected that the results would be quite similar. However, conceptual studies are not sufficiently detailed to make a certain, definitive judgment as to which system is best. Decisions by the Department of the Interior would have a great effect in determining how much helium consumption by these aircraft would be possible. Only design studies combined with system operation tests can answer the questions of mechanical operation and reliability.

Note, however, that all these systems for handling subcooled fuel are complex and involve the use of a great number of mechanical devices. The simplest method for using methane fuel is that of using saturated fuel in combination with tanks capable of holding a pressure differential of 1 or more atmospheres across their walls. Thus, only if these high-pressure tanks have associated with them an unacceptably high weight, will the use of subcooled fuel with all the complex gadgetry required look attractive. Eventually, extremely detailed studies will have to be made in order to determine which pressurization system should be used on a methane-fueled supersonic aircraft.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 2, 1969,
789-50.

APPENDIX A

METHODS AND EQUIPMENT WEIGHTS

General Methods and Equipment Weights

Heat into fuel. - The heat input into the fuel is computed in the following manner in this report. For simplicity, one average temperature is taken for the surface of the wing tanks and one for fuselage tank surfaces at any given instant. Reference 11 is used to give the wall temperature for speed above Mach 2. An emittance of 0.3 is used for the wing. For the fuselage the emittance is lowered to 0.1, since much of the fuselage tank area is exposed to the hot engines. Emittance is defined here as the ratio of the emitted radiant flux per unit area of a sample to that of a blackbody radiator at the same temperature and under the same conditions. The assumption is made that below Mach 2 the wall temperature will not vary greatly from the adiabatic wall temperature T_{aw}, and the following expression for turbulent flow is used (ref. 12):

$$T_{aw} = T_{\infty}\left(1 + \sqrt[3]{Pr}\,\frac{\gamma - 1}{2}\,M_{\infty}^2\right) \tag{A1}$$

(All symbols are defined in appendix B.) The temperature T_{aw} is somewhat higher than the actual wall temperature.

The insulation weight can then be computed. The insulation characteristics used for computation are those of a form of MIN K (table III). The insulation must be applied to the inside of the walls of the tank, since the tanks are integral with the aircraft skin. It is assumed that the insulation is placed on all sides of each tank, including interior walls, to protect the fuel from heat influx. It is further assumed that all tank walls, internal as well as external, are at the average skin temperature determined for that particular period of the flight.

The insulation thickness is computed by assuming that the fuel is subcooled 17° R (9.4 K) to prevent pressure boiloff, and an additional 12° R (6.7 K) to prevent that boiloff caused by heat influx. Enough insulation is then applied so that the fuel temperature will rise no more than 12° R (6.7 K). The tanks that are emptied early in the flight thus need less insulation thickness than those that must contain fuel until landing.

In the minimum helium loss portion of this study some saturated fuel is used. An adjustment in insulation thickness could be made for this case. However, with those thicknesses of insulation that result from assuming 29° R (16.1 K) of subcooling, changes in insulation thickness would cause very little variation in the total weight of insulation plus boiloff. Therefore, the thickness on each tank and, thus the total weight of insulation, was maintained constant.

Weight of helium and weight and size of bottle. - The onboard weight of helium is determined for a hypothetical emergency condition. If soon after takeoff it is necessary to dump 90 percent of the fuel prior to making an emergency landing, sufficient helium must be provided to fill 90 percent of the tank volume at 1-atmosphere pressure at a gas temperature of about 200° R (111 K) (just slightly warmer than the fuel). Moisture-laden air cannot be used as a pressurant because of the danger of ice formation.

The weight of the helium bottle is computed by assuming that the tank pressure is sufficiently high that stress rather than minimum gage determines the wall thickness. The bottle weight W_{bt} for a spherical tank of gas is

$$W_{bt} = \frac{3\rho_m RT_g}{2\sigma} W_g \tag{A2}$$

Note that the weight of the pressure bottle is independent of the bottle diameter and, thus, independent of the bottle pressure. The weight of the bottle is, however, a function of bottle material and gas temperature. The bottle material chosen is 2014 T6 aluminum. The gas temperature is arrived at by assuming that the helium bottle is submerged in the reserve fuel. A temperature of 200° R (111 K) is used for computation of the bottle diameter.

If the helium in the bottle cannot be kept cool, some helium must be vented off. Thus, for helium conservation it is important to keep the helium bottle submerged, except in rare instances. The pressure bottle diameter is therefore limited to no more than 5 feet (1.52 m), half the diameter of the fuselage tank. This assures that the helium can be kept cool unless 50 percent or more of the reserves are used, a very uncommon occurrence (refs. 13 and 14). Since the diameter of the sphere is now set, as well as the weight and temperature of the helium, the pressure is also set. It is assumed that the installation weights will be small compared to the bottle weight. These installation weights are therefore neglected in this study.

Weight of compressor. - In two of the helium pressurization methods presented in this report, compressors for the helium vapors are required. The empirical equations presented below are used to estimate their weights. Equation (A4) is from reference 15. The total compressor weight W_c is made up of the sum of the pump weight W_P and the drive train weight W_{dt}. The equations are as follows:

$$W_P = \dot{W}_{He} \sqrt{T_{p1}} \ln\left(\frac{p_2}{p_1}\right) \tag{A3a}$$

$$W_{dt} = 0.1 \text{ (pump power in hp)} \tag{A4a}$$

where $\dot{W}_{He}$ is in pounds per second, T_{p1} is in °R, and the resulting weights, W_P and W_{dt} are in pounds.

The equations in international units are

$$W_P = 1.3416\,\dot{W}_{He}\,\sqrt{T_{p1}}\,\ln\left(\frac{p_2}{p_1}\right) \tag{A3b}$$

$$W_{dt} = 0.0608\ (\text{pump power in kW}) \tag{A4b}$$

where $\dot{W}_{He}$ is in kilograms per second, T_{p1} is in K, and the resulting weights W_P and W_{dt} are in kilograms. Although these equations have been derived only for the compression of pure helium in this study, they are used even when some methane vapors are mixed with the helium.

Weight of ducting. - For both the helium circulation (HC) and helium rebottled (HR) systems, ducting is needed to transport pressurizing vapors. The diameter of a duct of given length L, friction factor f, and pressure drop ratio $\Delta p/p$ along its length can be computed by use of the following equation:

$$D = \gamma M^2\left[\frac{1 + (\gamma - 1)M^2}{2(1 - M^2)}\right]4fL\left(\frac{p}{\Delta p}\right) \tag{A5}$$

This equation is based on an equation in reference 16 with the additional assumptions made that dp/p may be represented by $\Delta p/p$ and that length L may be substituted for dx. The friction factor f for a smooth pipe is that obtained from reference 17. The pressure drop $\Delta p/p$ in any duct is set at 0.05. The length of the duct is set by the actual distances that must be traversed by the gas. The effects of bends and valves are not taken into account.

In order to allow the required amount of gas to flow, the duct diameter D for incompressible flow is

$$D = 2\sqrt{\frac{\dot{V}}{\pi M c_s}} \tag{A6}$$

Solving equations (A5) and (A6) simultaneously gives a unique answer for D and M. Note that no attempt is made to optimize the duct size.

The weight of ducting W_d is then simply

$$W_d = \pi D t_m L \rho_m \tag{A7}$$

The duct material used is titanium Ti-6Al-4V. The thickness is set either by the hoop stress in the duct or by the minimum gage. The maximum stress allowed is 95 810 psi (660 610 kN/m^2). A minimum gage of 20 mils (0.051 cm) is used. Ten percent is added to the weight to allow for installation penalties. No weight calculations for valves are made.

Weight of heat exchanger. - In the HC and HR systems the helium-methane vapor mixture must be cooled. A simple equation has been derived to approximate the weight of the heat exchangers necessary to perform this cooling.

The assumptions made are as follows:

(1) The helium-methane gas mixture to be cooled flows through a large pipe.

(2) Within this pipe are small tubes through which liquid-methane fuel flows on its way to the engines. This liquid methane cools the gas mixture.

(3) The methane enters as a liquid and just begins to boil upon exit.

(4) The pressure in the tubes is at least as high as the pressure in the pipe.

(5) The pipe and tubes are both designed to withstand maximum, internal, absolute pressure.

(6) The weight contribution of the tubes is about equal to that of the outside pipe.

(7) The effects on heat-exchanger weight because of differences in heat-transfer coefficients between various gas mixtures is small. In scaling from an air to a helium heat exchanger, this is a conservative assumption.

(8) The velocity of flow of the liquid methane through the tubes is constant.

(9) The velocity of flow of the vapors through the pipe is constant.

With these assumptions scaling relations can be developed. The total weight of the tubes W_t scales as

$$\frac{W_{t,2}}{W_{t,1}} = \left(\frac{\dot{W}_{f,hx,2}}{\dot{W}_{f,hx,1}}\right)\left(\frac{p_{hx,2}}{p_{hx,1}}\right) \tag{A8}$$

The external pipe scales as

$$\frac{W_{p,2}}{W_{p,1}} = \left(\frac{\dot{V}_{g,hx,2}}{\dot{V}_{g,hx,1}}\right)\left(\frac{p_{hx,2}}{p_{hx,1}}\right) \tag{A9}$$

The heat-exchanger weight W_{hx} then scales as

$$\frac{W_{hx,2}}{W_{hx,1}} = \frac{p_{hx,2}}{2p_{hx,1}}\left(\frac{\dot{W}_{f,hx,2}}{\dot{W}_{f,hx,1}} + \frac{\dot{V}_{g,hx,2}}{\dot{V}_{g,hx,1}}\right) \tag{A10}$$

In reference 3 a heat-exchanger weight of 1500 pounds (681 kg) was listed. This heat exchanger had a maximum internal pressure of 150 psi (1034 kN/m^2). The maximum rate of flow through it was 605 cubic feet per second (17.13 m^3/sec). The gas (air) was cooled by flowing as much as 914 pounds (415 kg) of liquid-methane fuel per minute through the cooling tubes. Substituting these numbers in equation (A10) results in

$$W_{hx} = (0.00547)p_{hx}(\dot{W}_{f,hx} + 1.511\ \dot{V}_{g,hx}) \tag{A11a}$$

for W_{hx} in pounds, p_{hx} in psi, $\dot{W}_{f,hx}$ in pounds per minute, and $\dot{V}_{g,hx}$ in cubic feet per second.

If W_{hx} is in kilograms, p_{hx} in kilonewtons per square meter, $\dot{W}_{f,hx}$ in kilograms per minute, and $\dot{V}_{g,hx}$ in cubic meters per second, the equation is

$$W_{hx} = (7.934\times10^{-4})p_{hx}(\dot{W}_{f,hx} + 24.2\ \dot{V}_{g,hx}) \tag{A11b}$$

These relations are used to estimate heat-exchanger weight in this study.

Helium Circulation System Methods and Equipment Weights

Choice of allowable temperature rise in gas. - It is assumed that, when any portion of the pressurant enters a tank, this gas begins to absorb heat and continues to do so until it exits the tank. The relation used to determine heat influx into the pressurant is

$$\dot{Q} = \sum \left[\frac{kA_g}{t_I}(T_e - T_i)\right] \tag{A12}$$

The film coefficient at the tank wall is assumed to be infinite, and, therefore, it does not enter the calculations.

With this model, if the temperature rise in the gas is small, the heat flow into the pressurant is constant, and the following relation between heat input, gas weight flow, and gas temperature rise results:

$$\dot{Q} = \dot{W}_g c_{p,g}\ \delta T \tag{A13}$$

When equations (A12) and (A13) are set equal to one another, the following expression relating $\dot{W}_g$ to δT results:

$$\dot{W}_g = \frac{\sum \left[\frac{kA_g}{t_I}(T_e - T_i)\right]}{c_{p,g}\ \delta T} \tag{A14}$$

Neither $\dot{W}_g$ nor δT can be limitless. Since the determination of the range of practical values of $\dot{W}_g$ and δT is beyond the scope of this report, some point at the knee of the curve would appear to be a reasonable choice. The actual temperature rise δT chosen is the temperature difference such that the rate of change of slope of the $\dot{W}_g$ against δT curve during cruise is 0.01. This is near the knee of the curve, but there is a slight bias in the direction of a lower $\dot{W}_g$. This point is represented by the following relation:

$$\delta T = 5.85 \left\{ \frac{\sum \left[\frac{kA_g}{t_I} (T_e - T_i) \right]}{c_{p,g}} \right\}^{1/3} \tag{A15}$$

This relation is used to determine δT. Gas weight flow $\dot{W}_g$ can then be determined from equation (A14).

Power required to compress pressurant gas. - If the weight flow, the pressure ratio, the gas temperature into and out of the fuel tanks, and the physical properties of the pressurant gas are known, the amount of power that must be supplied by the engines to compress this gas ΔP can then be computed by the following relation:

$$\Delta P = \dot{W} c_{p,g} \left\{ \frac{T_4 + \delta T}{\eta} \left[\left(\frac{p_2}{p_1} \right)^{(\gamma-1)/\gamma} - 1 \right] - \frac{T_4 \eta \left[\left(\frac{p_2}{p_1} \right)^{(\gamma-1)/\gamma} - 1 \right]}{(1 - \eta) \left(\frac{p_2}{p_1} \right)^{(\gamma-1)/\gamma} + \eta} \right\} \tag{A16}$$

This equation is based on the assumption that, after cooling, the gas is reexpanded through a turbine which, in turn, helps power the compressor. The additional assumption has been made that the adiabatic efficiency η is the same for the compressor and the expansion turbine. In this study a value of 0.85 is used for η.

The computation of power required is made at the point of maximum pressurant flow and compression ratio. It is assumed that at lower loads the off-design compressor characteristics are such that maximum ΔP will be required throughout the flight. The increase in fuel consumption is assumed to be in the same proportion as the increase in power over the whole flight. This can be represented by the relation,

$$W_{f,comp} = W_{f,flt} \frac{\int_0^{LD} \Delta P \, d\tau}{\int_0^{LD} P_E \, d\tau} \tag{A17}$$

Cooling requirement for pressurant. - When the pressurant vapors exit the fuel tanks, they are already in need of cooling. They are then compressed, and thus the temperature is further increased. The heat exchanger is sized such that the vapor temperature is lowered sufficiently so that after expanding through the turbine into the tanks, the temperature is that required for entry into the fuel tanks. If it is assumed that the compressor pressure ratio and the turbine expansion pressure ratio are equal to each other (p_2/p_1), the reduction in temperature that the heat exchanger must supply is computed by the following relation:

$$\Delta T = \frac{\delta T}{\eta}\left[\left(\frac{p_2}{p_1}\right)^{(\gamma-1)/\gamma}\right] - (T_4 + \delta T)\left(\frac{1}{\eta} - 1\right) + \frac{T_4}{\eta}\left[\left(\frac{p_2}{p_1}\right)^{(\gamma-1)/\gamma}\right] - \frac{T_4\left(\frac{p_2}{p_1}\right)^{(\gamma-1)/\gamma}}{\left(\frac{p_2}{p_1}\right)^{(\gamma-1)/\gamma} - \eta\left[\left(\frac{p_2}{p_1}\right)^{(\gamma-1)/\gamma} - 1\right]} \tag{A18}$$

In these calculations the temperature at which the pressurant leaves the expansion turbine and enters the fuel tanks T_4 is set at 190° R (106.7 K). The compressor and expansion turbine efficiencies are both assumed to be 0.85, as noted earlier. Actually, there are pressure losses in the heat exchanger and ducts; thus, the compression and expansion pressure ratios would not actually be equal. In this feasibility study the difference has been assumed to be small.

When the amount of temperature drop, the gas weight flow, and the physical properties of the gas are known, the amount of cooling, and thus the maximum fuel flow required through the heat exchanger, can be determined. Since the maximum fuel flow, the maximum pressurant gas flow, and the gas pressure can all be found, the weight of the heat exchanger can be determined by using equation (A11).

Helium Rebottled System Methods and Equipment Weights

Rate of gas removal. - The rates of pressurant removal in this helium rebottled system are computed in the following manner. For the case of a reduction in ambient pressure, which is the initial cause for a reduction in the amount of pressurizing vapor, it is assumed that the average temperature of the methane fuel is 172° R (95.6 K) with a resulting average vapor pressure of 2.7 psi (18.6 kN/m^2). When this vapor pressure and the ambient pressure are known, and a 200° R (111 K) pressurant temperature in the full tanks is assumed, the amount of helium that must be removed, and thus the total amount of gas that must be removed, in a given time period can be computed.

For the second cause for vapor removal, that of the heating of the gas from 200° R

(111 K) to wall temperature after the fuel has been expelled from a tank, the following relation is used to determine the maximum weight rate of vapor removal $\dot{W}_g$ in any tank:

$$\dot{W}_g = \frac{kA_{tk}}{c_{p,g} t_I} \left(\frac{T_e - T_i}{T_i} \right) \tag{A19}$$

It is assumed that at the end of fuel expulsion the vapor consists almost completely of methane gas. However, the helium gas remaining, no matter how small the amount, is saved.

Power required to compress pressurant gas. - The lowest pressure at which vapor exists in a tank is the expulsion vapor pressure of methane. Since this gas must eventually have a pressure equal to that in the high-pressure bottle, the required pressure ratio at any time can be determined.

With the maximum temperature into the compressor set at 300° R (167 K), as previously noted, and with the maximum pressure rise through the compressor known, ΔT can be computed from the following relation:

$$\Delta T = \frac{T_1}{\eta} \left[\left(\frac{p_2}{p_1} \right)^{(\gamma-1)/\gamma} - 1 \right] \tag{A20}$$

In this study the adiabatic efficiency η is assumed to be 0.85. The amount of power required to compress the gas is then computed by the relation

$$P_c = \dot{W}_g c_{p,g} \Delta T \tag{A21}$$

In order to determine the additional fuel that is required for compression, it is assumed that off-design characteristics are such that at all rates of flow, the compressor operates at maximum power. The rationale for computing the additional fuel used can then be represented by a modification of equation (A17)

$$W_{f,comp} = W_{f,flt} \left(\frac{\int_0^{LD} P_c \, d\tau}{\int_0^{LD} P_E \, d\tau} \right) \tag{A22}$$

APPENDIX B

SYMBOLS

A area, ft^2; m^2

A_g area in contact with gas, ft^2; m^2

c_p specific heat at constant pressure, Btu/(lb)(^{O}R); J/(kg)(K)

c_s speed of sound, ft/sec; m/sec

D duct diameter, ft; m

f friction factor

k thermal conductivity, Btu-ft/(ft^2)(hr)(^{O}R); J-m/(m^2)(hr)(K)

L duct length, ft; m

LD time of start of letdown

M Mach number

P power, Btu/sec; kW

ΔP power loss, Btu/sec; kW/sec

p pressure, psi; kN/m^2

Δp pressure drop, psi; kN/m^2

Δp_d pressure differential, psi; kN/m^2

Pr Prandtl number

$\dot{Q}$ heat influx per unit time, Btu/unit time; J/unit time

R gas constant, ft/^{O}R; (kN)(m)/(kg)(K)

T temperature, ^{O}R; K

ΔT temperature rise, ^{O}R; K

δT allowable temperature rise, ^{O}R; K

t thickness, in. or mils; cm

$\dot{V}$ volume flow per unit time, ft^3/sec; m^3/sec

W weight, lb; kg

$\dot{W}$ weight flow rate per unit time, lb/min; kg/min

γ ratio of specific heats

η compressor adiabatic efficiency

ρ density, lb/ft^3; kg/m^3

σ allowable stress, psi; kN/m^2

τ time, sec or min

Subscripts:

ac passengers on given aircraft

AHeP average annual world helium production

aw adiabatic wall

bo boiloff

bs basic system

bt bottle

c for compression

comp compressor

d duct

dt drive train

E all engines

ef extra fuel

e external

f fuel

flt	flight
g	gas
He	helium
HeL	helium loss
hx	heat exchanger
I	insulation
i	internal
JP	passengers on JP aircraft
m	metal
P	pump
pb	pressurant bottle
p_1	at pressure 1
s	system
t	total
tk	tank
w	wall
∞	ambient
1	initial
2	final
4	after expansion

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