## NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Auxiliary Propulsion and Pyrotechnics
Branch Internal Note

Shuttle
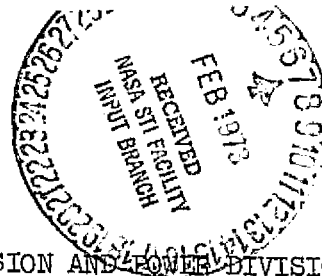Reaction Control System
Cryogenic Liquid Distribution System
Study

PROPULSION AND POWER DIVISION

## MANNED SPACECRAFT CENTER
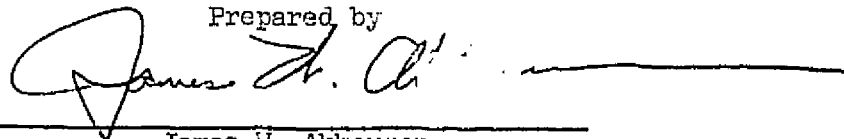
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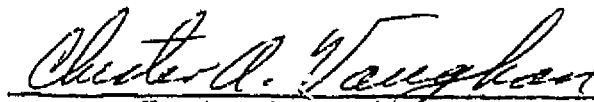
Shuttle
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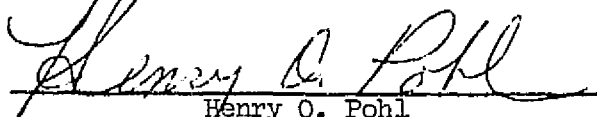Study

Prepared by

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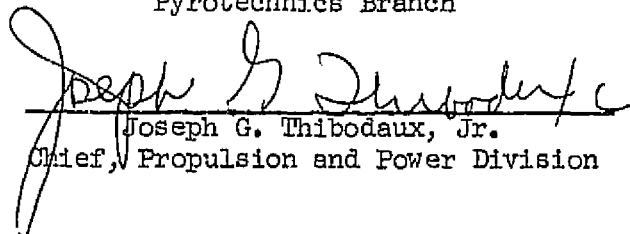James W. Akkerman

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## FIGURES

## 1.0 SUMMARY

Cryogenic liquid hydrogen and liquid oxygen distribution systems appear
entirely feasible for the shuttle reaction control system and can very
likely be operated for a 7-day mission without any boiloff. They are
relatively simple having only four active components; the pump (a low
pressure, slow response unit); a hydraulic motor; a relief valve; and
a bellows accumulator. All of these units are well within the state-
of-the-art.

The only questionable area in using a liquid distribution system for
the reaction control system is the ignition and pulse mode operation
of engines operating on cryogenic liquids. Boiloff of the cryogenics
in the dribble volume after each pulse could cause freezing problems
under certain pulse modes. Dribble volume losses in pulse mode opera-
tion will require about 29 pounds of reactants per thousand starts.

There is considerable additional effort required to refine the design;
i.e., recalculate the various parameters in a more exact method--with-
out the conservative assumptions. It appears--based upon the conserva-
tive estimates, that the system might be operated over a full 30-day
mission without boiloff losses--especially if all propulsion and power
requirements were included into this system, providing more flow of
cold fluid from the tanks and making the distribution system heat leak
more acceptable. Any boiloff might be used for life support and/or the
fuel cells.

The system dry weight can apparently be reduced by nearly 30 percent
from the weight involved with gas systems. The volume of the system,
exclusive of tankage, is reduced to about half of the gas system because
of the relatively small liquid accumulator. The concept offers the
advantage of eliminating the development cost and reliability penalty
associated with the heat exchanger required for the gas systems. Also,
since the liquid accumulators are relatively small and lightweight (500
psi operating pressure) the system weight is not particularly sensitive
to pump startup time, thereby simplifying the pump development. With
the low pressure involved, the pump power is in the range of capability
of the onboard power units. The choice of vacuum jacketed insulated
lines affords dual containment of the propellant--a significant relia-
bility improvement which eliminates the need for a large number of iso-
lation valves. Monitoring of the vacuum in the jacket is an ideal way
of verifying system containment in checkout and in flight. The devel-
opment cost for this type system should be a minimum and its inflight
performance should be near the maximum achievable which is consistent
with shuttle design goals.

## 2.0 INTRODUCTION

The National Aeronautics and Space Administration is presently conducting feasibility and preliminary design studies of a fully recoverable and reusable space transportation system, commonly referred to as the space shuttle vehicle. As presently conceived, the vehicle will consist of two separate elements, a booster stage and an orbiter stage, each of which is individually recoverable. The space shuttle vehicle is designed to provide low cost transportation to earth orbit to support a variety of missions, including logistic resupply of a space station.

In order to achieve maximum cost effectiveness, the space transportation system will be designed for up to 100 flights (reuses) over a 10-year operational lifetime and will be capable of relaunch within 2 weeks after landing. The system will be designed to minimize required postflight refurbishment, maintenance, and checkout.

The space shuttle vehicle will be launched vertically on rocket thrust alone, with the booster staging-off and flying back to the recovery site. The orbiter stage will proceed to orbit under main rocket propulsion and, in orbit, will maneuver as a true spacecraft. At the conclusion of its mission, the orbiter stage will reenter and also fly back like a conventional aircraft.

Hydrogen and oxygen were initially chosen as propellants for the main propulsion systems of both the booster and orbiter stages because of high performance, relatively low cost, and nontoxic, noncorrosive nature. These propellants have also been selected for other energy systems for the same reasons plus additional benefits derived from commonality between the main and auxiliary propulsion storage and feed systems. These benefits include possible use of main engine boost residuals for reaction control system (RCS) requirements and potential flexibility in distribution of orbital maneuvering propellant between the main engine and the RCS to provide capability for a wide range of missions.

At present, a variety of propellant feed systems are being studied for the reaction control system. These systems differ greatly in configuration and operating characteristics. One common characteristic, however, is the delivery of hydrogen and oxygen. Gas was initially selected because of the anticipated difficulty of delivering cryogenic liquids through a complex distribution system.

However, detailed studies of the gas type systems indicate that the propellant conditioning hardware and the associated inefficiency of gasification in conjunction with larger vehicles and impulse requirements results in a significant inert weight fraction on the order of 0.5.

Weight penalties for the gas system can only be reduced at the expense of system safety and high development cost. A liquid distribution system can operate without a turbopump, a propellant thermal conditioner (i.e., heat exchanger) or a gas accumulator, reducing the weight and cost and enhancing the reliability, but poses the problem of liquid distribution.

Cryogenic distribution lines have characteristically been a problem in the past because almost invariably a pump has been located at the end of the line. Any heat leak or pressure drop in the line caused cavitation problems in the pump--especially when the storage tank liquid was near saturation with vapor. However, a special system using pumps located near the tanks can provide sufficient heat capacity to avoid boiling, thus making a cryogenic liquid distribution system appear desirable for a reaction control system. This paper describes such a system and its operational characteristics for use in a shuttle type vehicle.

## 3.0 SYSTEM THERMODYNAMICS

The primary consideration for the concept of using a cryogenic liquid distribution system in the shuttle is the heat leak situation. As in every fluid system, it is most desirable to avoid two phase flow. Actually, to guarantee single phase (liquid only) flow, the pressure must be maintained at a level far enough above the boiling point to avoid transient boiling during normal hydraulic transients. A pressure about 25 to 30 percent higher than the boiling point is normally considered acceptable--especially in systems where hydraulic transients are somewhat damped by fluid compressibility and/or the use of accumulators.

Using this criteria, the thermodynamics of the working fluids can be evaluated. The primary consideration here is to determine the amount of heat that the fluid can accept before developing a vapor pressure which might cause a two phase situation. Then, an analysis of the heat leak into the system can be made to determine whether a realistic system can be built within the limits of acceptable heating.

The key thermodynamic properties of oxygen are shown in figure 1. (Pressure, temperature, density and enthalpy.) The thermodynamic process begins with the fluid at about 30 psia in the main storage dewar. Here, its vapor pressure is 30 psia also, since it will likely be boiling during most of the mission. It may be subcooled by hydrogen boiloff in the pump area, which will improve the situation somewhat, but for this analysis the worst case situation is considered.

A pump pressurizes the fluid to system pressure after being triggered by either a high temperature condition or a low pressure condition. In either case, as the accumulator fills, the pressure rises and will level off at 500 psia as the relief valve opens or the accumulator fills. At this state point, the liquid is considerably subcooled. Its temperature is 1₁0°R almost exactly the same temperature that it was in the dewar, and its density is about 69.5 lb/ft³ still about the same as it was in the tank. Also, the vapor pressure of the fluid is still only 30 psia. In this condition, the fluid can accept considerable heat without boiling. In fact, it can be heated until it reaches 240°R and still have a vapor pressure of only 300 psia. During this heating process, the fluid density drops from 69.5 lb/ft³ to 55.5 lb/ft³ and its heat content increases by 28.6 Btu/lb. This is the heat the oxygen can accept and still be able to drop in pressure from 500 psia to 300 psia without boiling.

A similar analysis for hydrogen indicates that about 156 Btu/lb may be accepted by the hydrogen. Actually above 187 psia the hydrogen is supercritical, thereby always guaranteeing a single phase flow. The

Density 55.5 lb/ft$^3$

Density
69.5 lb/ft$^3$

Temp 240$^o$R

Temp
175$^o$R

500
400
300

Pressure
Psia

30

176$^o$R

5                    34        Enthalpy, Btu/lb
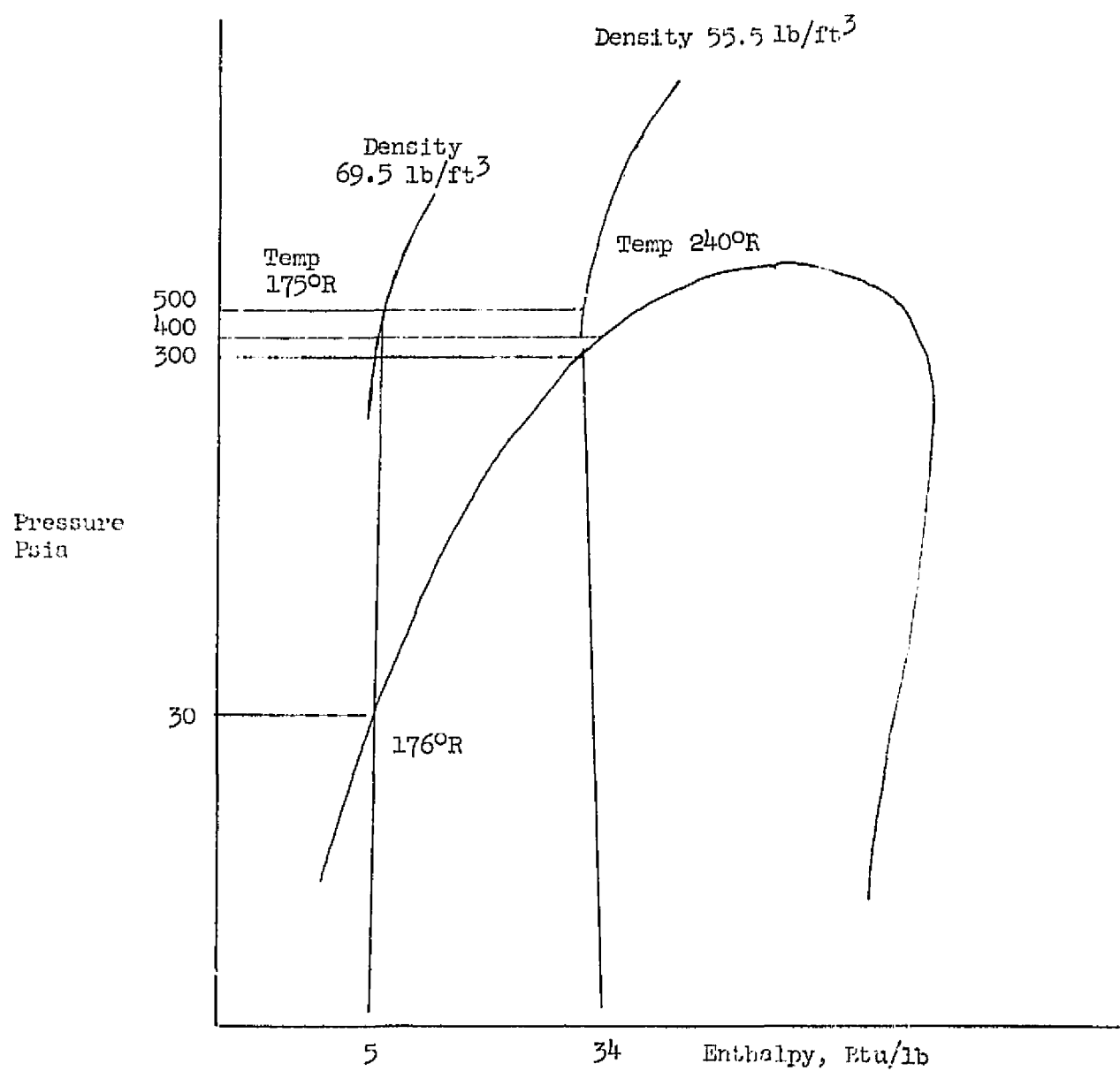
Figure 1 - OXYGEN THERMODYNAMIC PROPERTIES

somewhat arbitrary limit of 78°R and 2.0 lb/ft$^3$ for the fluid is selected here for the sake of analysis. Actually, further decreases in density and additional heat leak may be acceptable, depending upon how the flow control is to be implemented in the using hardware.

It is interesting to note here that if two phase flow does happen to occur it will be in the oxygen side of the system, thereby always reducing the O/F ratio momentarily--a fail safe condition.

A final note of interest is that the fluid in the distribution system may be at either extreme of the thermodynamic conditions; i.e., oxygen at 175°R and 69.5 lb/ft$^3$ or 240°R and 55.5 lb/ft$^3$ and hydrogen at 44°R and 4.4 lb/ft$^3$ or 78°R and 2.0 lb/ft$^3$.

## 4.0 SYSTEM DESCRIPTION

The first step in making a cryogenic liquid distribution system work
for a reaction control system (RCS) is to put the pump at the upstream
end of the plumbing in or near the propellant storage tank. This reduces
or eliminates the problem of cavitation in the pump and establishes a
thermodynamic condition in the cryogenic fluids such that a significant
amount of heat can be absorbed without any boiling occuring in the lines.
The only question is whether the improved thermal capacity of fluid (re-
sulting from pumping) is sufficient to absorb the heat leak into the
distribution system without causing boiling. Also, since any heat leak
will cause the propellant to increase in volume, some provision must be
made to allow thermal expansion; e.g., an accumulator. A liquid accu-
mulator is desirable in any case to avoid starting the pump every time
the RCS is used. Finally, if the duty cycle has a long period with no
activity, any heat leak at all, no matter how small, will finally cause
the fluid to expand to the limits of the accumulator. Therefore, a
relief valve is required. The vented fluid should be dumped back into
the storage tank so that it can be vented through the tank cooling sys-
tem; e.g., thermodynamic vent. For conditions of no flow, some circula-
tion in the distribution system may be required to avoid local boiling.
A fan system may be required unless adequate conduction along the pipes
can be achieved and/or the duty cycle and heat leak combine to eliminate
hot spots.

A system for distribution of cryogenic liquids in an RCS for a shuttle
type spacecraft is shown in figure 2. It will require a main line about
120 feet long to reach near the ends of the vehicle. Also, an addi-
tional manifold will be required to further distribute the fluids to
individual rocket engines. About 40 feet of line will be required at
each end of the vehicle for this purpose. A schematic for this system
is shown in figure 3. The components required are:

    a. Pumps

    b. Pipes (thermally insulated and vacuum jacketed)

    c. Accumulators

    d. Relief valves

    e. Recirculation fans

A description of each of these parts follows. A discussion of the use
of this system is included in the next section.

Forward Manifold

Pump Assembly

Aft Manifold

Main Distribution Line

Re... .? Valve

Forward Accumulator

Aft Accumulator
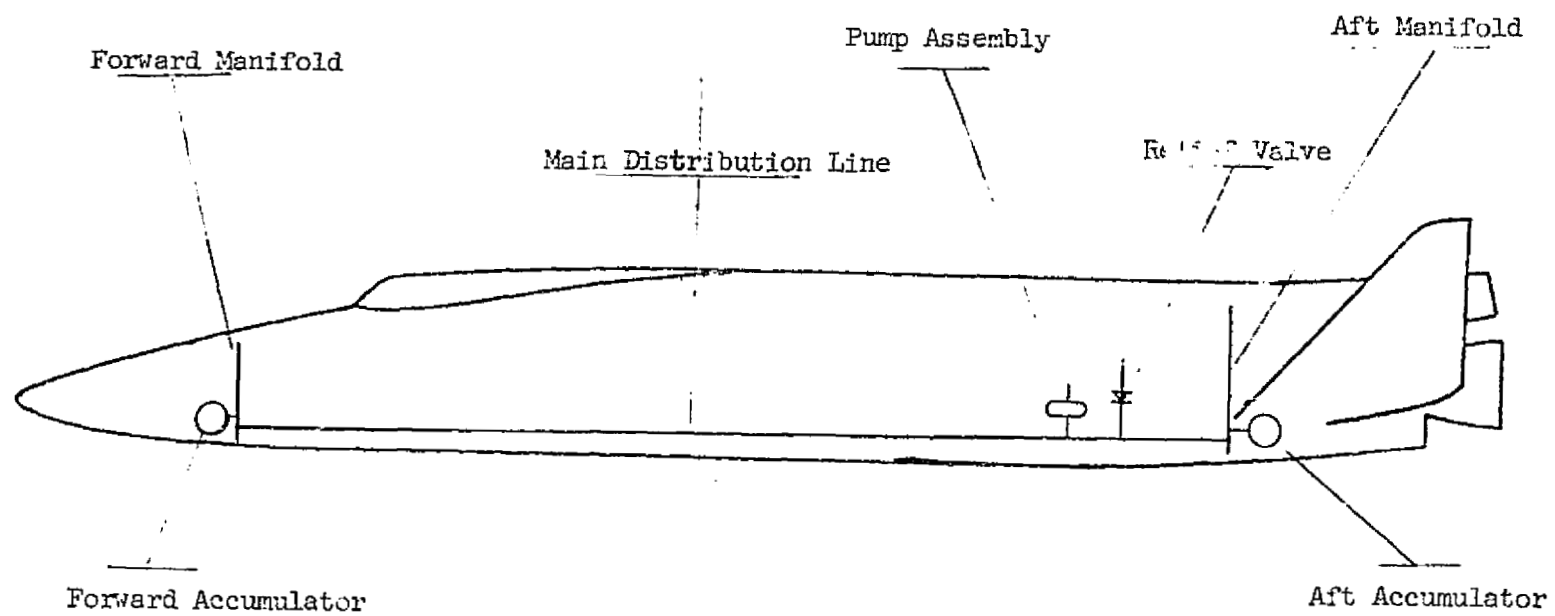
Figure 2 - SHUTTLE CRYOGENIC LIQUID REACTION CONTROL SYSTEM DISTRIBUTION SYSTEM INSTALLATION

CIRCULATION
FAN

RELIEF VALVE
500 LB/IN.$^2$

LIQUID LINES

30 LB/IN.$^2$

PUMP

BELLOWS
CONTRACTED

STORAGE TANK

BELLOWS
FULLY EXPANDED
$(P = 500$ LB/IN.$^2)$
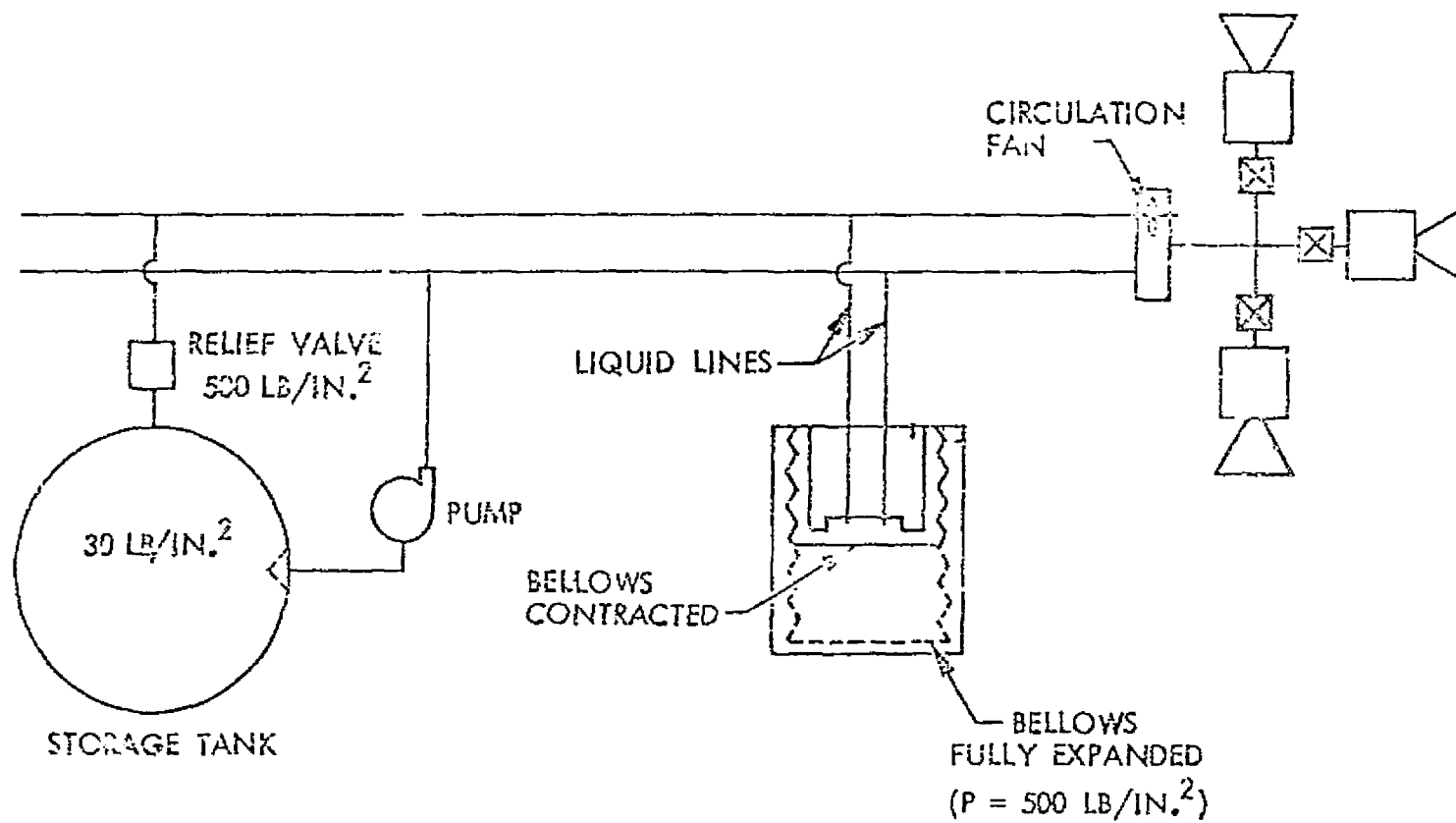
ONE PROPELLANT SYSTEM SHOWN
OTHER PROPELLANT SYSTEM SIMILAR

Figure 3 - CRYOGENIC LIQUID REACTION CONTROL SYSTEM DISTRIBUTION SYSTEM SCHEMATIC

The pumps must be sized for enough capacity to operate the system at the maximum flow rate to be expected. The flow requirement during operation of the propulsion system has been estimated to be about 20 pounds per second total flow at an oxidizer to fuel flowrate ratio of about 4:0. This requires four pounds per second of hydrogen and 16 pounds per second of oxygen. If a specific impulse value of 430 seconds is achieved, this will provide a total equivalent thrust level of 8,600 pounds to be shared among the rocket engines involved. For the purpose of this paper, a nominal operating pressure of 450 psia has been selected. The power required is outlined in appendix A at 28 horsepower from the oxygen pump and 112 horsepower from the hydrogen pump. The total is 140 horsepower, and assuming positive displacement pumps operating at a 94 percent efficiency, a pump power requirement of 149 horsepower results.

A hydraulic motor can be used to drive the pumps without a severe weight penalty. Presently available hydraulic motors can operate at about 93 percent efficiency, thus requiring about 160 horsepower from the onboard power unit. The excellent life and reliability of these units would make them a logical choice. This is well within the capacity of the onboard power unit. The necessary motors would weigh about 54 pounds (10 pounds for oxygen and 44 pounds for hydrogen) and with redundancy, the total would come to 162 pounds. The pumps themselves would weigh about 3 pounds for the oxygen and about 10 pounds for the hydrogen giving a total with redundancy of 39 pounds. Another 465 pounds has been estimated for the power unit and hydraulic lines to support this approach. The power unit propellant consumption is 4 lb/hp-hr or 89 pounds.

The next element requiring detail consideration is the plumbing itself. Assuming the above flow rates, and a pressure drop of 20 psi maximum, the oxygen line size is 1.81 inch inside diameter and the hydrogen line is 1.92 inch diameter (see appendix B). Assuming that recirculation is necessary, the two oxygen lines need to be 1.28 inch inside diameter. These two lines would flow in parallel during system operation and would provide counter flow during "off" periods. Hydrogen requires 1.36 inch lines.

Several ways of providing thermal insulation for the lines have been considered, but the one offering the most interesting advantage is the use of a vacuum jacket. Adequate thermal protection can be achieved for both ground operations and in flight. Also, the vacuum jacket provides redundant containment as well as a semiautomatic checkout feature for containment in the system. This is the only really safe way to implement hydrogen plumbing where only a minor leak can cause a serious explosion hazard. A few layers of reflective insulation will be required to keep the vacuum jacket cool and minimize heat transfer by radiation. Ten layers of aluminized mylar is included.

The weight of this type plumbing system should be on the order of 0.862 pounds per foot for oxygen, totaling 172 pounds for the installation in a typical 200 foot long shuttle design. The hydrogen pipes would weigh about 182 pounds because of the slightly larger size. This weight is based upon the use of aluminum stressed at 17,500 psi. The weight would probably double because of various supports, thermal expansion joints attachment, etc. giving a plumbing weight total of 714 pounds. The heat leak for this type installation is typically 0.5 Bt/hour/ft$^2$ for both hydrogen and oxygen resulting in a heat leak of 157 Btu/hour. Other heat leaks must be added to this, however. For example, the valve electrical wires, engine interfaces, pumping inefficiencies, etc. These will be considered later.

The third item requiring consideration is the accumulator. For the purpose of analysis, a positive expulsion device is visualized using a bellows. Although heavier than other possible devices, it is considered "state-of-the-art" equipment and will provide a most realistic weight estimate. Helium is used as the pressurizing agent. Several alternatives exist as to where the accumulator is located. One alternative is to put it into the main tank which would eliminate the heat leak problem. However, additional area of the main tank would be involved for heat leak consideration. In order to avoid unnecessary interfaces, a design with a remote accumulator and helium supply is selected. Further, each accumulator has been divided into two parts for the sake of redundancy such that one unit is located at each end of the vehicle. If the accumulator is lost, the number of cycles of operation of the pump will simply double and the hydraulic character-istics of the system will degrade slightly on one end of the system. If the second accumulator is lost, the system will continue to function but not with normal hydraulic transients and the pump cycles would be-come excessive--a good reason to return. The weight, volume, and heat leak of the accumulators required to support a 100 cycle type system are shown in appendix C.

The results are as follows:

|  | O$_2$ | H$_2$ |
|---|---|---|
| Weight | 22.0 lb | 139.0 lb |
| Volume | 2.5 ft$^3$ | 12.5 ft$^3$ |
| Heat Leak | 1.6 Btu/hr | 4.8 Btu/hr |
| Diameters | 1.68 ft | 2.88 ft |

The total for both accumulators for both ends of the vehicle are:

| Weight | 322.0 lb |
|---|---|
| Volume | 30.0 ft$^3$ |
| Heat Leak | 12.7 Btu/hr |

A relief valve is required to avoid overpressurization in the system. A flow capacity equal to the pump flow rate is required. The unit should not weigh more than about 10 pounds even in a triple redundant configuration. An alternate approach is to use a solenoid valve and a pressure switch for control. Both concepts would weigh about the same.

One feature of the system that is very desirable is the use of vacuum jacketed pipes. Although there are many ways to provide thermal protection, the use of a vacuum jacket provides redundant containment--a feature always considered desirable in the past but never justifiable. Redundant containment will eliminate the need for most isolation valves. Hence, no isolation valves are shown on the schematic for the basic distribution system.

Finally, circulation fans complete the installation. The need for recirculation of the cryogenic fluids to avoid local hot spots and possible boiling, is determined by the duty cycle of operation and the severity of the heat leak. Also, the conductivity of the pipes will affect this consideration. For this study, recirculation is assumed to be necessary and small fans are included for this purpose but they may not actually be required.

These fans could be mounted in the accumulators to circulate fluid through the double plumbing with very low flow rates. In the event of a flow demand, the fluid would flow backward through the fan so that both legs of the system supply fluid. Four fans might be required at about 2 pounds each. The combined power of these fans could be about .0219 horsepower, resulting in heating of the fluid at a rate of 55.7 Btu/hr. These fans would circulate the entire volume of fluid every 15 minutes with a head pressure of 1 psi. The fans would draw 9.32 watts of power. Detail study of this requirement is required. The worst case type analysis shown here is for concept analysis only.

Another item affecting system performance is the heat leak and weight involved with the connection to the RCS engine. The volume between the system and the engines must be minimized to achieve good thrust response and minimize dribble volume (the propellant lost after valve closure) but the connection must be long enough to minimize heating. A design for this interface has been worked out using a bellows connector with 1/4 inch convolutions spaced 0.050 inch apart; i.e., 20 convolutions per inch. Three inches of this bellows is actually 30 inches long thermally. Although not optimized for minimum dribble volume and minimum heat transfer, this design results in 33.2 Btu/hr to the hydrogen side and 9.4 Btu/hr to the oxygen side for a total of 42.6 Btu/hr for 30 engines. The dribble volume involves a loss of 29.3 pounds of reactants per 1000 shutdown cycles. A shorter flex line would probably be more desirable, or possibly one with a higher pressure drop (smaller diameter). The design outlined here (all calculations are in appendix D) is based upon a 25 psi pressure drop and a wall thickness of 0.020 inch,

neither of which have been optimized for the application. The results
indicate that the volume and weight are acceptable, however. With a
detail design study, this tradeoff can be optimized.

The one consideration not completely analyzed here which could signifi-
cantly affect system weight is the compressibility of the fluids. Both
hydrogen and oxygen are considerably compressible at the thermodynamic
state points considered here. This would decrease the size and weight
of the accumulators required. It is possible that the hydrogen may not
require a bellows and helium pressurization--only a tank for enough
volume to achieve a "springy" effect. A pressure regulator would allow
appreciable pressure fluctuations without cycling the system pump. The
oxygen system is not supercritical (as the hydrogen is) but will also
benefit to some degree from consideration of compressibility. This
analysis requires the use of automatic computation to achieve ac urate
results.

## 5.0 SYSTEM OPERATION

The system operates much the same as other systems flown previously. The operation begins with a checkout to verify containment and functional verification of the hardware. Containment is verified by monitoring the vacuum jacket on the pipes. Proper pump, valve, and accumulator functioning is verified by special tests using pressurized gas as the test fluid. The data from these tests would probably be analyzed automatically.

Servicing of the system would begin with pressurization of the accumulator with helium. The helium pressure would be regulated to maintain a steady 450 psia on the backside of the bellows in the accumulator. Next, the oxygen and hydrogen tanks would be serviced and the system pumps switched on. The system chilldown would begin. Any oxygen or hydrogen boiled during system filling would vent back to the main tank. The pumps would run continuously until the system temperature level was below the maximum allowable value of about $78^{\circ}R$ on the hydrogen and $240^{\circ}R$ on the oxygen. The helium would begin to chill down, and the regulator would maintain the 450 psia pressure. When the chilldown process is completed, the helium servicing line can be disconnected and the system is ready to fly. The time for chilldown is an automatic checkout of the heat leak for the system.

In flight, the system pump continues to respond to two signals, pressure and temperature. If the pressure falls below 400 psia, indicating the accumulator is empty, the pump is turned on. Also, independent of the pressure signal, the oxygen pump is turned on if the temperature goes above $240^{\circ}R$ in the oxygen or the hydrogen pump is turned on if the temperature goes above $78^{\circ}R$ in the hydrogen. The pump supplies cold fluid ($175^{\circ}R$ oxygen) to the distribution system until the temperature is back to an acceptable level of about $200^{\circ}R$. If this occurs when the accumulator is almost empty, the temperature of the fluid may be reduced adequately (back to $200^{\circ}R$) before the accumulator is entirely filled, and no venting occurs. If this doesn't occur, the relief valve will vent warm oxygen back to the main tank until the distribution system is again back to $200^{\circ}R$. A similar operation will occur on the hydrogen side.

An alternate mode for cooldown would be to simply program a specific pumping period for this purpose. Either way of operation would produce the same results.

Under normal operating conditions, enough fluid would be used out of the system such that no venting back to the main tank would be required. Replacement of the expended fluid with cold fluid from the main tanks would continuously provide a cooling effect to the systems, keeping the

temperatures below the maximum of $240^{O}R$ in the oxygen and $78^{O}R$ in the hydrogen. This is discussed in detail under system thermal performance in the next section.

Continuously during flight, the cold fluids would be recirculated about the system to cool local areas where heat leak is highest. This would also provide mixing of the fresh cold $44^{O}R$ hydrogen with any warmed $78^{O}R$ hydrogen. Likewise, the $176^{O}R$ oxygen from the main tank would be mixed with any warmed $240^{O}R$ oxygen in the system, keeping the temperatures as low as possible at all times and making the heat leak more acceptable.

The flight monitoring system would continuously measure the vacuum level in the vacuum jacket, as well as the cycles of operation of the bellows accumulators. Pressure variations in the accumulators would provide accurate indication of the volume changes in the accumulator, indicating proper stroking of the bellows. A leak in the bellows would simply fill the helium side of the accumulator with fluid reducing its effective volume and increasing the number of pump cycles for the mission. Failure would probably be gradual and definitely detectable. The compressibility of the fluids would probably provide adequate operation even with both accumulators failed completely, but may consume the life of the pump in a single mission--requiring replacement of one unit before the next flight. The bellows spring rate can be chosen to guarantee leakage of the oxygen out of the bellows instead of the helium into the system.

Failure of the plumbing would result in pressurization of the vacuum jacket. This would be no problem, however, since the multilayer insulation is exposed to space vacuum and would adequately jacket the system from excessive heating. Leakage of the vacuum jacket can be monitored by sensing the pressure level inside the vehicle shell. Assuming no catastrophic rupture, the vehicle could be flown until the jacket indicated excessive leakage; i.e., pressurization of the vehicle skin to over $10^{-4}$ torr which would seriously reduce the insulation effectiveness. This pressure can be achieved with very small leaks even in a vehicle which is fairly well vented. Return would be caused by loss of insulation effectiveness--not the loss of fluid.

The system would be used continuously throughout the mission, supplying attitude control and minor onorbit velocity corrections as required. The most severe operating condition is an off situation where no warm fluid is used, and no cold fluid is pumped into the system. In this case, the vehicle suffers a boiloff loss corresponding to the total heat leak. This is not excessive but must be traded against the alternative of shutting down the system until it is needed again and then rechilling the system. Extra helium for the accumulators would have to be carried along because if the system is allowed to warm up, the helium must be vented to prevent overpressurization of the accumulator.

Return and landing of the vehicle would be followed by venting of the system and preparation for the next flight. In-flight data of pump performance, valve operation, etc. would provide most data for pre-flight analysis and support of flight readiness.

## 6.0 PERFORMANCE AND WEIGHT ANALYSIS

The next consideration is to estimate the amount of heat which can be expected to leak into the system. The calculations outlined in the system and component descriptions establish the individual component heat leakage as follows:

|  | Total Btu/hr | $O_2$ Btu/hr | $H_2$ Btu/hr |
|---|---|---|---|
| Plumbing | 157.0 | 78.5 | 78.5 |
| Accumulator | 12.7 | 3.2 | 9.5 |
| Fan Energy | 55.7 | 12.7 | 43 ) |
| Solenoid 150 (average of two 50 watt operating 1000 sec) | 94.8/miss. | 47.4/miss. | 47.4/miss. |
| Wire Leads (300) | 5.8 | 2.4 | 3.4 |
| Interfaces | | | |
| 30 Rocket Engines | 42.8 | 9.4 | 33.4 |
| Pump-Motor Losses | 274.0/pumping | 106.2 | 167.8 |

Note that the pumping losses are omitted from this total as are the solenoid valve heating values. The pumping losses actually act to reduce the heat capacity of the pumped fluid by increasing its heat content. Therefore, the actual heat capacity of the fluid must be adjusted accordingly. The values shown are based upon pumping for 5 seconds or 80 pounds of $O_2$ and 20 pounds of $H_2$. The heat capacity of 80 pounds of pumped $O_2$ (500 psi 175°R) is 2288 Btu, from which 14.5 Btu must be removed, resulting in 2274 Btu/80 lbs or 28.4 Btu/lb. Similarly, the hydrogen heat capacity must be adjusted from 156 Btu/lb down to 153 Btu/lb. These values are based upon a pump with 94 percent efficiency and a motor with 93 percent efficiency--an achievable value for positive displacement machines. For example, a bellows pump powered by helium can deliver pressurized propellant with practically no heating. The only heating occurs from flow friction in these devices and they may be weight competitive with rotating machinery for the amounts of fluid involved with the shuttle. For the purpose of this analysis, however, the conservative approach is taken. Hydraulic turbines may be used which will be less efficient (about 70 to 80 percent) but as shown above, this will not affect the thermodynamics of the system appreciably.

Using these heat capacity numbers and the above heating loads, the amount of time to warm up one accumulator full of liquid can be calculated. For oxygen the time is calculated as follows:

$$T = \frac{(80\ lbs)(28.4\ Btu/lb)}{106.2\ Btu/hr} = 21.4\ hrs.$$

For hydrogen the number is:

$$T = \frac{(20\ lbs)\ \chi\ 153\ Btu/hr}{167.8\ Btu/hr} = 18.2\ hrs.$$

After these periods of time with no use of the fluid, the accumulator would reach full pressure of 500 psi (and maximum temperature) and the pump would be turned on to recool the system. As the warm fluid is vented back into the storage dewar, boiloff will occur. Present plans are for the cooling of both storage dewars ($H_2$ and $O_2$) to be accomplished using vented hydrogen. Assuming a heat absorption by the vented hydrogen to be 156 Btu/lb the amount of vented fluid to continuously maintain the distribution system in a "ready" condition is calculated as follows:

$$Wt = \frac{274.0\ Btu/hr\ heat\ leak}{156\ Btu/lb\ vented} = 1.76\ lb/hr$$

This same 274.0 Btu/hr can also be removed from the distribution system by using the fluid in the engines instead of venting back to the storage dewar. If the oxygen can be used at a rate of 3.7 lb/hr the cold fluid pumped into the system to replace this expended oxygen will absorb the 106.2 Btu/hr heat leak in the oxygen system

$\left( \dfrac{106.2\ Btu/hr}{28.4\ Btu/lb} = 3.7\ lb/hr \right)$. Likewise, the hydrogen flow rate must be

on the order of about 1.10 lb/hr $\left( \dfrac{167.8\ Btu/hr}{153\ Btu/lb} = 1.10\ lb/hr \right)$.

Use rates of this level are guaranteed in any normal duty cycle. If, however, the system is completely isolated from usage, the 1.76 lb/hr boiloff rate is not excessive.

Consideration of the heat leak and the thermodynamics as outlined above provide indication of the feasibility of the system. Consideration of the weight of the system will reflect on desirability.

A weight estimate summary for the system (exclusive of propellant and tankage) is as follows:

|  | Total | $O_2$ | $H_2$ |
|---|---|---|---|
| Pumps | 39 | 9 | 30 |
| Motors | 162 | 30 | 132 |
| Power Supply | 465 | shared | |
| Power Supply Propellant | 89 | | |
| Accumulators | 322 | 44 | 278 |
| Fans | 8 | 4 | 4 |
| Relief Valves | 20 | 10 | 10 |
| Plumbing | 354 | 172 | 182 |
| Brackets and Mounts | 354 | 172 | 182 |
| Residuals | 257 | 248 | 9 |
| Total | 2070 | 689 | 827 |

This weight estimate is conservative in the sense that no compressibility factors have been assumed for the fluids while sizing the accumulators. Also, the fans may not really be required--especially on a small vehicle.

A significant factor is whether all the 465 pounds of power supply and hydraulic lines should be charged to this system. The required run time is very short (about 500 seconds) and can easily fall within the duty cycle of the power system. The required 100 additional starts for the power system may require refurbishment more often, but should not actually impact spacecraft weight.

## 7.0  SYSTEM DESIGN, DEVELOPMENT, AND MAINTENANCE

A flight weight system for distribution of cryogenic liquids will require careful attention to detail.  No new design techniques or different analytical tools would be required because previous experience with rocket engine feed lines is available.  The most significant effort in the design phase will be to optimize the various system parameters in light of the requirements involved.  An extensive systems engineering effort will be required to evaluate all the contingency requirements and design alternatives.  A math model for system characterization would certainly be a part of the design effort.

Special attention would be required for the extended life, repairability, and weight limitation of the system.  Cost effectiveness will set the design in many instances.  For example, turbomachinery can be used for pumping hydrogen and a significant weight advantage results.  However, the comparative cost between the turbomachines and the hydraulic motor driven--positive displacement pumps may significantly influence the design decision.

Thermal expansion and contraction of the plumbing will be a very significant factor in the design.  Cyclic fatigue of the parts induced by thermal stresses will be a major limiting factor in system life.  Special attention to minimizing these stresses will be required.

The system development should be fairly straightforward.  Breadboard systems operated on the ground should provide adequate design evaluation.  Of primary interest is the fact that only two factors need be measured--heat leak and pressure drop.  Dynamic transient pressures must be evaluated, but should be nominal because of the large accumulators included primarily to limit pump cycles.  The controls required are simple--pressure switches and thermal switches--and adequate design should be simple to demonstrate.

The development system should be operated somewhat continuously throughout the flight program to verify adequately the life capability of the system.  This will provide early indications of life limited components--before they show up in flight, and will provide a facility for training flight crews and investigating malfunction modes experienced in flight.

All of the parts required for the system have been built previously for use on other cryogenic systems.  The only possible problem area is the development of a bellows type accumulator.  Recent hardware tests of these devices indicate, however, that better life can be expected at cryogenic temperatures than when used in ambient temperature applications.  Positive displacement pumps for cryogenics have been built using bellows for active elements.  Units of approximately the proper size for the shuttle accumulators have been tested for use in flourine and hydrogen.

The maintenance of the system can be minimized by design. The use of expendable elements (bellows-seals-motors, etc.) can be minimized and probably will be for the sake of cost effectiveness. The compatibility of the $H_2$ and $O_2$ with typical material of construction and the ease of removal of residue propellants by venting make the systems practically maintenance free. The small number of active components further minimize the maintenance problem.

## 8.0 SYSTEM INTEGRATION CONCEPTS

The shuttle spacecraft is planned to provide payload weight in orbit at
a cost far reduced from any previous vehicle. This can only be accom-
plished by superior design derived by a careful systems engineering ap-
proach to the task.

One of the primary tasks of the systems engineering function is to pro-
vide proper management of the available energy. Hydrogen and oxygen
are one of the most energetic combinations available. However, misuse
of this energy potential can result in serious system performance degra-
dation.

Efficient energy management requires minimizing rejected heat. The use
of space radiators, water boiler cooling or other means of rejecting
heat to space is a definite inefficiency. This has been done in the
past because the systems and/or heat exchangers for conserving this
energy weighed less than the reactants to supply the losses.

However, in the case where cryogenic reactants are used, the energy
level of the fluids is low enough to minimize the size of equipment re-
quired to accept rejected energy. This absorbed energy is then trans-
ferred back to the beginning of the cycle. Thus, we can see that the
cooling for the hydraulic systems can be accomplished with the reactants
for the turbomachinery which produces the hydraulic energy. Likewise,
reactants for the fuel cells can be gassified by the waste heat from
the fuel cell operation. The oxygen required by the environmental con-
trol system can be vaporized efficiently and effectively by the metabo-
lic heat load. The cooling required in rocket engines can be derived
from the low temperature reactants. The heat absorbed on a regenera-
tively cooled rocket chamber and nozzle is carried directly back into
the combustion process. The result is that all energy or mass leaving
the spacecraft is for some useful end result; i.e., propulsion, power
generation, etc.

Another concept of the integration of all onboard energy systems is the
minimization of complexity and weight. Each unit which uses reactants
requires them at a fairly high pressure for the sake of unit efficiency.
However, for storage efficiency, the reactants ($H_2$ and $O_2$) must be con-
tained in fairly low pressure light weight vessels (30 psi). Hence,
the fluids must be pumped to a high pressure. A single set of pumps
capable of supplying the highest pressure required at the highest flow
rate required can serve all the systems. If five units are involved
each having triple redundant pumps, at least 15 pumps are involved, of
5 different configurations. Spares, maintenance, checkout and general
logistics for this much hardware is expensive and inefficient of time

and effort.  A single configuration with ample re...ncy could improve the reliability of the vehicle tremendously.

## 9.0 CONCLUSIONS AND RECOMMENDATIONS

A system for distribution of liquid hydrogen and liquid oxygen in the shuttle vehicle reaction control system operating in a pulse mode appears to be entirely feasible. Little or no boiloff of the fluid is caused by the distribution system, and the mission duration limits are essentially those imposed by the storage of cryogenic liquids in the main tanks.

The liquid/liquid distribution system could offer excellent integration possibilities for the shuttle concept, each system sharing the burden of the pumping and distribution system weight penalty. While no specific consideration has been given to the various interfacing systems, there is no obvious problem with operating on fluids as delivered in the liquid or supercritical condition. One possible exception is the attitude control system rocket engines which operate in a pulse mode duty cycle. While there are no apparent thermal problems with attaching this unit to the distribution system, there may be problems with ignition and heat transfer in the engine itself--an engineering problem deserving early attention. The maintenance, repair, and general logistics of the system appear to be consistent with the reusability objectives for the shuttle spacecraft. The development cost for this type of system should be a minimum and its inflight performance should be near the maximum achievable. Above all, the system offers simplicity for reliability and inherent safety as required for manned vehicles. These features are consistent with the space shuttle concept and should be considered further in more detailed studies and in preliminary hardware testing.

APPENDIX A - MOTOR AND PUMP PERFORMANCE CALCULATIONS

$$\text{Pump Power} = \frac{\Delta \text{ Pressure} \times \text{Flow Rate}}{\text{Density}}$$

$$= \frac{(470 \text{ lb/in}^2)(16 \text{ lb/sec})(144 \text{ in}^2/\text{ft}^2)}{69.5 (\text{lb/ft}^3)(550 \text{ ft lb/sec hp})}$$

$$\text{Power}_{(\text{oxygen})} = 28.3 \text{ horsepower}$$

$$\text{Power}_{(\text{hydrogen})} = \frac{(470)(4)(144)}{(4.4)(550)} = 112 \text{ horsepower}$$

Total power required from the motor must include the pump inefficiency

$$\text{Efficiency} = \frac{\text{output power}}{\text{input power}}$$

or

$$\text{Input power} = \frac{\text{output power}}{\text{efficiency}}$$

$$\text{Power}_{(\text{oxygen motor})} = 28.3/.94 = 30.1 \text{ horsepower}$$

$$\text{Power}_{(\text{hydrogen motor})} = 112/.94 = 119 \text{ horsepower}$$

The power required for the motor must include the hydraulic motor inefficiency. A value of 0.93 is assumed for the motor.

$$\text{Power}_{(\text{oxygen})} = 30.1/0.93 = 32.4 \text{ horsepower}$$

$$\text{Power}_{(\text{hydrogen})} = 119/0.93 = 127.9 \text{ horsepower}$$

The pump motor heat losses are calculated from the inefficiencies and the 5.0 sec required per pumping cycle.

$$\text{Heat loss}_{\text{oxygen}} = \frac{(32.4 \text{ hp} - 28.3 \text{ hp})(5 \text{ sec})(2545 \text{ Btu/hp-hr})}{(3600 \text{ sec/hr})} = 14.5 \text{ Btu}$$

$$\text{Heat loss}_{\text{hydrogen}} = \frac{(127.9 - 112)(5)(2545)}{3600} = 56.2 \text{ Btu}$$

APPENDIX B.- DISTRIBUTION SYSTEM LINE SIZING

$O_2$ Line Sizing

$$P_a \quad = \quad 400 \text{ psia} \quad \Big\rangle \quad \Delta P = 20 \text{ psi}$$

$$P_b \quad = \quad 380 \text{ psia}$$

$$T \quad = \quad 225^\circ R$$

$$\bar{\mu} \quad = \quad 6.1 \times 10^{-5} \text{ lb/ft-sec}$$

$$\bar{\rho} \quad = \quad 59.2 \text{ lb/ft}^3$$

$$\dot{\omega} \quad = \quad 16.0 \text{ lb/sec}$$

$$L \quad = \quad 100 \text{ ft}$$

$$D \quad = \quad \left[ \left( \frac{(1728)(32)}{\pi^2 \, g_c} \right) \frac{f L \dot{\omega}^2}{\bar{\rho} \, \Delta P} \right]^{1/5} = 5.19 \ f^{1/5}$$

$$f = .0014 + \frac{.135}{N_{RE} \ 0.32}$$

$$N_{RE} = \frac{DG}{\mu} = \frac{40.2 \times 10^5}{D}$$

iteratively solved

$$D = 1.57"$$

For 1.57" lines

$$\text{Vol} = \frac{\pi}{4} (1.57)^2 \ 100 \ (12)$$

$$= \frac{2323 \text{ in}^3}{1728} = 1.34 \text{ ft}^3$$

$$\times 69.5 \text{ lb/ft}^3 = 93 \text{ lb max. residual}$$

Two lines having the same flow area require diameters of:

$$D = \frac{1.57}{\sqrt{2}} = 1.11"$$

If $\dot{\omega} = 4.0$ lb/sec

P-2

and Pa = 380
Pb = 355 ⟩ $\Delta P = 25$ psi

T = 225°R

L = 1.0 ft

D = 1.135 ft $^{1/5}$

$N_{RE}$ = $\dfrac{1.005 \times 10^5}{D}$

D = .434" for single engine feed lines

### $H_2$ Line Sizing

Pa = 400 psia
Pb = 380 psia ⟩ $\Delta = 20$ psi

T = 70°R

$\bar{\mu}$ = $0.28? \times 10^{-5}$ lbm/ft sec

ρ = 2.25 lbm/ft³

$\dot{\omega}$ = 4.0 lbm/sec

L = 100 ft

Pa - Pb = $\dfrac{\dot{\omega}^2}{\rho A^2 gc} \left[ \dfrac{2\, \bar{f}\, L}{D} - \ln \dfrac{Pb}{Pa} \right]$

f = $0.0014 + \dfrac{0.135}{Re\ 0.32}$

Re = $\dfrac{48\, \dot{\omega}}{\pi D \mu}$ = $\dfrac{217 \times 10^{-5}}{D}$

Iteratively solved    D = 1.67 in

for 1.67" lines    Vol = $\dfrac{\pi}{4} (1.67)^2 (100)(12)$

= $\dfrac{2628}{1728}$ = 1.521 ft³ × 2.25 = 3.423 residual

Two lines having the same flow area require diameter of D = $\dfrac{1.67}{\sqrt{2}}$ = 1.18"

iteratively solved for the small flex line to an engine

$$P_a \quad = \quad 380$$

$$P_b \quad = \quad 355 \qquad \Delta P = 25 \text{ psi}$$

$$L \quad = \quad 1.0 \text{ ft}$$

$$\dot{w} \quad = \quad 1 \text{ lb/sec}$$

$$\bar{f} \quad = \quad .2 \text{ (using bellows hose)}$$

$$D \quad = \quad .925''$$

APPENDIX C.- ACCUMULATOR SIZING

The accumulators are sized to provide five seconds of full flow rate (80 pounds of oxygen and 20 pounds of hydrogen).

For oxygen using 1 $ft^3$ of active displacement, cycling between 400 and 500 psi, 4 $ft^3$ of helium volume is required for a total volume of 5 $ft^3$.

$$W_{helium} = \frac{PV}{RT} = \frac{(500)(144)(4)(4)}{(1545)(180)} = 4.1 \text{ lb}$$

A pressure vessel for 500 psi and 5 $ft^3$ weighs about 15 pounds.

A bellows weighs about the same as a 500 psi cylindrical stainless steel vessel of equivalent volume--1 $ft^3$ at 10 lb/$ft^3$. This unit would weigh about 10 pounds.

The vacuum jacket and insulation for the shell would weigh about the same as the shell - 15 pounds.

The total is then:

$$W_{total}O_2 \text{ accumulator} = W_{shell} + W_{helium} + W_{bellows} + W_{vessel and jacket}$$

$$= 15 + 4 + 10 + 15$$

$$= 44 \text{ lbs}$$

$O_2$ accumulator size for dual installations

$$r = \sqrt[3]{\frac{(3)(2.5)}{4\pi}} \qquad \text{Vol} = 4/3 \; \pi r^3$$

$$r = 0.842 \text{ ft} \qquad\qquad \text{Dia} = 1.68 \text{ ft}$$

Surface area $\quad = \quad 4\pi r^2$

$$= \quad (4)(3.14)(0.842)^2$$

$$= \quad 8.91 \text{ ft}^2 \text{ each}$$

For the hydrogen accumulator 5 $ft^3$ of active displacement is required. Cycling between 400 and 500 psi, 20 $ft^3$ of helium volume is required for a total volume of 25 $ft^3$.

$$\text{Wt helium} = \frac{PV}{RT} = \frac{(500)(144)(20)(4)}{(1545)(50)} = 74.6 \text{ lbs.}$$

A pressure vessel for 500 psi service and 25 cubic feet volume weighs about 75 pounds.

A bellows would weigh about the same as the 500 psi cylindrical stainless steel shell of equivalent volume (5 ft3); i.e., 50 lbs.

The vacuum jacket for the unit would weigh about 75 lbs for the jacket and 3.4 lbs for the insulation. (insulation weight of .13 lb/ft$^2$ for 26.0 ft2).

$$W_{total} \; H_2 \; accumulator = W_{shell} + W_{helium} + W_{bellows} + W_{insulation}$$

$$= 75 + 75 + 50 + 78$$

$$= 278 \; lbs$$

Hydrogen accumulator size for a single unit

$$Vol = 4/3 \; \pi r^3$$

$$r = \sqrt[3]{\frac{(Vol)(3)}{4\pi}} = \sqrt[3]{\frac{(25)(3)}{4\pi}}$$

$$r = 1.81 \; ft \qquad Dia. = 3.62 \; ft.$$

Accumulator for dual installation

$$r = 3 \; \frac{(12.5)(3)'}{4\pi}$$

$$r = 3.27 \; ft \qquad Dia. \; 2.88 \; ft$$

$$Surface \; area = 4\pi r^2 = 4(3.14)(1.14)^2$$

$$= 26.0 \; ft^2 \; each$$

The estimate of heat leak for the accumulators is difficult because of the unknown effect of the helium separating the cold bellows from the warm tank wall. For the purpose of this paper, the accumulators are assumed to be hydrogen dewars of equivalent surface area. Based upon data from existing tanks as documented in the Handbook of External Refrigeration Systems NAS9-10412, February 22, 1971, an 8-ft sphere with 1100 lbs hydrogen capacity leaks 36.5 Btu/hour or .182 Btu hr-ft$^2$. Another example from the final report on NAS9-10583, July 2, 1970, reports as little as 0.0325 Btu/hr ft$^2$. Using the more conservative value our heat leak results as:

$Q = A \times \text{Rate} = (52_{\text{(hydrogen)}} + 92.8_{\text{(oxygen)}})(.182)$

$Q = 9.5 \text{ Btu/hour (hydrogen)} + 3.2 \text{ Btu/hour (oxygen)}$

$= 12.7 \text{ Btu/hour (total)}$

APPENDIX D.- FLEX LINE HEAT LEAK AND DRIBBLE VOLUME

Assume that the line size required is 0.5 in for the oxygen and 1.0 for the hydrogen.

(see the calculation in Appendix B)

Using a 10/1 bellows; i.e., heat path length is 10 times the actual length, with 0.020 wall thickness a convolution spacing of 0.050 inch results with an I.D. of .5 inch and an O.D. of 1.0 inch.

Area for conduction = $\pi D$ (thickness)

where D is the average diameter (assumed to be .75 in)

$$A = (3.14)(.750)(.020) = .047 \text{ in}^2$$

If the length is 3.0 inches (or 30 in. conduction paths)

$$Q = \frac{KA\Delta T}{L} = \frac{(8 \text{ Btu/hr ft}^2)(.047 \text{ in}^2)(300^\circ F)(30)}{(144)(\text{in}^2/\text{ft}^2)(2.5 \text{ ft})}$$

$$Q = 9.4 \text{ Btu/hr for 30 hoses}$$

The estimate for hydrogen simply requires increasing this value by the proper ratio of temperature and size:

$$Q_{H_2} = 9.4 \left(\frac{530}{300}\right) \cdot \left(\frac{1}{.5}\right)$$

$$\left(\begin{array}{c}\text{temp dif}\\\text{ratio}\end{array}\right)\left(\begin{array}{c}\text{dia}\\\text{ratio}\end{array}\right)$$

$$Q_{H_2} = 33.2 \text{ Btu/hr}$$

The estimated dribble volume for these lines is:

$$Vol_{O_2} = \frac{\pi D^2 L}{4} = \frac{(3.14)(.5)^2(3)}{4} = .59 \text{ in}^3$$

$$Vol_{H_2} = \frac{\pi D^2 L}{4} = \frac{(3.14)(1^2)(3)}{4} = 2.36 \text{ in}^3$$

$$Wt_{O_2} = \frac{.59}{1728} (70)(1000) = 23.9 \text{ lb/1000 starts}$$

$$Wt_{H_2} = \frac{2.36}{1728} (4)(1000) = 5.46 \text{ lb/1000 starts}$$

29.3 lb/1000 starts TOTAL