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Review of Orbital Propellant Transfer Techniques and the Feasibility of a Thermal Bootstrap Propellant Transfer Concept

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December 1971

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REVIEW OF ORBITAL PROPELLANT TRANSFER TECHNIQUES AND THE FEASIBILITY OF A THERMAL BOOTSTRAP PROPELLANT TRANSFER CONCEPT

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ABSTRACT

This study was performed in support of the NASA Task B-2 Study Plan for Space Basing. The nature of space-based operations implies that orbital transfer of propellant is a prime consideration. The intent of this report is (1) to report on the findings and recommendations of existing literature on space-based propellant transfer techniques, and (2) to determine possible alternatives to the recommended methods.

The reviewed literature recommends, in general, the use of conventional liquid transfer techniques (i.e., pumping) in conjunction with an artificially induced gravitational field. The rationale for this selection was the apparent least technological risk for a near-term approach to propellant transfer.

An alternate concept that was studied, the "Thermal Bootstrap Transfer Process," is based on the compression of a two-phase fluid with subsequent condensation to a liquid (vapor compression/condensation). This concept utilizes the intrinsic energy capacities of the tanks and propellant by exploiting temperature differentials and available energy differences. Energy for pumping is obtained by venting receiver tank chilldown gases through a turbo-expander. The vapor content of the compressed two-phase fluid is condensed by transferring its latent heat of vaporization to the donor tank propellant residual. The condensing heat load causes boil-off in the donor tank propellant, which more than satisfies the requirement for donor tank pressure maintenance.

The results of this study indicate the thermodynamic feasibility of the "Thermal Bootstrap Transfer Process" for a specific range of tank sizes, temperatures, fill-factors and receiver tank heat transfer coefficients.

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FIGURES

I. INTRODUCTION

A. BACKGROUND

The NASA Task B-2 Study Plan for Space Basing required an analysis of on-orbit propellant operations. This analysis was to give special attention to the characteristics, locations, advantages and/or disadvantages of orbital propellant storage facilities to support extensive space operations. In addition, operations utilizing the space tug were to be emphasized. The nature of space-based operations implies that orbital transfer of propellants is a prime consideration. Therefore, an investigation of the suitability of existing propellant transfer techniques, as well as possible advanced propellant handling procedures, was in order. The intent of this report is to review recommendations from existing literature on transfer techniques and to determine if there are alternatives to the recommended methods.

The literature on the subject presents data on the boil-off losses and energy requirements associated with transfer as functions of propellant type, tank volume, tank temperatures, and transfer technique. These data relate to either of two distinct environmental circumstances: (1) propellant transfer under conditions of artificially created gravity forces, or (2) propellant transfer and acquisition under zero-gravity conditions. The means for creating artificial gravity fields are linear acceleration or rotational acceleration. Zero-gravity transfer processes reported in the literature depend upon the creation of electrostatic forces or surface tension forces to situate propellant in the regions of tank outlets or pump inlets.

Subjective inputs to the conduct of these studies included utilization of existing stages as the basic system building blocks (Saturn S-II/S-IVB stage designs), specific docking port provisions, particular traffic model and mix of using subsystems, design characteristics and orbital parameters of a storage system, and the mission success probability (i.e., subsystem reliability).

B. APPROACH

The approach taken in this study was to review existing literature on the subject of orbital propellant transfer with critical attention given to opportunities for enhancing propellant transfer processes by innovation. As a direct result of the literature review, an effort was undertaken to evaluate a novel approach to the problem of on-orbit propellant transfer.

II. DISCUSSION OF "STANDARD" ORBITAL TRANSFER SYSTEMS

Although a literature search and evaluation were conducted in the study reported herein, a detailed evaluation and resume of these voluminous reports is not considered appropriate. Each of the reports recommended that these operations be conducted using ullage control while transferring propellant with conventional liquid pumping hardware. With such transfer techniques, sizeable propellant expenditures accrue due to chilldown and pressurization functions. Also, electrical power provisions are required for accomplishing the transfer, and orbital perturbations result due to long duration low-level accelerations. The necessity for rigid docking, as well as the structural dynamic stability characteristics of quasi-rigid assemblies, are recognized as problems that must be solved before this transfer method can be implemented. However, these problems are not considered insurmountable.

The studies cited in the references were directed toward the selection and/or comparison of previously defined approaches for specific spaced-based operations. In particular, Refs. 1 and 2 relate to the NASA Baseline Space Program with emphasis on lunar and planetary mission capabilities. The quantities of propellant involved for either the Reusable Nuclear Shuttle or the Chemical Interorbital Shuttle are considerably in excess of those contemplated for the DoD/NASA mission model space activities circa 1980-1990.

The results of these studies (boil-off, translation impulse propellant, propellant residuals, electrical power requirements, etc.), and the recommendations based thereon, reflect the effects imposed by large orbital propellant requirements. Examples of the above effects are the following:

1. Propellant boil-off during quiescent storage of an orbiting propellant depot or storage system depends essentially upon projected surface area of the containing system and its provision of insulating material for thermal control. The boil-off rate, therefore, becomes a smaller percentage of the total propellant capacity in a large system (related to surface-to-volume ratios) than is the case in the smaller OOS-sized propulsion stages. The

definition of the orientation of major propellant storage facilities with respect to the solar flux is a significant factor in consideration of tradeoffs between attitude stabilization propellant and boil-off as a function of system gross weight.

2. Repressurization for transfer and depressurization upon transfer completion reflect major differences in propellant penalty, depending upon the size of the storage facility.

3. The tradeoff between propellant expenditure for acceleration and deceleration to control the liquid/vapor interface during transfer, as opposed to propellant transfer time, is a factor which is sensitive to the weight and capacity of the transferring storage system.

4. The frequency of Space Shuttle deliveries of propellant significantly affects the state of temperature and pressure on board the storage facility, so that differences in the mission timelines between the Baseline Space Program operations and the DoD/NASA space operations will impose an effect.

The conclusions and recommendations in Refs. 1 and 2 are interpreted as being practical, attainable, near-term judgements which do not require significant advances in the various technology areas. References 3, 4, and 5 reflect considerations of a point-OOS design as influencing orbit propellant transfer operations. The alternatives considered are those which represent the conventional approaches described and discussed elsewhere. They lead generally to the conclusion that artificial gravity liquid/vapor interface control and conventional liquid-phase pumping offer the least risk approach to the propellant transfer operation.

In the following pages, a novel approach which may enhance orbital propellant transfer operations is examined briefly. The "Thermal Bootstrap Transfer Process" offers the potential of simplifying orbital propellant transfer operations while utilizing the intrinsic thermal energy available in receiver tank components as the energy source for the transfer process. Simplification results from the lack of necessity for rigid docking and acceleration of the assembled systems. The propellant loss due to chilling the receiver tanks to the cryogenic temperatures may be utilized for pumping power instead of the electrical power necessary for conventional techniques.

III. TWO-PHASE FLUID TRANSFER

For implementing a propellant transfer operation in the near future, the currently proposed phase separation methods are probably best because of the apparent least risk. However, from a technology standpoint, a two-phase transfer method may have advantages over the phase separation methods. The following discussion presents the results of a study performed on a proposed means of two-phase transfer.

A. PROCESS DESCRIPTION

The basic processes required to transfer propellant in zero gravity without phase separation are the following: (1) two-phase pumping, (2) condensing and subcooling, (3) receiver tank childown, (4) donor tank pressurization, and (5) pumping power generation. The "Thermal Bootstrap Process" accomplishes these necessary functions by utilizing the intrinsic energy capacities of the tanks and propellant through exploitation of temperature differentials and available energy differences. Receiver chilldown gas (combusted with oxygen if necessary) provides the necessary pumping power. Condensation of the vapor content of the two-phase pump discharge is accomplished by transferring excess heat to the donor tank propellant residual. The condensing heat load causes boil-off in the donor propellant, which fulfills its pressurization requirement.

The thermodynamics of the transfer process are shown in Fig. 1. The propellant is stored at equilibrium saturated conditions along the line E-E'. This assumes that there are no noncondensables within the tank, which is a requirement for this type of system. Since the propellant tanks are assumed to contain both liquid and vapor at a saturated condition, the bulk or average state point of the propellant is at some point 1. It is assumed that sufficient circulation exists (such as by means of an impeller) within the tanks so that any macroscopic sampling of the propellant will indicate propellant properties at state point 1. The energy necessary to create and sustain a uniform mixture

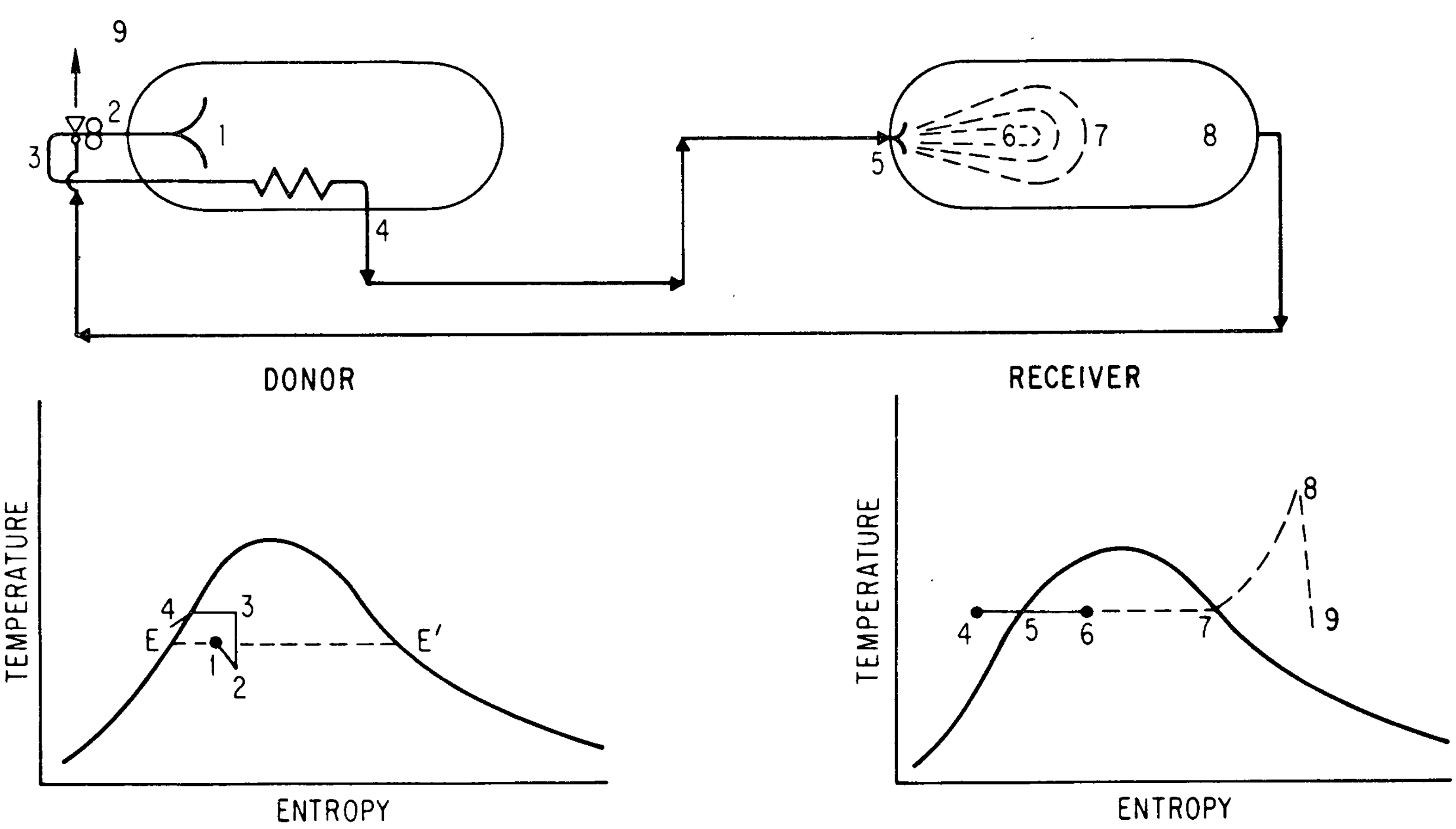

Figure 1. Transfer Process Schematic

of liquid and vapor in the donor tank is considered to be minimal. The requirement for developing a control device to induce the flow of two-phase fluid into the pump is discussed in Subsection E.

From state point 1, the propellant is introduced into the pump assembly. The propellant is first introduced to a header where the temperature and pressure decrease along a constant enthalpy line to state point 2. Typically, the pressure at state point 2 is 2 or 3 psi lower than the pressure at point 1. The propellant is then compressed to a suitable state point, 3, such that its pressure and corresponding temperature differential ($\sim 10^\circ$R) allows the transfer of the heat of vaporization to the donor tank residual. After condensation, the propellant is subcooled to state point 4. The minimum difference in temperature between states 4 and 1 is approximately 5°R.

Pump work per unit weight of propellant is the difference in enthalpy between states 2 and 3. The condensation and subcooling requirement is the difference in enthalpy between states 3 and 4. The heat rejected between states 3 and 4 is absorbed by the bulk propellant at state point 1. The heat is removed from the tank by evaporating a portion of the propellant from 1 to E'. Since the tank volume is constant, and propellant is being removed from the tank by both pumping and evaporation, the propellant bulk properties (state point 1) continually shift toward the right along the line E-E'. (It is assumed and later shown that there is sufficient evaporation within the tank to maintain constant temperature and pressure.) The process in the receiver tank follows two paths: (1) from point 5 to point 6, the propellant is retained in the liquid state by preventing its contact with the warm tank walls; (2) the fluid which is directed laterally contacts the tank wall and vaporizes to points 7 and 8. The fluid after expansion in the turbine is at state point 9.

B. METHOD OF ANALYSIS

As the vapor/liquid ratio of the donor propellant increases, both the required pump work and the condensing/subcooling of the bulk propellant increase. In order to account for this dynamic behavior of the fluid during the transfer process, a finite difference computer program was used to determine the effect of fluid property changes during the transfer. Actual properties of the saturated liquid and vapor were used in the analysis, and the properties of the liquid/vapor mixture within the dome were determined by continually computing the "quality" of the fluid. The enthalpy changes of the pure vapor and liquid were determined by assuming constant specific heats. Consequently, the change in energy for both the pure liquid and the pure vapor was calculated by using $\Delta h = C_p \Delta T$, where h = enthalpy, C_p = specific heat, and ΔT = temperature difference.

The following procedure was used in calculating the transfer requirement:

1. The initial state of the propellant is input to the computer program; a constant volumetric pump flowrate was assumed, and a time increment was selected.
2. State point 2 is determined by assuming a constant enthalpy pressure drop in the header ($\sim$ 2 psia).
3. State point 3 is determined, based on a pump efficiency of $\sim$ 85% and the required temperature difference between states 3 and 1; the pump work required to achieve state point 3 is then calculated.
4. The amount of cooling required to achieve state point 4 is calculated. State point 4 is approximately 5°R greater than the temperature along E-E′ and is at the same pressure as state point 3.
5. The amount of bulk propellant evaporated in order to provide the cooling is calculated. The increase in vapor within the tank due to liquid removal (assuming constant donor tank pressure and temperature) is calculated. The difference is the amount of vapor removed from the tank.
6. A new bulk propellant state point 1 due to the removal of propellant by transfer and evaporation is determined.
7. Steps 1 through 6 are repeated until the required amount of propellant is transferred.

There are some propellant conditions for which state point 3 falls in the compressed liquid region. For this situation, the end-point enthalpy is calculated differently. The amount of pump work required for either the wet compression or the liquid compression is based on the fluid pressure leaving the saturated liquid line, as determined from the saturation properties. The amount of compression work required to reach the predetermined pressure line is calculated from $v\Delta p$ (v = specific volume, Δp = pressure difference). This is a valid assumption because the specific volume of the propellant does not change appreciably over the pressure range of interest. The enthalpy at this point is assumed to be the initial enthalpy plus the amount of cooling required to get to state point 4.

Because it appears that a significant requirement for this concept will be the work required to compress the fluid, utilization of the heat content of the receiver tank as a possible energy source for pumping was investigated. The energy available from receiver boil-off was compared with that required to drive the compressor. If the liquid propellant is introduced into a warm (~ 400°R) receiver tank, some of the propellant will evaporate. The heat transfer coefficient may range from a high of 1000 Btu/hr-ft^2 (which may correspond to a stable film boiling coefficient) to 100 Btu/hr-ft^2. It was assumed that the heat transfer area varied linearly from zero to the surface area of the tank, depending on the amount of liquid in the tank. The receiver tank cooling vapor was assumed to leave the tank in a superheated condition with a temperature rise of 80% of the maximum temperature rise. This superheated vapor is then passed through a turbo-expander where energy is extracted with an exhaust temperature of approximately 75°R.

The calculations were performed for the transfer of hydrogen. The transfer of a corresponding quantity of oxygen is more easily accomplished than hydrogen transfer and therefore was not evaluated.

C. RESULTS

Figures 2 and 3 present the results of the calculations for hydrogen transfer. Figure 2 shows the pump compression work requirement for donor tank pressures (P_D) of 15 to 20 psia, and available turbo-expander work for two heat transfer coefficients. The high heat transfer coefficient refers to a typical stable film boiling coefficient of 1000 Btu/hr. The low heat transfer coefficient refers to a coefficient that is an order of magnitude smaller than

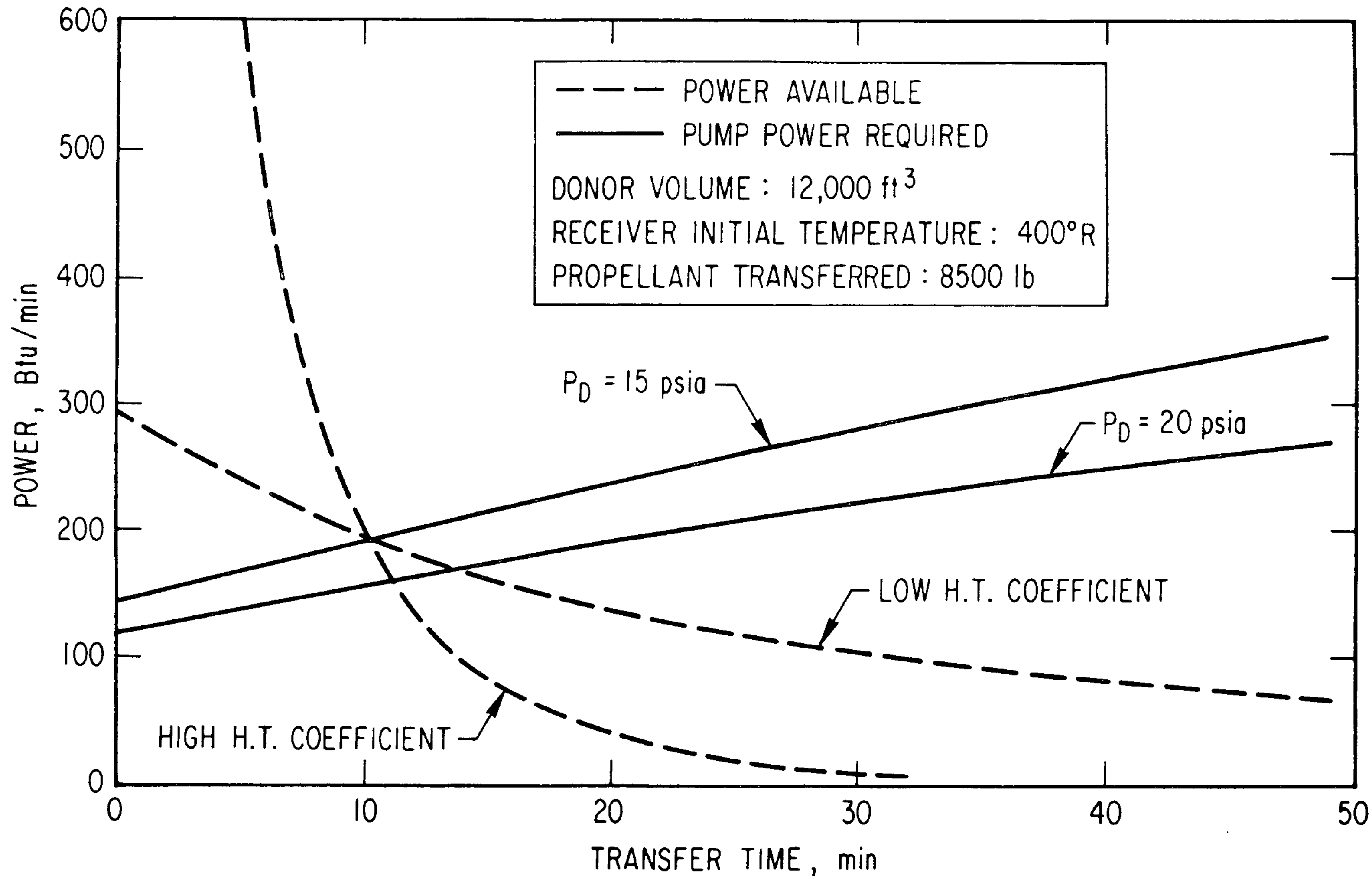

Figure 2. Power Available and Required vs Time for Hydrogen Transfer

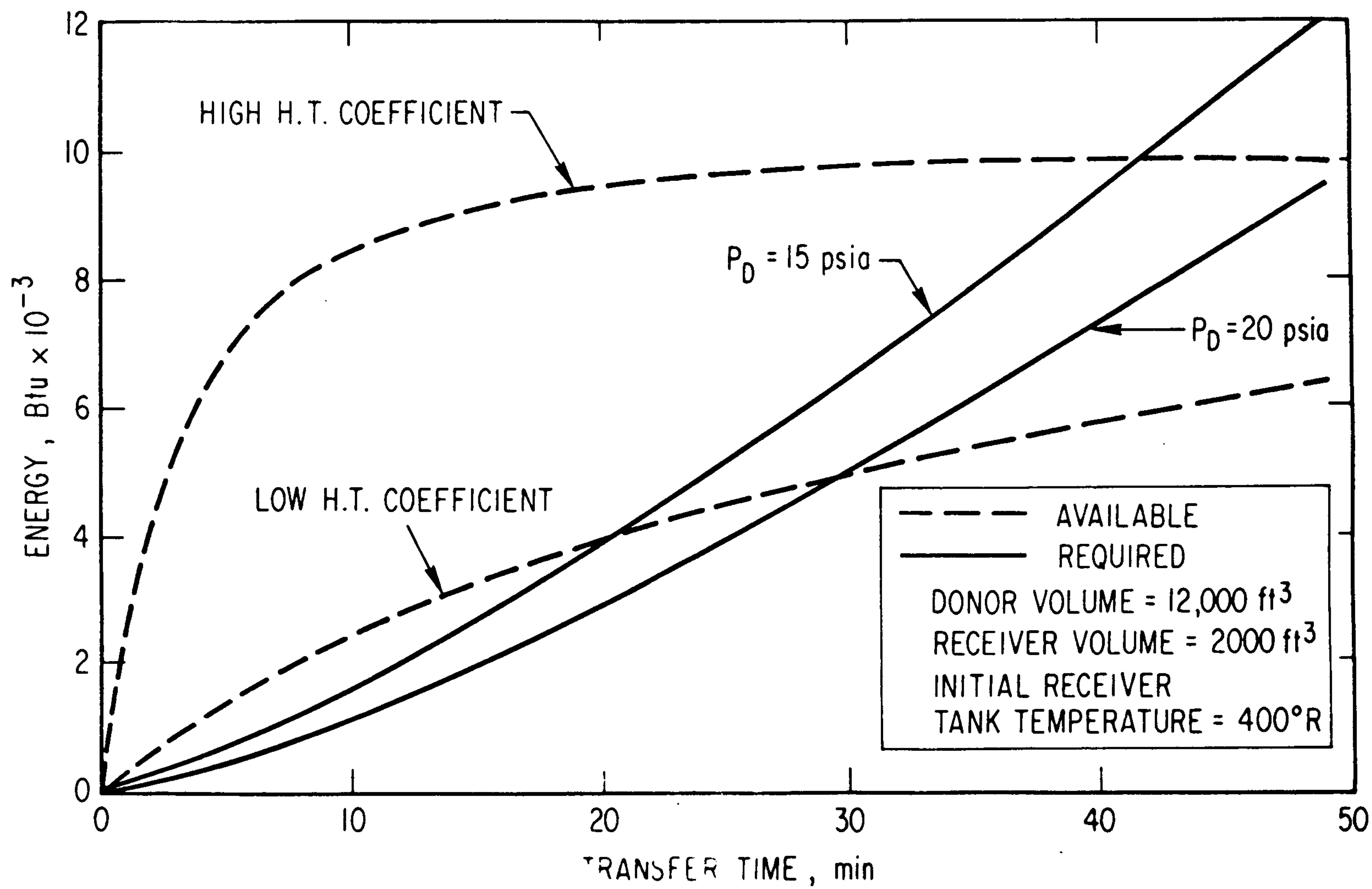

Figure 3. Total Energy vs Transfer Time for Zero-G Hydrogen Transfer

the high coefficient, which is considered a practical value in light of the effects of low-g's. For the cited conditions of a donor tank of 12,000 ft^3, initially 95% full of liquid and transferring 8500 lb of liquid hydrogen to a 400°R receiver tank, Fig. 2 shows that the power demand exceeds the available power after about ten minutes.

Figure 3 shows the integrated energy required and available at any particular time in the transfer process. The figure indicates that, for a donor tank pressure of 20 psia and a high heat transfer coefficient, the total energy available is sufficient to provide the necessary compression work. For the lower heat transfer coefficient condition, the available energy timeline does not satisfy the pump requirement timeline.

D. CONCLUSIONS

An examination of Figs. 2 and 3 leads to several conclusions. For certain donor tank conditions and receiver tank heat transfer conditions, there is sufficient total energy available, but the available energy rate does not coincide with the demand rate. This means that in order to match the available rate with the demand rate, either the produced energy must be stored or the energy production rate must be controlled. A third alternative is to use a gas generator to provide the necessary energy to heat the hydrogen gas. The use of a gas generator burning oxygen-hydrogen is an attractive alternative because of the availability of both of these reactants.

Figure 4 shows the receiver tank temperature and the amount of receiver tank boil-off as a function of time. The high heat transfer condition has essentially reached equilibrium at the end of the transfer process. The low coefficient condition, however, has not reached equilibrium. The propellant evaporation is on the order of 40 lb of hydrogen (assuming a 400-500°R tank). Therefore, the amount evapoated does not appear to be of consequence.

Figure 5 shows the amount of boil-off within the donor tank, which is used as a heat sink. The boil-off weights in Fig. 5 refer to the amount of venting required to maintain constant temperature and pressure within the donor tank. Consequently, these values refer to the difference between the amount of

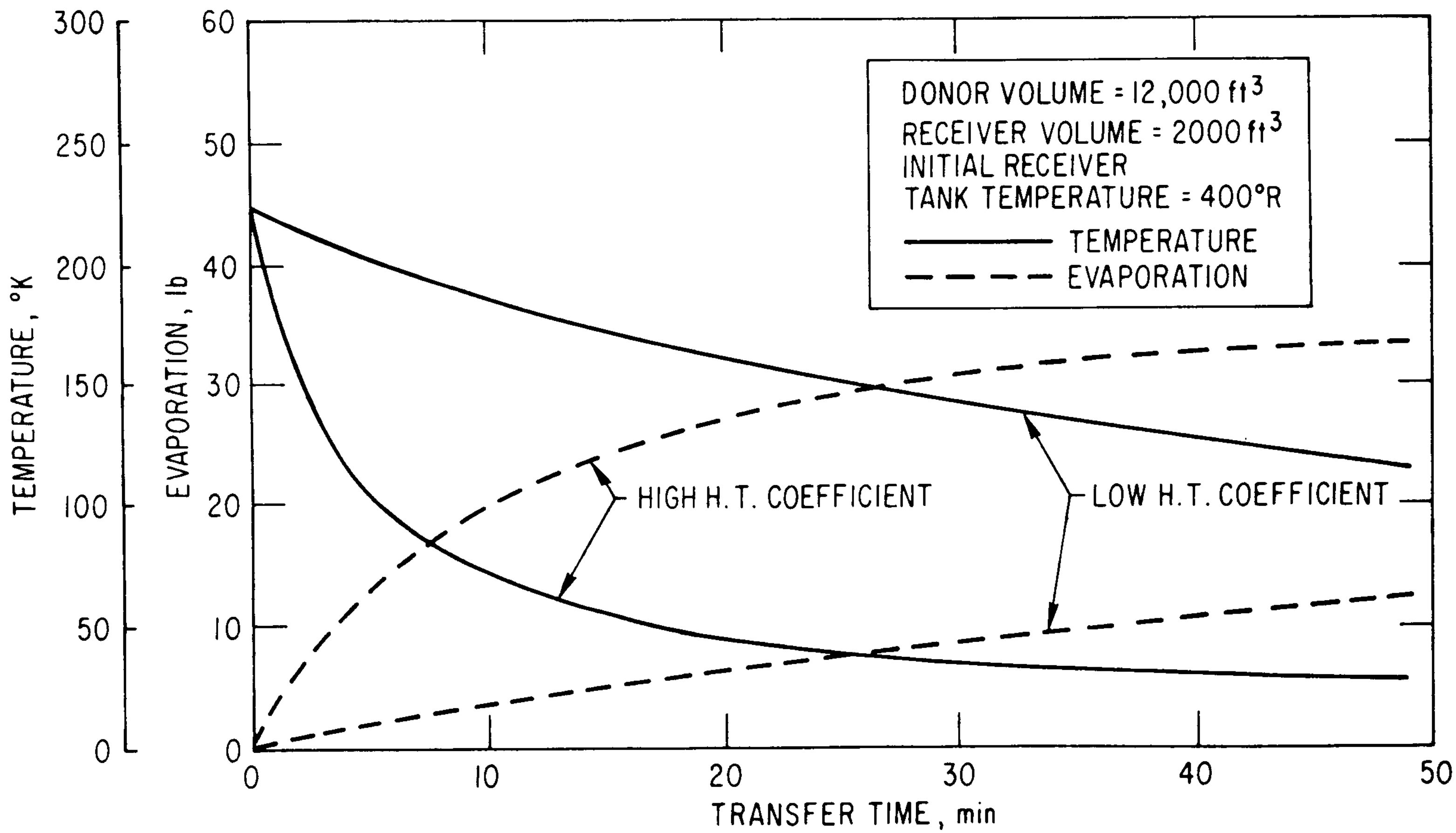

Figure 4. Receiver Tank Temperature and Evaporation vs Time for Hydrogen Transfer

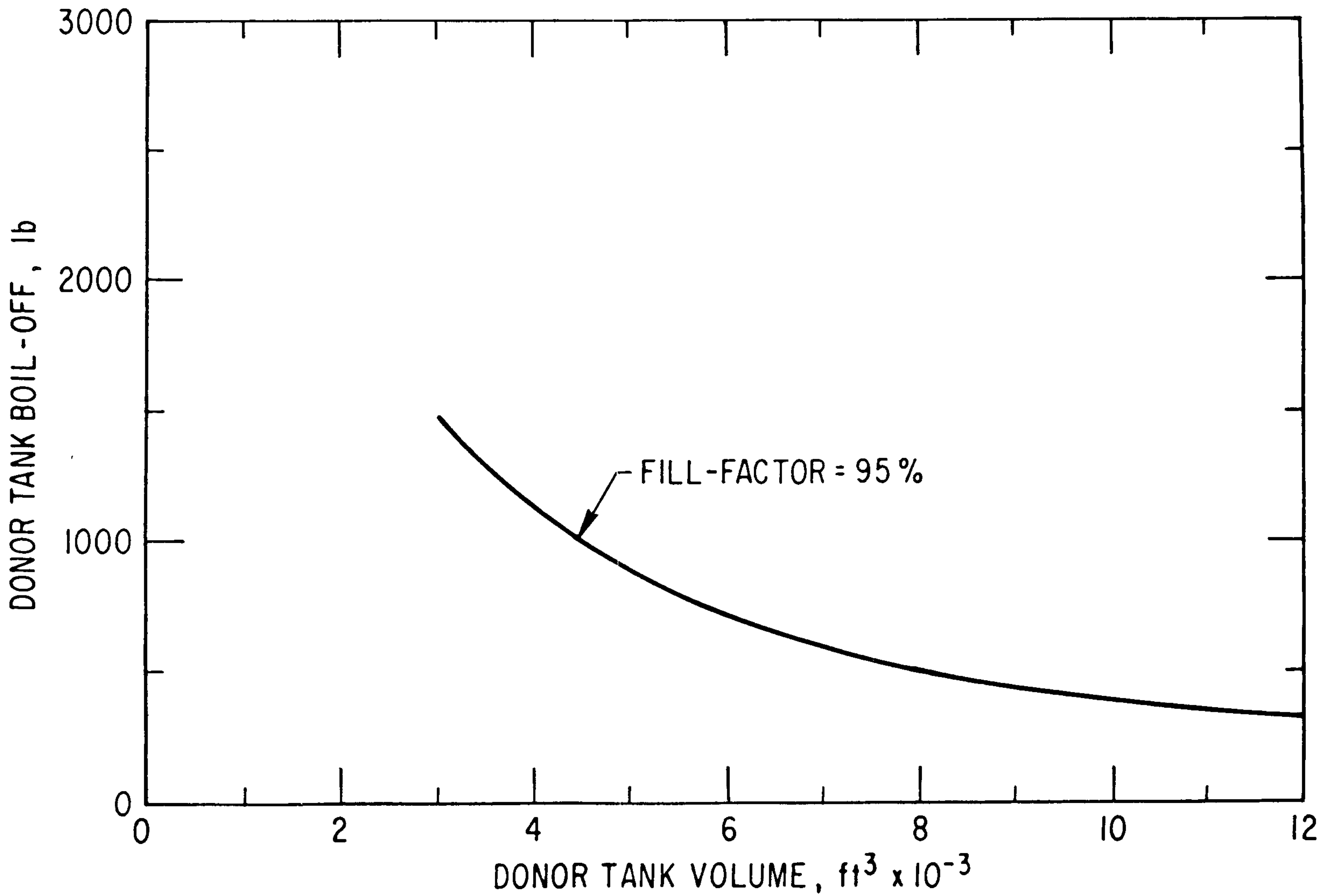

Figure 5. Donor Tank Boil-Off vs Donor Tank Volume for Transfer of 8500 lb H_2

evaporation due to transfer liquid cooling and the vapor replacement requirement. Although Fig. 5 indicates that for some conditions the boil-off may amount to about 10% of the transfer requirement, this amount may be tolerable because of the simplicity of the transfer method compared with other concepts. Therefore, it appears that a more definitive evaluation of this method must be undertaken in order to accept or reject it on the basis of parameters other than boil-off penalties.

E. TECHNOLOGY REQUIREMENTS

In addition to the thermodynamic consideration, feasibility of a propellant transfer concept must be based also on the technology requirements to implement the system. Although the emphasis of this study was placed on the thermodynamics of the process, it is recognized that hardware requirements and performance will be major considerations. The areas recognized as requiring further technology development include the hardware for two-phase fluid introduction to the header of the pump, a high-capacity condensing heat exchanger, and a propellant outlet in the receiver tank.

Current pump technology permits a cryogenic propellant NPSH of approximately 1 ft; additionally, some pumps are able to withstand some cavitation without seriously degrading performance. However, further effort is required in this area to design a pump assembly to accept, on a nominal basis, a two-phase fluid.

The problem of a zero-g condensing heat exchanger must also be solved. Small heat exchangers have been built and operated on this principle, but none have the capacities required for this application. The effectiveness of the heat exchangers must also be improved in order to decrease the required pinch temperature and, consequently, the pump work.

Although adequate energy is available within the receiver tanks to accomplish the propellant transfer, the rate of pressure energy generation and the points in time at which the gases are evolved must be controlled. Therefore, variable distribution orifices in the receiver tank inlet fitting must be developed. A typical schematic is shown in Fig. 6. In addition, liquid retention screens,

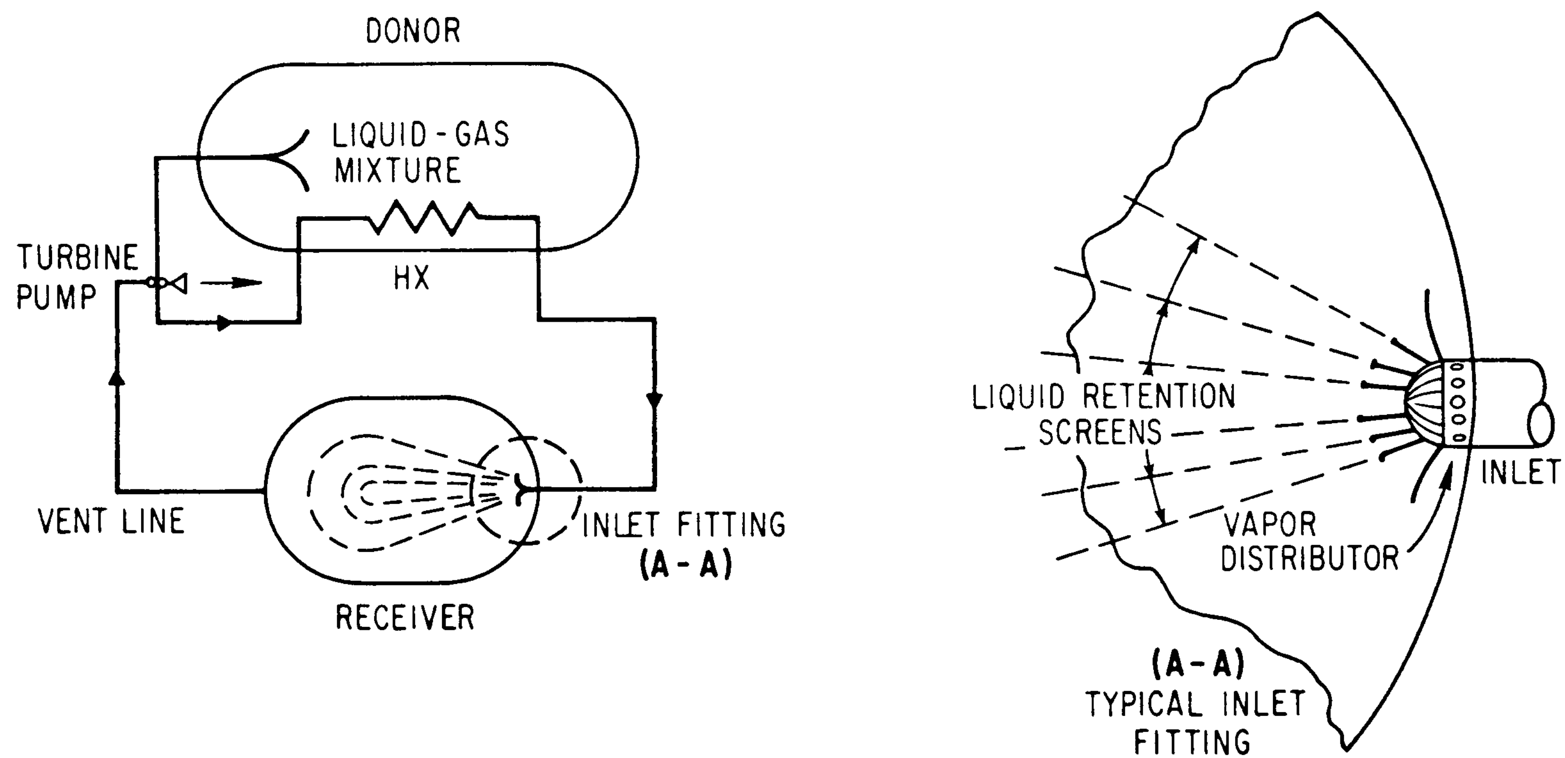

Figure 6. Thermal Bootstrap Propellant Transfer System Schematic

which will act in conjunction with the distribution fitting and prevent uncontrolled contact of liquid with the tank walls, must be developed. Control of the pressure and temperature in the receiver tank system conventionally requires venting of appreciable quantities of vapor. The receiver tank will probably be designed to operate as a large-scale thermodynamic vent to provide for vapor venting.

The initial chilldown phase of a conventional transfer process results in large quantities of warm gas, which introduce sizeable back-pressures against which the incoming propellant must be pumped. This phase therefore requires sizeable vented propellant losses. In the latter phases of propellant transfer, when the ullage space in the receiver tank has become relatively small, and ullage gas temperature is minimum, a further increase occurs.

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IV. SUMMARY

The critical aspects of propellant transfer in orbit are the following:

1. Energy must be available to pump and transport fluid against the flow resistance encountered due to line length and receiver tank back-pressure.
2. The donor tank fluid must be maintained relatively homogeneous, such as by circulation fans, in order to avoid excessive compression work on the transferred fluid.
3. Pressure maintenance of the donor tank is necessary in order to stabilize pump inlet conditions.
4. Control of the condition and phase of the transferred propellant within the receiver tank must be accomplished during the entire transfer process, and especially during the early and latter phases of the transfer process when large temperature rates of change and/or pressure variations are encountered. Final condition of the transferred propellant must be such that its end-pressure and corresponding temperature are suitable for ultimate use as a propulsive fluid for the receiver propulsive system.

Instead of using conventional electrical power for the mass transfer between donor and receiver tanks, the thermal energy within the receiver tanks can be utilized as the source of turbine working fluid, as mentioned earlier. The available thermal energy in a spent stage tank system which has reached thermal equilibrium in the space environment is sufficient to accomplish the complete propellant transfer, based upon the thermodynamic analysis shown. The availability of this energy, however, is a function of time and is not generally consistent with the requirement for pump power; it must be moderated by control of the admission of the of the propellant into the receiver tank.

It may be concluded that, although the existing liteature on orbital propellant transfer contains extensive information on the tradeoffs between propellant losses and expenditures for accelerative phase separation transfer operations, the studies suggest the implementation of minimum-risk approaches to the problem. In-depth investigations of zero-gravity techniques were not performed. Propellant losses and expenditures were determined for various system capacities and the ground rules for traffic models representing the NASA Integrated Space Program (Ref. 2) and the DoD Mission Model (Refs. 4 and 5), with accelerative phase separation as the baseline approach. The problems of c.g. migration during transfer, coupled dynamic instability, and operational complexity were not thoroughly investigated. The "Thermal Bootstrap Process" and other zero-gravity techniques obviate these problems.

The data generated in this study indicate that the thermal bootstrap transfer process utilizing the thermal energy content of the receiver tank appears to be a thermodynamically practical approach to on-orbit propellant transfer for particular conditions of tank volumes and initial temperatures. Additionally, the potential for significant simplification of orbital propellant transfer processes seems to exist for this or similar concepts. However, certain operational contingencies must be recognized in order for the process to be both feasible and practical. The first of these contingencies would be that each receiver tank be allowed to vent down to a residual propellant quantity such that, during the nominal loiter time between the completion of a mission and the initiation of a succeeding mission, the tank and its residual gases would reach an appropriate space equilibrium average temperature that would allow the process to function. This appears to be a practical requirement in light of the projected mission timelines and mission frequency.

The method studied herein is based on the principle of vapor compression/condensation. The primary emphasis of this study was placed on demonstrating the thermodynamic feasibility of the concept. It was shown that, thermodynamically, the concept is feasible. The penalties associated with the concept are dependent on the transfer condition of both the donor and receiver tanks. The amount of boil-off within the donor hydrogen tank (which is used as a heat sink) is dependent on the tank fill-factor and may range from approximately 300 to 1200 lb for the transfer of 8500 lb of hydrogen. The corresponding pump work needed to provide the compressed propellant may range up to 12,000 Btu.

Utilization of the thermal bootstrap transfer process for the collection of excess orbiter propellant as it may accumulate at a storage facility in orbit is practical in terms of donor tank boil-off requirements but not in terms of available thermal energy. The requirement for pumping power, in this case, might well be provided by the orbiter power system. The advantages of simplification of transfer operations, however, will still remain. Rigid docking, artificial gravity, and auxiliary pressurization of the donor tank may be unnecessary.

Hardware requirements may be a major consideration in determining the overall feasibility of the thermal bootstrap concept. Three of the areas which have been identified as requiring further definition are: (1) the two-phase inducer section for the pump, (2) the zero-g condensing heat exchanger, and (3) the propellant distribution controller in the receiver tank. It is believed that the problems associated with these three areas require additional evaluation. Although the study reported here has established the basic thermodynamic feasibility of the proposed concept, a more detailed analysis will be required before operational feasibility can be established.

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