Integration of Cryogenic Dynamic Power System with Vehicle Cooling System

GERALD L. MCARTHUR* AND JAMES H. TARTER†
The Bendix Corporation, Southfield, Mich.

The effect of the integration of a space vehicle cooling system with a cryogenic dynamic power system on propellant and tankage weight and volume has been studied for several power system arrangements. The systems analyzed include one in which all the waste heat produced within the vehicle is absorbed by the cryogenic (hydrogen-LOX) propellants, two in which only part of the waste heat is absorbed by the propellants, and one in which none of the waste heat is absorbed by the propellants. The power system should be designed to utilize as low a percentage of hydrogen as is practical. It is concluded from this study that the minimum propellant weight and volume is obtained when only part of the vehicle cooling load is radiated into space. For missions of long duration, the propellant and tankage weights will far exceed the fixed weights of radiators and power equipment.

Nomenclature

f = ratio of hydrogen weight to total propellant weight
F = useful fraction of propellants loaded into tank
Δh_H = enthalpy change of hydrogen in accepting waste heat, Btu/lb
Δh_O = enthalpy change of oxygen in accepting waste heat, Btu/lb
J = Joule's constant, 778 ft-lb/Btu
k = specific heat ratio of working fluid
M = apparent molecular weight of working fluid, lb/lb-mole
P = electrical power output, kw
p_e/p_i = pressure ratio across prime mover
Q = energy absorbed by propellants, kw
R = gas constant, 1544 ft/°R
S = specific propellant consumption based on propellants expanding through prime mover, lb/kw-hr
S_T = specific propellant consumption based on propellants loaded into tank, lb/kw-hr
T = temperature of working fluid at prime mover inlet, °R
T_c = temperature at combustor inlet, °R
T_H = temperature of hydrogen in tank, °R
T_O = temperature of oxygen in tank, °R
t = time, hr
$\dot{W}$ = total propellant flow rate, lb/hr
$\dot{W}_H$ = hydrogen flow rate, lb/hr
$\dot{W}_O$ = oxygen flow rate, lb/hr
W_f = fixed weight, lb
w_s = specific weight of power system, lb/kw-hr
w_H = ratio of hydrogen tank weight to hydrogen weight
w_O = ratio of oxygen tank weight to oxygen weight
w_r = radiator weight, lb/kw
η_p = adiabatic efficiency of prime mover
η_g = electrical generator efficiency

Presented as Preprint 2517-62 at the Space Power Systems Conference, Santa Monica, Calif., September 25–28, 1962. A portion of the work on this paper was done under the Bendix Aerospace Power Program which is supported by the Red Bank, Bendix Products Aerospace, Utica, Bendix-Pacific, Bendix Systems, and Research Laboratories Divisions of The Bendix Corporation. The authors wish to thank the Bendix Research Laboratories for assistance in preparation and permission to publish this paper. The authors also wish to thank Paul Maker, Staff Engineer of the Bendix Research Laboratories, for his valuable suggestions and assistance in the preparation of this paper.

* Assistant Head, Energy Conversion Systems Department, Energy Conversion and Dynamic Controls Laboratory, Research Laboratories Division.

† Engineer, Energy Conversion Systems Department, Energy Conversion and Dynamic Controls Laboratory, Research Laboratories Division.

Introduction

ALL spacecraft require some type of nonpropulsive power to provide the energy required for guidance, attitude control, environmental control, communications, and other functions dictated by the mission. A number of methods have been used or proposed for supplying this nonpropulsive power. One such method is the use of stored chemical energy which is converted to thermal energy in reaction products and subsequently expanded through a turbine or other heat engine to drive an electrical generator.

Of the many chemical combinations available as potential sources of spacecraft nonpropulsive power, a liquid hydrogen-liquid oxygen system has perhaps the greatest appeal. This is chiefly due to the low specific propellant consumption obtainable, and to the potential for integrating the hydrogen-oxygen power system with environmental control and life support systems. Many interesting system concepts have been proposed in which a number of functions are combined to arrive at an efficient use of cryogenic hydrogen and oxygen for spacecraft nonpropulsive power.[1–7] The stoichiometric combustion temperature of the hydrogen-oxygen reaction is almost 6000°F. For the lowest propellant consumption in the power system, the combustion gases should have a high temperature and a low molecular weight. On the other hand, lower temperatures, which lengthen operational life and improve reliability of system components, may be obtained by using an excess of hydrogen (which also results in a considerably lower molecular weight). Figure 1 shows two curves for percent hydrogen vs final combustion temperature; one for liquid reactants at cryogenic storage temperatures, the other for gaseous reactants preheated to 260°F.

With respect to integration aspects, work to date demonstrates no advantage in integrating the crew oxygen supply with the power system tankage; where spherical tanks can be used, there is little weight penalty for storage in separate tanks, and the regulatory hardware is essentially the same. Furthermore, separate storage gives the advantage of a crew emergency supply. Removal of atmospheric contaminants with cryogenic fluids results in complex and heavy equipment.[8] Superficially, the hydrogen and oxygen power system would appear to be well suited for integration with the attitude control system since exceptionally high specific impulse may be obtained, but, if supercritical tankage is used (and this appears to be most desirable), there is the problem of obtaining the heat inputs required to maintain pressure in the tanks.

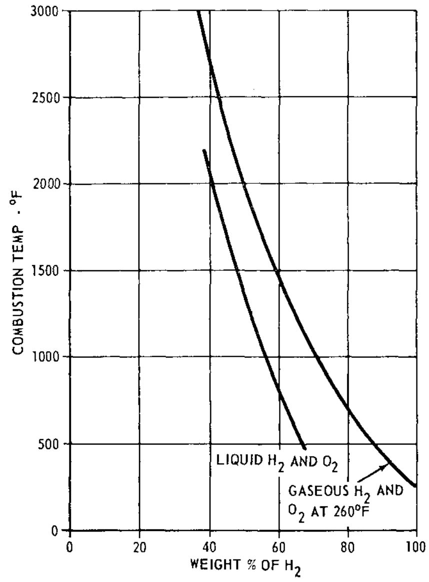

Fig. 1 Temperatures from combustion of hydrogen with oxygen.

Unlike the electrical power system in which the waste heat from the load can be recovered readily, the reaction controller rejects most of its energy in the exhaust gases where recovery is difficult and probably impractical.

One of the most promising integration approaches is that of using the propellants as heat sinks for the vehicle cooling system. The extremely low temperature and high specific heat of cryogenic hydrogen make it especially attractive in this regard. In this paper our attention will be limited to studying the effect on dynamic power system weight and volume of this last integration possibility.

Propellant Storage

Except for missions of short duration, the weight of the cryogenic propellant tanks and pressurization systems will be equalled or exceeded only by the weight of the propellants themselves. The selection of a storage system must be governed not only by vehicle and mission requirements, but also by considerations of reliability and by the current and predicted capabilities of the specific components required. The resulting system must be of minimum weight and volume and yet be able to perform its function with a desired degree of reliability.

It is important to insure that the propellants are withdrawn from the tanks in a single, continuous phase during space (zero gravity) flight. Several methods of achieving this goal have been suggested, such as schemes for rotation (artificial gravity), or for setting up a capillary system within the tank to channel only liquid to the exit port. However, the two methods currently considered most practical are the storage of the propellants at a subcritical pressure within a pressurized flexible container, or storage at an overcritical pressure.

The subcritical storage system uses an externally supplied gas (usually helium) to maintain the tank pressure at the desired level as fluid is withdrawn. The pressurizing gas is supplied to the tank from a high-pressure bottle through a pressure regulator. A major problem in the design of a subcritical storage system is selection of a satisfactory flexible material. The most promising test results[8, 9] on flexible bladders at liquid hydrogen temperatures have been obtained with bladders fabricated from multiple layers of Mylar film or Mylar-coated Dacron.

Supercritical storage is achieved by adding sufficient heat to the storage tank to maintain the fluid at a pressure greater than the critical value (736 psia for oxygen, 191 psia for hydrogen), to insure that the fluid in the tank is in a single phase. The heat input may be supplied by an electrical heater or by circulating some warm fluid through a heat exchanger immersed in the tank.

The supercritical system has the disadvantages that relatively heavy tanks are required and that only a certain percentage of the propellants loaded can be used, since the heat input rate required to maintain the supercritical state climbs rapidly after 85–90% of the propellant has been expelled (Figs. 2 and 3). Furthermore, densities and temperatures change continually as the fluids are withdrawn from the tank, creating problems in control.

An outstanding advantage of supercritical storage is its inherent simplicity. The insulation requirements for supercritical storage are considerably less severe than those for subcritical storage, since a heat input is required to maintain the pressure. In the subcritical case, either heat inputs must

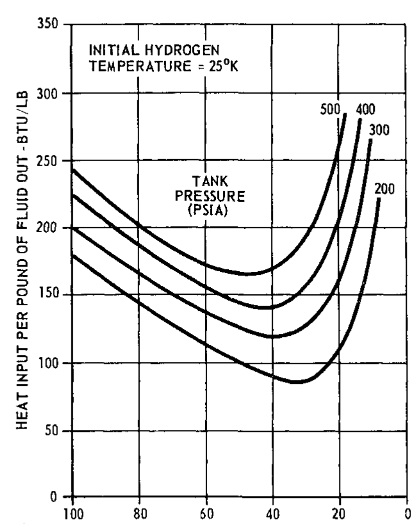

Fig. 2 Heat input per lb of fluid out vs percent of fluid remaining.

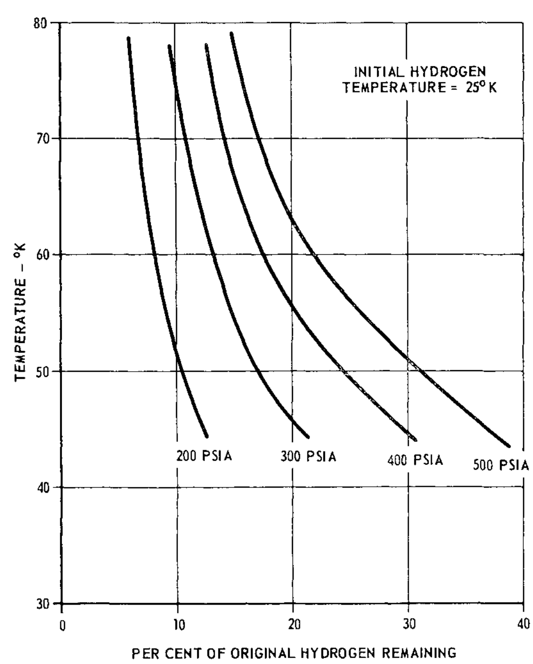

Fig. 3 Percent weight of hydrogen remaining vs temperature.

be kept sufficiently low to prevent the fluid from boiling, or a vent loss must be accepted and some method devised to insure that only vapor is vented. Selection of the insulation system is extremely important. The lowest thermal conductivities are obtained by the use of evacuated double-wall construction, with the space between the walls filled with alternate layers of metal foil to reduce radiation and insulations to reduce conduction.

In this insulating scheme, the inner vessel must be suspended within the outer vessel in such a way that the tankage system can withstand imposed acceleration loads and be capable of adjusting to differential expansions resulting from changes from room to cryogenic temperatures.

Estimates of the weights of both subcritical and supercritical hydrogen (Fig. 4) and oxygen (Fig. 5) tanks have been made as an aid to the calculations for this study. Fluid properties were taken from Refs. 10–13. The pressure vessels were assumed to be 6061-T-6 aluminum spheres. Factors of safety followed the recommendations of Mil-T-5208A. Working stresses were based on room temperature values. Some savings in weight would result if stresses at the cryogenic temperatures were used. In an actual application, vehicle requirements may force the use of nonspherical (heavier) tanks with a resulting increase in tank weight. Multilayer evacuated insulation enclosed in a magnesium outer shell was assumed. It was assumed that the heat leakage through supports and lines could be held to 50% of the total. The insulation thickness for the supercritical tanks was based on the minimum heat input for a propellant consumption of 3.75 lb/hr using 50% hydrogen. The insulation thickness of the subcritical tanks was based on preventing the propellants from boiling during a 25-hr mission assuming the hydrogen to be subcooled to 27°R and the oxygen to 135°R. Different mission requirements will change insulation thickness and alter tank system weight. Subcritical system weights include a bottle of pressurizing gas inside the tank.

Examination of Figs. 4 and 5 shows that a subcritical hydrogen tank must operate at pressures of 50 psia or less to compete, regarding weight, with a supercritical tank. Thus with a subcritical tank, if any pressure in excess of 50 psia is required by the system, pumping must be used. This creates a fairly complex pressurization system. A case could be made for the selection of subcritical oxygen storage, since a subcritical oxygen tank can be pressurized to several hundred psia and still weigh less than a supercritical tank. However, oxygen tank weight is not nearly as large a fraction of total system weight, and the inherent simplicity of supercritical storage has led to the selection of supercritical oxygen storage for the systems to be discussed next.

Integration of Vehicle Cooling with Power System

If the cryogenic propellants supplying the space vehicle power system are also used to absorb waste heat from the vehicle internal environment and equipment, the hydrogen and oxygen flows must be balanced so that the requirements of both the cooling system and the power system are simultaneously satisfied. The point of balance, which defines the required oxygen/hydrogen ratio and the required specific propellant consumption may be determined by plotting the characteristics of the power system and the cooling system on the same set of coordinates.

It can be shown that the specific propellant consumption obtained from the expansion of a gas to produce power is given by

$$S = \frac{3413}{\eta_p \eta_g \left(\frac{k}{k-1}\right)\left(\frac{1544}{778M}\right) T \left[1 - \left(\frac{p_e}{p_i}\right)^{\frac{k-1}{k}}\right]} \tag{1}$$

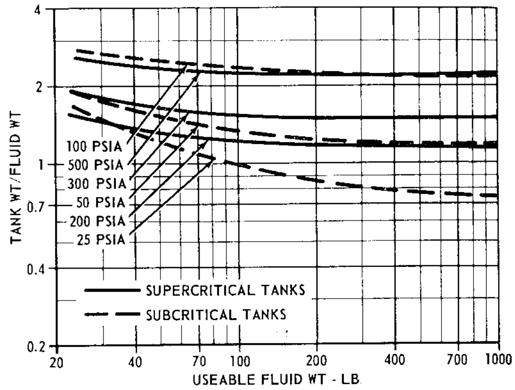

Fig. 4 Weights of hydrogen tanks.

It can also be shown that

$$S = \left(\frac{Q}{P}\right)\left[\frac{3413}{f\Delta h_{\mathrm{H}} + (1-f)\Delta h_{\mathrm{O}}}\right] \tag{2}$$

Equation (1) defines specific propellant consumption in terms of power-generating equipment requirements. Since k, M, and T are functions of f and T_c, Eq. (1) actually gives S as a function of f, p_e/p_i, and T_c. Equation (2) defines specific propellant consumption in terms of cooling requirements. Since the enthalpy changes of the propellants are dependent on propellant storage conditions and T_c, Eq. (2) essentially gives S as a function of Q/P, f, T_c, T_{O}, and T_{H}. Since S could be eliminated by combining Eqs. (1) and (2), we actually have a functional relationship between Q/P, f, T_c, T_{O}, T_{H}, and p_e/p_i. Selection of values for any five of these parameters defines the value of the sixth, as well as the value of specific propellant consumption required for the conditions selected.

The values of the propellant storage temperature T_{O} and T_{H} are functions of the type of propellant storage selected and also of time, since the temperature of the propellants increases with time. The level of the combustor inlet temperature is limited by the maximum temperatures at which the various loads within the vehicle reject their waste heat. It has been assumed that heating loads from the environmental control system will be rejected at around 75°F and those from electronic systems will be rejected at around 300°F, while a small fraction of the heating load may be rejected at 450°F if hydraulic or pure electrical systems are on board. It should be noted that the assumption has been made of no heat recovery from the prime mover exhaust. However, this form of regeneration would result in some decrease in specific fuel consumption.

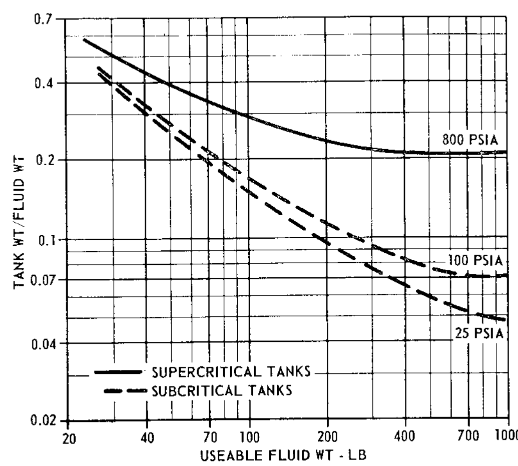

Fig. 5 Weights of oxygen tanks.

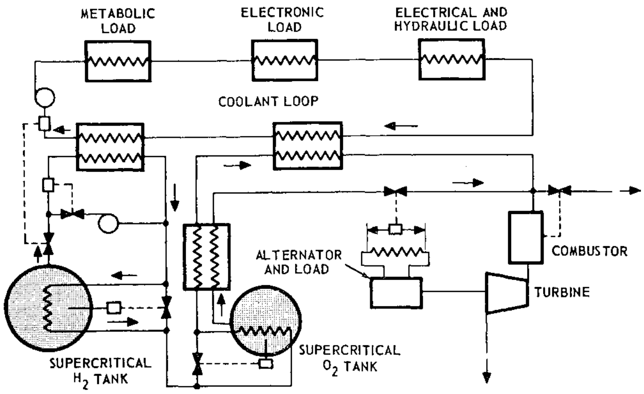

Fig. 6 H_2-O_2 dynamic system with integrated cooling system.

Estimates of Weights for Various Systems

Integrated Power and Cooling

A typical schematic of a dynamic power system with integrated cooling is shown in Fig. 6. This schematic does not show any redundancy (which may be required for reliability). The propellants are stored supercritically—the hydrogen at 200 psia and the oxygen at 800 psia. The various vehicle heating loads reject energy to a coolant loop, which in turn transfers the energy to the hydrogen stream. The hydrogen heat exchangers have been staged to give a hydrogen temperature of 260°F at the inlet of the combustor with 70–80% effective heat exchangers. This results in a maximum hydrogen temperature for minimum size heat exchangers. It is assumed that hydrogen flow is controlled by the coolant low temperature and the oxygen flow is controlled by power demand. Tank pressure is controlled by a valve bypassing the tank heating coil which opens as tank pressure increases. Since the percentage of the hydrogen may be too high to support combustion, provision is made for dumping excess hydrogen as combustor temperature decreases.

The prime mover pressure ratio has been taken as 100. The electrical alternator is assumed to have an efficiency $\eta_g = 0.85$.

If all waste heat is accepted by the propellants, the ratio Q/P is then $1/\eta_g = 1.18$. It is assumed that 85% of the propellants originally loaded into the supercritical tanks can be used. This assumption allows for a small propellant reserve since 90% could be used in an emergency. For an 85% usage factor, the hydrogen temperature range has been assumed to be 45° to 97°R and the oxygen temperature range 190° to 342°R.

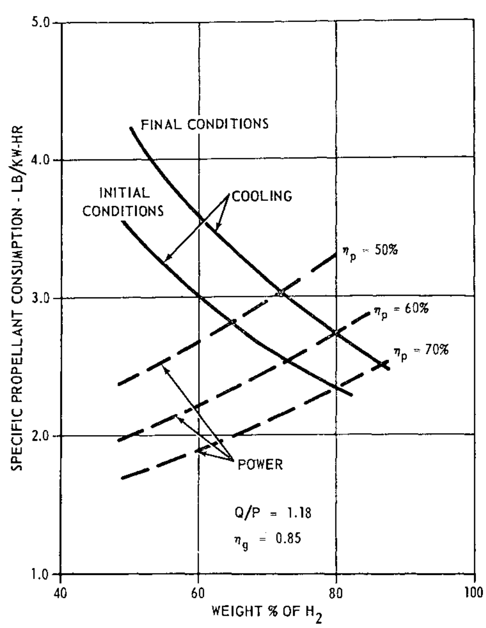

Fig. 7 Matching of propellant consumption.

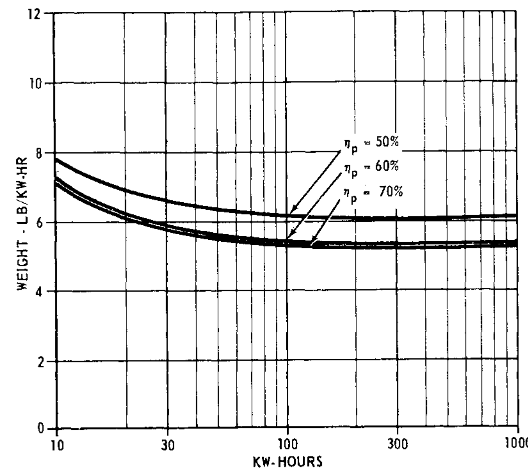

Fig. 8 Weight of tanks and propellants for power system integrated with cooling system.

Figure 7 has been plotted from Eqs. (1) and (2) and shows the operating points for a cryogenic dynamic power system with completely integrated cooling, operating under the assumptions discussed in the previous paragraphs. Two cooling requirement curves have been plotted from Eq. (2), one for the initial storage conditions and one for final storage conditions. The power requirement curves have been plotted from Eq. (1) for prime mover efficiencies of 50, 60, and 70%. The two sets of curves intersect for a range of 64 to 86% hydrogen in the initial mixture. The high hydrogen ratios obtained indicate that cooling requirements dominate the demand for hydrogen. Another significant fact revealed by Fig. 7 is the change in the operating point as storage temperatures increase.

The weight of a system with completely integrated cooling may now be estimated with the aid of Fig. 7. The specific weight of such a system in lb/kw-hr is given by

$$w_s = S_T[1 + fw_H + (1 - f)w_O + (W_f/Pt)] \qquad (3)$$

where $S_T = S/F$.

In what follows, the fixed weight W_f *will be neglected*; the fixed weight can be significant for shorter mission durations, but the detailed calculations required for its evaluation are beyond the scope of this paper.

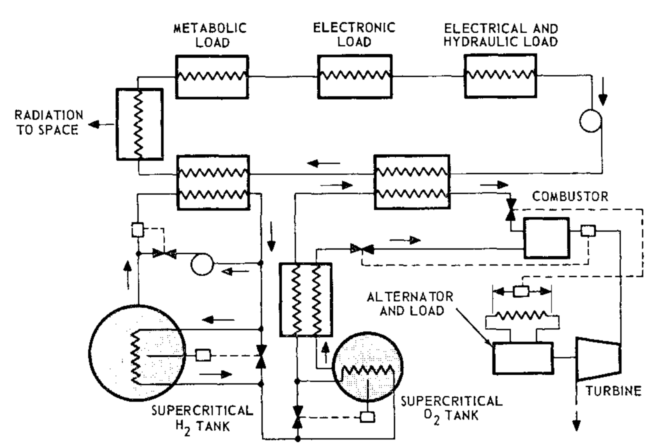

Fig. 9 H_2-O_2 dynamic system with partially integrated cooling system.

Table 1 Propellant volumes of power systems integrated with cooling system

Prime mover eff., %	Propellant volume, ft³/kw-hr
50	0.547
60	0.590
70	0.594

The primary interest here is in the efficiency of propellant utilization which is indicated by Eq. (3) with $W_f = 0$. Figure 8 shows, on this basis, the specific weights of tanks and propellants for an integrated power and cooling system for power requirements of 10 to 1000 kw-hr. It is interesting to note that there is little decrease in weight for prime mover efficiencies greater than 60%. The volumes of the propellants for the power system completely integrated with the cooling system are given in Table 1.

Cooling Partially Integrated with Power System

The previous estimate for the system in which the waste heat is completely absorbed in the propellants indicates that propellant requirements are dominated by cooling load rather than by power load. As a result, specific propellant consumption is high compared with systems in which propellant use is set primarily by power requirements. Analysis shows that the minimum weight system in which vehicle cooling loads are absorbed by the propellants is that in which only enough waste heat is absorbed to bring the propellants to the maximum temperature possible prior to combustion. The fuel-oxidizer mixture ratio in such a system should be that which gives the highest combustion temperature consistent with adequate prime mover life and reliability. Having defined the mixture ratio and combustion temperature, the specific propellant consumption may be computed from Eq. (1). Knowing S and f, the Q/P ratio may be computed from Eq. (2).

If the prime mover is a turbine, the maximum temperature should be no higher than 1800°F. This is based on a reasonable extrapolation of the present state-of-the-art. If a positive displacement machine is used, higher temperatures can be accommodated. This will be especially true if an internal combustion engine is used. For an internal combustion engine, temperatures of 3800° to 4000°F are quite possible. Table 2 shows the Q/P ratios required to preheat the propellants to 260°F in systems operating at 1800° and 3800°F, respectively.

Table 2 Characteristics of power systems partially integrated with cooling system

Temp., °F	f	η_p	S, lb/kw-hr	S_T, lb/kw-hr	Q/P, min.	Q/P, max.
1800	0.53	50	2.50	2.94	0.73	0.88
1800	0.53	60	2.08	2.45	0.61	0.74
1800	0.53	70	1.77	2.08	0.52	0.63
3800	0.30	50	2.09	2.46	0.36	0.47
3800	0.30	60	1.74	2.05	0.30	0.39
3800	0.30	70	1.49	1.75	0.26	0.33

Table 3 Volumes of propellants for power systems partially integrated with cooling system

Prime mover eff., %	Propellant vol. for 1800°F, syst-ft³/kw-hr	Propellant vol. for 3800°F, syst-ft³/kw-hr
50	0.408	0.211
60	0.340	0.175
70	0.289	0.150

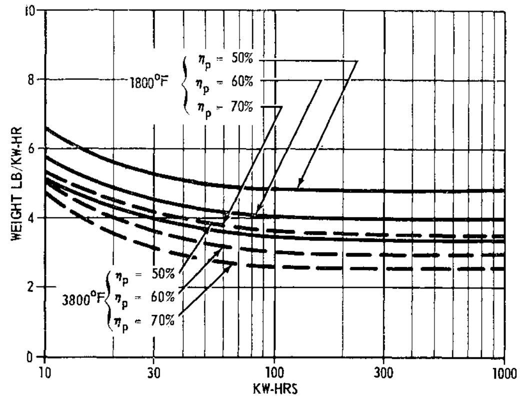

Fig. 10 Weight of tanks and propellants for power system partially integrated with cooling system.

The schematic of such a partially integrated system is shown in Fig. 9; it is quite similar to that shown previously. A space radiator has been added to the coolant loop to reject energy not absorbed by the propellants. Hydrogen flow is controlled by power demand and oxygen flow by combustor temperature.

The equation for the specific weight of the system is the same as Eq. (3) except that a term for radiator weight must be added.

$$w_s = S_T \left[1 + f w_H + (1 - f) w_O + \frac{W_r}{t} + \frac{W_f}{Pt} \right] \tag{4}$$

Figure 10 shows the specific weights of tanks and propellants (i.e., Eq. (4) with W_r and W_f neglected) for a power system with the cooling and power only partially integrated. The volumes of these systems are shown in Table 3.

These results emphasize the desirability of operating with small ratios of hydrogen weight to total propellant weight. An alternative to using a prime mover which can tolerate extremely high temperatures is the use of a reheat cycle to permit the use of low percentages of hydrogen. In the reheat cycle, additional oxygen is reacted with the excess hydrogen in the working fluid between prime mover stages. This addition of energy in the working fluid between stages improves the specific propellant consumption for a given temperature and also reduces the percent of hydrogen.

No Integration of Cooling and Power System

In this case, the power subsystem schematic is simplified considerably (Fig. 11), and a malfunction in either the cooling subsystem or power subsystem will not affect the other. A coolant loop and radiator, which are not shown in the schematic, are still required, so that the number of components in the vehicle has not been diminished. Figure 1 shows that if cryogenic hydrogen and oxygen are used, an initial mixture ratio containing 44% hydrogen must be used to obtain an 1800°F combustion. Equation (1) gives values

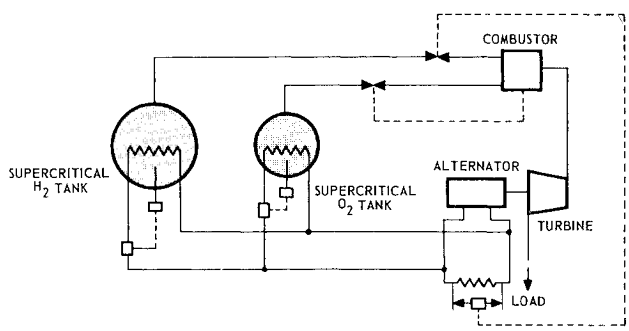

Fig. 11 Nonintegrated H_2-O_2 dynamic system.

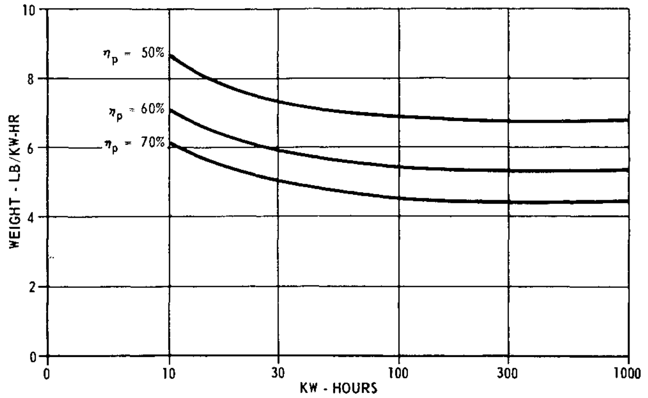

Fig. 12 Weight of tanks and propellants for power system not integrated with cooling system.

of S = 2.19–3.08 lb/kw-hr for this mixture ratio, an 1800°F temperature, prime mover efficiencies of 50 to 70%, and a pressure ratio of 100.

Since waste heat is no longer available to supply the energy to keep the tanks supercritical, an electrical heater must be used. Approximately 0.053 kw-hr/lb of propellant expelled is required for this purpose. This is a severe penalty, as is shown by the weights of tanks and propellants shown in Fig. 12. Note that the weights are in the range of 4.46 to 6.80 lb/kw-hr which overlaps the range of weights for the power system which was completely integrated with the cooling system. The volumes for this system are shown in Table 4.

Table 4 Volume of propellants for power system not integrated with cooling system

Prime mover eff., %	Propellant vol., ft^3/kw-hr
50	0.510
60	0.405
70	0.335

Conclusions

The results of this study indicate that if the hydrogen and oxygen supply of a cryogenic dynamic power system is also used to absorb all waste heat produced within a space vehicle, the required weight and volume of the propellants becomes large. This is a consequence of the fact that the cooling system provides the greater demand on propellant flow, forcing the power system to operate with less than maximum possible propellant economy.

The minimum specific propellant consumption, and hence the minimum system weight and volume chargeable to propellant storage, are obtained when only power system demand determines propellant flow with a portion of the vehicle waste heat used to preheat the hydrogen and oxygen to the highest temperature possible prior to combustion. Some vehicle waste heat must then be rejected to space through a radiator.

Minimum system weight and volume result when the relative amount of hydrogen is reduced to approach the optimum mixture ratio which lies on the fuel-rich side of the stoichiometric ratio. Reduction of the percentage of hydrogen not only improves specific propellant consumption but also reduces volume and weight of tanks, since a given weight of oxygen occupies less space and requires a lighter tank than the same weight of hydrogen. These lower percentages of hydrogen may be used if the prime mover is of a type which can tolerate the resulting high temperatures or if a reheat cycle is used.

Total separation of the power and cooling systems simplifies the power system schematic considerably. However, specific propellant consumption increases considerably over that of an equivalent system in which waste heat is used to preheat the hydrogen and oxygen. In addition, electrical power will be required to supply the energy to pressurize supercritical tanks, since waste heat is no longer available for this purpose. This exacts a significant penalty in increased propellant consumption. In fact, if it were an absolute requirement that there be no connection between the power and cooling systems, serious consideration would have to be given to the use of subcritical tankage.

For short duration, constant-power missions, it can no longer be concluded that a power system with a partially integrated vehicle cooling system adds less weight to the vehicle than a power system with a totally integrated vehicle cooling system. The crossover point is roughly that mission length at which the difference in weight of propellants and tanks between the two systems is equal to the weight chargeable to the radiator required by the system with a partially integrated cooling system. For example, assuming a radiator weight of 1 lb/ft^2 (giving a weight chargeable to the radiator of 20 lb/kw of energy rejected) and a prime mover efficiency of 60%, a weight crossover between the completely integrated system and the 1800°F partially integrated system occurs at approximately 6 hr.

References

[1] Breaux, D. K., Burriss, W. L., and Schultz, R. L., "Missile and space vehicle non-propulsive power concepts," Soc. Automot. Engrs. Paper 234A (1960).

[2] Zwick, E. B. and Zimmerman, R. L., "Space vehicle power systems," ARS J. **29**, 533–564 (1959).

[3] Burris, W. L. and Mason, J. L., "An integrated cryogenic system for spacecraft power, thrust, and cooling," Am. Soc. Mech. Engrs. Paper 61-AV-39 (1961).

[4] Raymond, E. J., "The selection of accessory power systems for long duration manned space vehicles," Soc. Automot. Engrs. Paper 154A (1960).

[5] Deacon, W. K. and Wood, H. J., "Chemical power systems for missiles and space vehicles," Soc. Automot. Engrs. Paper 496A (1962).

[6] Coyler, D. B. and Bjeklie, J. W., "Development of an advanced design cryogenic space power system," Soc. Automot. Engrs. Paper 515B (1962).

[7] Traynelis, K. A., "Study of integrated cryogenic fueled power generating and environmental control systems," Aeronaut. Systems Div. Tech. Rept. 61-327 (1961).

[8] Waggoner, J. N. and Burriss, W. L., "Environmental control of spacecraft for durations up to two weeks," ARS J. **32**, 1019–1028 (1962).

[9] Sirocky, P. J., "Transfer of cryogenic liquids by an expulsion-bag technique," NASA TN D-849 (1961).

[10] Woolley, H. W., Scott, R. B., and Brickwedde, F. G., "Compilation of thermal properties of hydrogen in its various isotopic and ortho-para modifications," Natl. Bur. Std. Res. Paper RP-1932 (1948).

[11] Johnson, V. J., "A compendium of the properties of materials at low temperature (phase I) Part 1: properties of fluids," Wright Air Develop. Div. TR 60-56 (1960).

[12] Hilsenrath, J., *Tables of Thermal Properties of Gases*, Natl. Bur. Std. Circular 564 (1955).

[13] "Pressure enthalpy diagram of oxygen," U. S. Bur. Mines (1928).