FOREWORD

This investigation was performed by the AiResearch Manufacturing Company, a Division of The Garrett Corporation, under Project No. 6373, "Equipment for Life Support in Aerospace," and Task No. 637302, "Respiratory Support Equipment," for the Sustenance Branch, Life Support Systems Laboratory, 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio.

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ABSTRACT

This program was directed toward the design and development of a low-pressure storage system for the storage of liquid oxygen, the conversion of the liquid to usable, gaseous state, and the controlled delivery of the gaseous oxygen under omnigravic conditions.

The program was an extension of the feasibility study of a system employing an internal relief valve, and provided for, in particular, the minimization of evaporation loss of stored liquid oxygen through standby venting caused by heat leakage to the stored liquid, and the development of suitable fluid capacity gauging equipment.

This report presents an account of the design and development of a subcritical liquid oxygen storage and conversion system and outlines the final engineering conclusions and recommendations.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

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TABLE OF CONTENTS

SUBCRITICAL LIQUID OXYGEN
STORAGE AND CONVERSION SYSTEM
FOR OMNIGRAVIC OPERATION

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

SUBCRITICAL LIQUID OXYGEN
STORAGE AND CONVERSION SYSTEM
FOR OMNIGRAVIC OPERATION

SECTION I

INTRODUCTION

1. General - Use of liquid oxygen as a method of storing oxygen for breathing purposes in manned space vehicles provides desirable space and weight advantages. However, a means of storing and converting the liquid to gas, while operating at low pressures and under varying gravity conditions, presents many problems, both in design and construction.

2. Background - The system described in this report differs from conventional methods as follows: (1) A thermal shorting valve is used for providing heat to the storage vessel for liquid vaporization and maintaining system pressure; (2) An internal pressure regulating valve is used; (3) An internal heat exchanger is used for vaporization of any liquid state of the fluid prior to withdrawal from the vessel; (4) A quantity gauge is used to measure the proportion of liquid in the remaining two-phase fluid in a zero gravity environment. The following sections present an account of the design and development of a subcritical liquid oxygen storage and conversion system for omnigravic operation.

SECTION II

DESIGN REQUIREMENTS

The design requirements used as a basis for the design of the storage and conversion system are as follows:

(a)	Acceleration forces:	1. Standard gravity force 2. Acceleration to and including 14 g 3. Zero gravity
(b)	Supply line operating pressure:	30 to 60 psig
(c)	Ambient operating temperature range:	-65°F to 260°F
(d)	Standby loss rate:	Not over 1.0 lb of liquid oxygen in a 24-hour period
(e)	Operating loss rate with flows in excess of 200 cu cm per min:	Zero
(f)	Storage vessel working pressure:	150 psig max
(g)	Capacity:	$5^{+0.25}_{-0.0}$ liters
(h)	Time to fill:	10 min at fill pressure of 20 psig
(i)	Buildup time to reach required operating pressure:	30 minutes max
(j)	Flow rate:	Up to 5 gaseous liters per minute measured
(k)	Maximum size:	13-in. high, 15-in. dia
(l)	Maximum weight:	11 lb.

(m) Other conditions:

1. Completely self-operable system
2. System to contain a heat valve, an internal relief valve, and an evaporating coil
3. System to contain an electrical quantity gauging device. Permissible gauge error not to exceed 1.25 percent of indication under standard conditions and 1.50 percent under extreme conditions.
4. Consideration should be given to frequencies up to 1000 cps for vibration.
5. Safety relief valve or valves with provisions for overboard venting

SECTION III

DESCRIPTION OF SYSTEM OPERATION

1. System Description - The subcritical liquid oxygen storage and conversion system consists of the following components: an internal vessel, an intermediate shell, intermediate insulation, an external vessel, a thermal shorting valve, an internal pressure regulator, an internal heat exchanger, a fill line check valve, a vent line check valve, a system pressure relief valve, a regulated pressure relief valve, a fill valve, a matrix type electrical quantity gauge, and associated lines and fittings. These components, integrated as shown schematically in Figure 1, define a system for the storage of liquid oxygen and for liquid-to-gas conversion in a zero gravity environment.

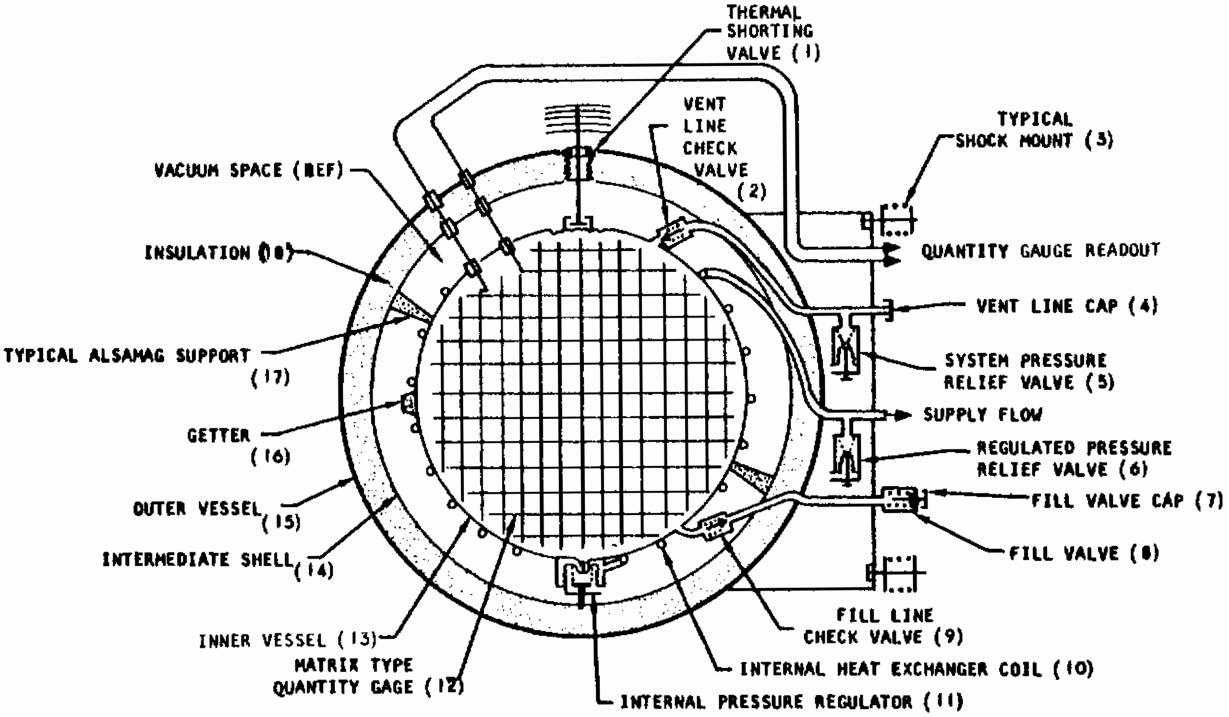

Figure 1. Arrangement of System Components

2. System Operation Theory - The following paragraphs describe the system operations in the sequence in which they would normally occur.

   a. Filling Operation - The system is filled with liquid oxygen through the fill valve by first opening the vent port and then connecting a line with quick disconnect adapter to the fill valve from the supply tank. The adapter opens the fill valve, and transfer of fluid is accomplished by pressurizing the supply source. Filling is continued until a liquid stream is observed at the vent port. The supply is then depressurized, and the supply line is disconnected from the fill valve which closes the valve automatically. The vent port and the fill valve are then capped to provide a leak tight system.

   b. Build-Up Operation - When the filling operation is complete, the thermal shorting valve, which is in contact with the interior vessel, conducts heat into the vessel causing the fluid temperature and pressure to rise. Pressure build-up continues until the interior vessel pressure reaches the calibrated setting of the thermal shorting valve. When this pressure (130 psig) is reached, the contact area of the valve separates from the inner vessel and ceases to transfer heat to the inner vessel. Pressure build-up is complete when this occurs.

      Pressure build-up may be observed by connecting a pressure gauge to the vent port.

   c. Standby Operation - After pressure build-up is complete, the inner vessel, although separated from the outer vessel by the opening of the thermal shorting valve contact, continues to gain heat but at a greatly reduced rate through lines and container supports, and intrasurface radiation. This leakage of heat causes the inner vessel pressure to slowly increase. If no oxygen is withdrawn from the system to compensate for this increasing pressure, the system pressure relief valve opens to limit the system pressure to 150 psig. The relief valve continues to cycle as required through standby.

   d. Supply Operation - The supply operation makes use of the fact that the temperature of an equilibrium mixture of liquid and vapor changes with changing pressures. The fluid being withdrawn from the storage vessel is passed through the internal pressure regulator in which the fluid pressure is throttled from the vessel storage pressure to the system delivery pressure causing a corresponding temperature decrease. The pressure regulator senses delivery pressure and closes when there is no flow demand on the system. The expanded fluid, at the lower temperature, is passed through the internal heat exchanger and heat is added by means of the temperature differential. The fluid then passes to the vessel exterior.

The internal heat exchanger is designed for adequate vaporization when 100-percent liquid enters through the internal pressure regulator, which assures vapor delivery under all liquid-vapor mixture states. Since the storage pressure is being used for supply purposes, heat must be added to the remaining fluid in the vessel in order to maintain the required storage pressure level during withdrawal of fluid. The thermal shorting valve is sensitive to pressure drop and again comes in contact with the interior vessel. Heat transfer continues until pressure build-up reaches the required storage pressure level. The thermal shorting valve contact then separates from the interior vessel, thus continuing to maintain the operating pressure as required.

SECTION IV

DESCRIPTION OF COMPONENT FUNCTIONS

1. **Storage Vessel** - The storage vessel is a double-walled spherical container with a 9.04-inch ID inner vessel (13, Figure 1) and an 11.50-inch ID outer vessel (15, Figure 1). The walls are 0.025-inch thick, formed from 304 stainless steel. The evacuated annular space between the vessels contains an intermediate shell (14, Figure 1) of 0.016-inch thickness and 10.50-inch ID and made from 304 stainless steel. The intermediate shell serves as a retainer for insulation which is also located within the annular space. The outer surface of the inner vessel, the inner surface of the outer vessel, and both surfaces of the intermediate shell are copper-plated and highly polished.

   The inner vessel is designed for a nominal operating pressure of 130 psig and can withstand an internal hydrostatic test of 250 psig.

2. **Insulation** - The insulation (18, Figure 1) consists of layers of fiberglass sheet which are compressed into the annular area between the intermediate shell and the inner wall of the outer vessel.

3. **Thermal Shorting Valve** - The thermal shorting valve (Figure 2) is welded to and forms a permanent part of the outer shell for maximum assurance against gas leakage into the evacuated annular area between the vessels.

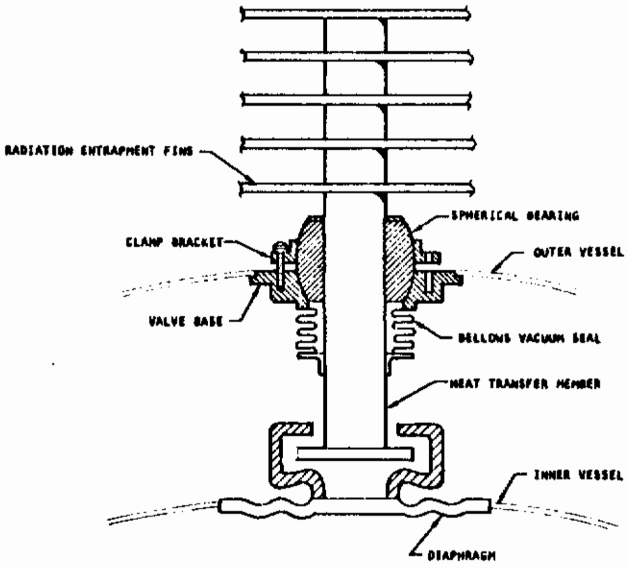

Figure 2. Thermal Shorting Valve

Thermal contact between the inner vessel and the thermal shorting valve is regulated by means of a beryllium copper diaphragm, attached to the inner vessel, which acts as an expansion bellows. The inside of the diaphragm references inner vessel pressure and the outside of the diaphragm references the evacuated annular area between the vessels. The valve, therefore, is referenced to absolute inner vessel storage pressure.

When the pressure in the inner vessel drops below 130 psig, the diaphragm retracts allowing the copper heat transfer poppet to contact the inner vessel. The valve assembly is designed to permit adjusting of the poppet for trimming of the unit. The stem of the thermal valve is a 5/8-inch OD copper rod which extends through the outer vessel wall. The poppet stem is mounted in a spherical stainless steel bearing which is itself mounted to the base of the valve. A small bellows is attached to the stem and the outer vessel to form a vacuum seal. Curved aluminum radiation entrapment fins are mounted at the top of the heat transfer member for maximum energy absorption. The fins are blackened to increase the radiative mode of heat transfer to the valve.

4. <u>Internal Pressure Regulator</u> - The internal pressure regulator (Figure 3) is constructed of 304 stainless steel, and is designed to provide absolute pressure regulation of the fluid downstream of the regulator. To accomplish this, the regulator valve bellows is connected on the inside to the evacuated annular space between the vessels and on the outside to the outlet or discharge line pressure. When the outlet or discharge line pressure drops due to flow demand, the spring-loaded regulator bellows expands and opens the valve poppet to allow flow through the valve. If the discharge line pressure rises above the regulator setting of 30.0 psia, the regulator bellows closes the valve poppet, stopping flow until the pressure lowers as a result of flow demand.

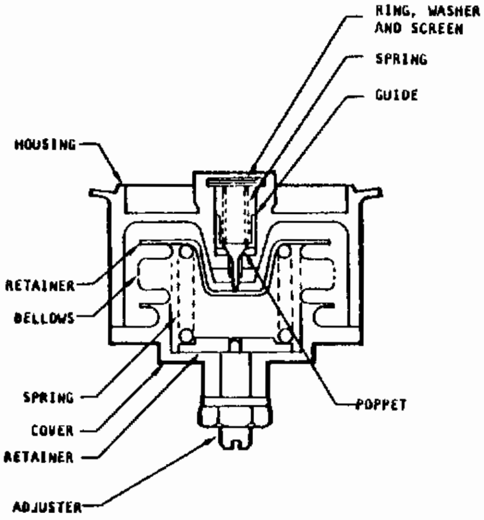

Figure 3. Internal Pressure Regulator

5. Internal Heat Exchanger - The internal heat exchanger coil (10, Figure 1) is made of 1/8-inch OD by 0.010-inch wall 304 stainless steel tubing. The total coil length measures 20 ft, unwound, and is spiralled around the outside of the inner vessel and brazed in place. An additional 1.67-ft length is suspended between the inner and outer vessel to minimize heat transfer. Connection through both vessels is accomplished with machined fittings which are welded into the vessels. The tubing, in turn, is silver-brazed into the fittings.

   One end of the heat exchanger coil is connected to the internal pressure regulator outlet port. The other end is connected to the outlet or discharge line of the system. The function of the internal heat exchanger is to ensure vaporization of the liquid being withdrawn, by means of the temperature gradient that exists between the stored fluid and the fluid within the heat exchanger. The internal heat exchanger has two purposes: (1) to ensure vaporization of fluid withdrawn for use, and (2) to conserve fluid and stabilize operation during low demand.

6. Fill Line Check Valve - The fill line check valve (Figure 4), located as shown in Figure 1 (9), is employed to prevent possible liquid migration from the inner vessel to the fill line during zero gravity operation. The valve is of 304 stainless steel welded construction and is welded in place near the inner vessel surface. The valve is an axial flow type and has a spring-loaded poppet which permits flow for the filling operation only. When the filling operation is complete and the vent line is capped, differential pressure closes the check valve, stopping the fill operation. The valve poppet OD and housing ID are precision-ground to allow a thermal expansion of 0.0005 inch.

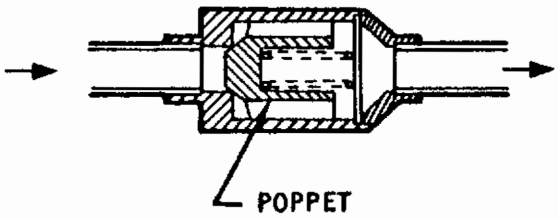

Figure 4. Fill Line Check Valve

7. **Vent Line Check Valve** - The vent line check valve (Figure 5), located as shown in Figure 1 (2), is designed to allow liquid or vapor flow during the fill operation and to check liquid flow during zero gravity operation. The valve consists primarily of 304 stainless steel, with the exception of the sintered bronze porous plug, and is of welded construction. The valve is welded in place near the inner vessel surface. The valve is an axial flow type and has a spring-loaded poppet which seats against the porous plug. This feature acts to separate fluid phases for better system pressure relief valve operation. The valve poppet OD and housing ID are precision-ground to allow a thermal expansion of 0.0005 inch.

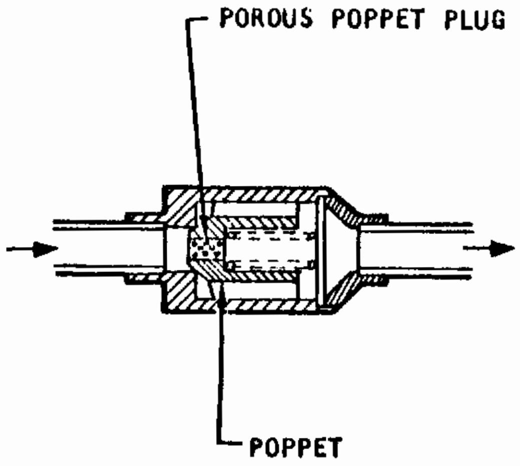

Figure 5. Vent Line Check Valve with Porous Plug

8. **System Pressure Relief Valve** - The system pressure relief valve (Figure 6) consists of a spring-loaded poppet which is designed to be forced open when the system pressure reaches the calibrated value of the valve, 150^{+0}_{-5} psig, and to limit the pressure to this value. The valve is of 304 stainless steel construction and is welded in place in the vent line external to the vessel as shown in Figure 1 (5).

9. **Regulated Pressure Relief Valve** - The regulated or discharge line pressure relief valve (Figure 6) consists of a spring-loaded poppet which is designed to be forced open when the discharge line pressure exceeds the calibrated value of the valve, 60^{+0}_{-5} psig, and to limit the pressure to this maximum value. The valve is of 304 stainless steel construction and is welded in place in the discharge line external to the vessel as shown in Figure 1 (6).

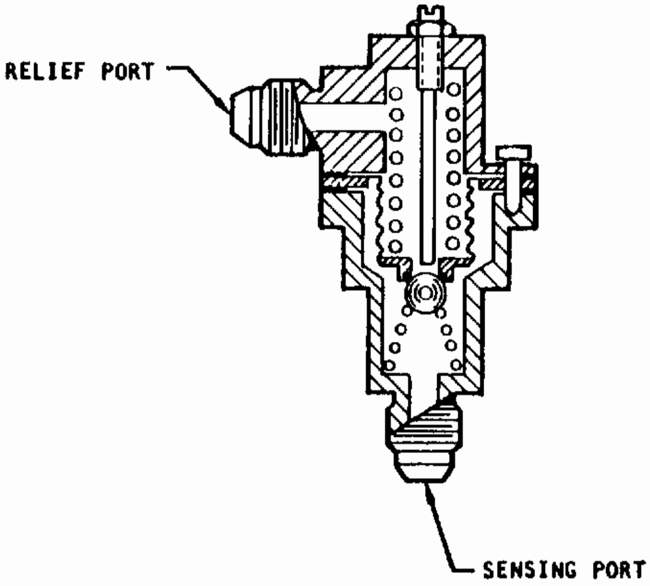

Figure 6. Regulated Pressure or System Pressure Relief Valve

10. Fill Valve - The fill valve (Figure 7) consists of a spring-loaded closed poppet for primary sealing and a seal cap for the secondary seal. The poppet is designed to be forced open when the fill port is engaged with the quick disconnect fitting of the supply source line. The valve is of 304 stainless steel construction and is welded in place on the fill line as shown in Figure 1 (8).

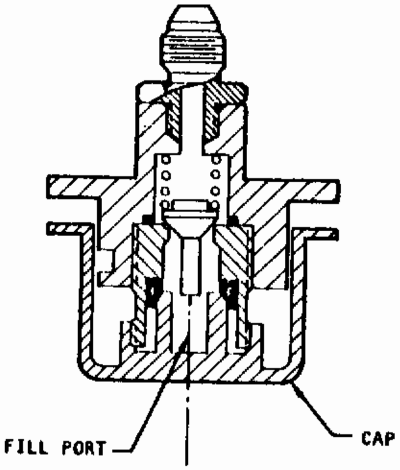

Figure 7. Fill Valve

11. <u>Quantity Gauge</u> - The quantity gauge (12, Figure 1) is a capacitance-type system which utilizes the difference in dielectric constant for vapor and liquid oxygen. A cubical matrix is constructed from two conductors which are electrically insulated from each other and the inner vessel by Teflon spacers. This matrix structure subdivides the entire volume into capacitor cubes. The cube size is determined by the accuracy required of the gauge under all attitudes and gravitational fields. Variation in capacitance of the system serves to unbalance a bridge circuit which forms the input to a transistorized amplifier. The amplifier signal drives a servo motor which causes an appropriate dial indication.

12. <u>Getter</u> - In order to ensure a good permanent vacuum, a getter housing was incorporated in the design of the inner vessel and is located as shown in Figure 1 (16). The getter consists of a 304 stainless steel housing welded to the exterior surface of the inner vessel which contains Linde Molecular Sieve No. 5A pellets for the absorption of residual gases.

SECTION IV

HEAT TRANSFER CALCULATIONS

1. <u>Requirements</u> - The specification for this system requires that the evaporation loss shall not exceed one lb of liquid oxygen per day. Using a value of 91.6 Btu per lb as the heat of vaporization of oxygen (when vented to sea level pressure), the permissible loss is equivalent to 3.82 Btu per hr. The major sources of heat transfer are summarized and calculated in the following paragraph. Figure 8 provides a diagram for clarification of symbols used.

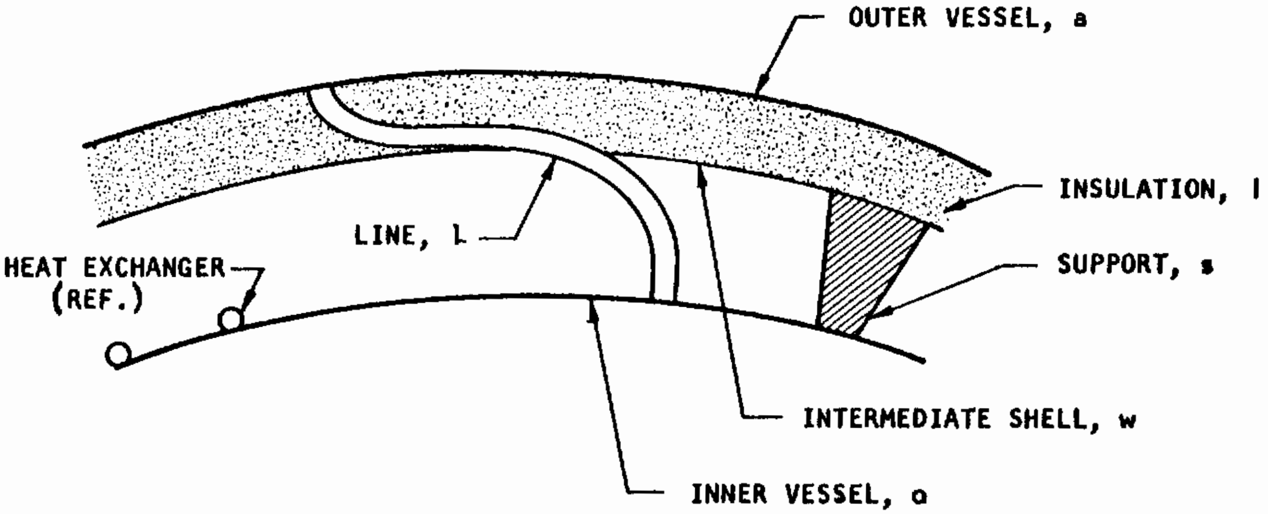

Figure 8. Calculation Diagram

2. <u>Calculations</u>

A. Q_w = Rate of heat transfer through vessel walls, Btu/hr

and: $$Q_w = K_I \frac{(\pi D_a D_w)(T_a - T_w)}{t_I} = \sigma F_s F_\varepsilon A_o \left[\left(\frac{T_w}{100}\right)^4 - \left(\frac{T_o}{100}\right)^4 \right] + 4 Q_s$$

B. Q_L = Rate of heat transfer through lines, Btu/hr

and: $$Q_L = 3\,\frac{K_L\,A_L\,(T_a - T_o)}{L}$$

C. Total heat transfer, Btu/hr = Q_T

and $$Q_T = Q_w + Q_L$$

Where: K_i = thermal conductivity of insulation = 4×10^{-4} Btu/hr/ft/^{0}R

K_L = thermal conductivity of lines = 7.5 (mean) Btu/hr/ft/^{0}R

D_a = diameter of outer vessel = 0.958 ft

D_w = diameter of intermediate shell = 0.875 ft

T_a = temperature of outer vessel = 530^{0}R

T_w = temperature of intermediate shell = 435^{0}R

T_o = temperature of inner vessel = 220^{0}R

t_i = thickness of insulation = 0.042 ft

σ = Stephan-Boltzmann Constant = 0.173

F_s = shape factor = 1

F_E = emissivity of inner vessel = 0.015

A_o = area of inner vessel surface = 1.77 ft^2

A_L = cross sectional wall area of tube = 6.54×10^{-5} ft^2

L = length of tube = 1.667 ft (each)

Q_s = known Alsamag support heat transfer = 0.200 Btu/hr

number of lines = 3

number of supports = 4

Upon substitution, we find that:

$$\text{A.}\quad Q_W = \frac{.0004 \times (3.1416 \times .958 \times .875)\ (530 - 435)}{.042} =$$

$$.173 \times 1 \times .015 \times 1.77 \times \left[\frac{435}{100}^{4} - \frac{220}{100}^{4} \right] +$$

$$(4 \times .200)$$

(or) $2.37 = 2.37$

therefore: $Q_W = 2.37$ Btu per hr

$$\text{and B.}\quad Q_L = \frac{3 \times 7.5 \times .0000654 \times (530 - 220)}{1.667}$$

therefore: $Q_L = .27$ Btu per hr

and C. $Q_T = 2.37 + .27$

therefore: $Q_T = 2.64$ Btu per hr

The allowable heat transfer = 3.82 Btu per hr

Heat transmitted by other means, such as conduction and convection of residual gas in the vacuum space and three tube lines, radiation shape factor variation at the thermal shorting valve, and as a result of the internal heat exchanger, is neglected.

SECTION V

CONCLUSIONS

1. General - The conclusions and recommendations outlined in the following paragraphs evolved from performance tests which were conducted on the subcritical liquid oxygen storage and conversion system. Photographs showing three views of the system are presented in Figure 9.

2. Thermal Shorting Valve - No mechanical or functional difficulties were encountered during the performance testing of the thermal shorting valve. It is felt that the valve could be improved from a weight standpoint, however, use of this concept for heat transfer required to maintain system operating pressure was proved to be a feasible method.

3. Internal Pressure Regulator - Excessive fluid losses through the regulator pressure relief valve were noted during delivery, as a result of internal regulator failure in controlling delivery line pressure and flow. This condition is believed to have been caused by distortion of the regulator valve seat, which was caused by high temperatures during the welding of the regulator to the internal vessel.

   Further development of this component is required before its reliability can be established. New seat and poppet designs should be explored to provide a design which will not appreciably change valve operation when subjected to the heat required for assembling the component to the system.

4. Quantity Gauge - The quantity gauge function was not used during system tests, since a check of the gauge revealed that it was electrically shorted against the internal vessel wall. This condition occurred during the out-gassing operation, which was performed at 800°F, causing the Teflon gauge supports to collapse the gauge, and rendering the gauge inoperable.

   The use of a matrix-type quantity gauge has been proven in the past as a reliable means of quantitatively gauging fluids in other systems; and, in fact, the gauge for this application met all requirements prior to the out-gassing operation. The feasibility of a matrix-type quantity gauge for this application is believed to be an accurate and reliable method for quantity measurement of liquid oxygen in any of the required environments.

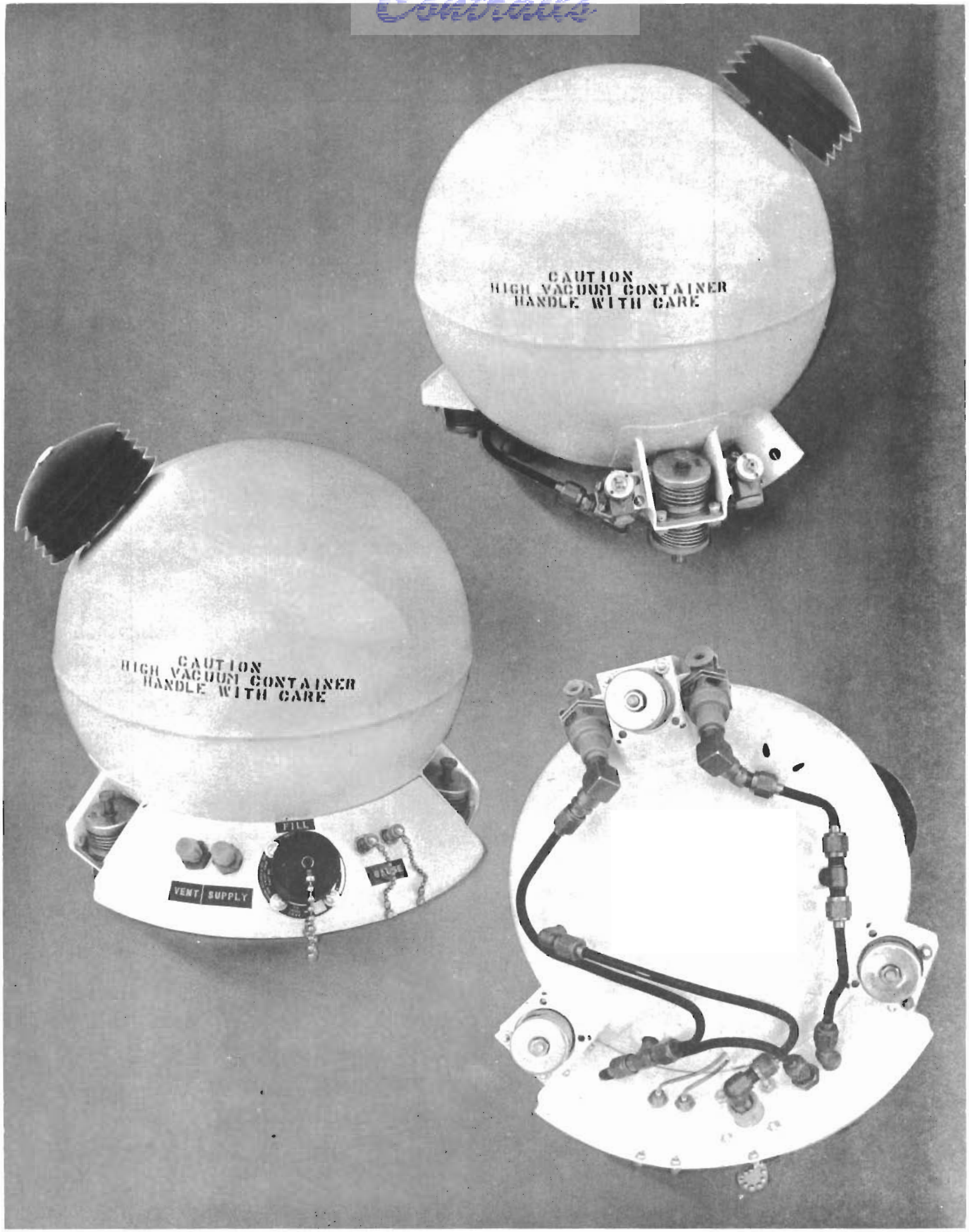

Figure 9. Subcritical Liquid Oxygen Storage and Conversion System for Omnigravic Operation