A CRYOGENIC HELIUM PRESSURIZATION SYSTEM FOR THE LUNAR EXCURSION MODULE

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In order to effect a large weight reduction on the Lunar Excursion Module, the Grumman Aircraft Engineering Corporation has proposed the use of a cryogenic helium pressurization system. Since the LEM utilizes a pressure-fed propulsion system, relatively high tank pressures (225 psia), with attendant large pressurant masses are required. The use of helium stored in the supercritical state, because of its high density and low molecular weight (with a subsequent storage vessel size reduction), can provide the pressurization cycle required for the LEM while affecting a large weight decrease from the currently employed ambient system. Here, "supercritical" is used in the terminology of cryogenics, implying that the system is operating in the region of the critical temperature, but well above the critical pressure.

At the critical temperature, the specific volumes of the liquid phase and the gas phase are equal. Above this temperature, a fluid will not separate into two phases of different densities during an isothermal compression from large volumes. In other words, the liquid phase will not separate out. This phenomena is illustrated best with the aid of the P-v-T surface shown in Figure 1.

Consider that a system is initially in the thermodynamic state shown by point A. Now, if an isothermal compression was carried out in a transparent cylinder, one would observe the beginning of condensation into the liquid phase at the point where the isotherm meets the saturated vapor surface. As the compression process continues, the quantity of the liquid phase increases, while the vapor phase decreases. At the thermodynamic state represented by point B one would be sure that the fluid in the cylinder was wholly in the liquid phase. Now, another possibility exists; one could start with the system initially in the same state as shown previously (state point A) and carry out the process represented by the path from state point A to state point B, which curves around the critical point. (Of course, this process is not isothermal.) Although the end state of the system is the same in both processes, at no time in the second process did the fluid separate into two phases. Certainly, the fluid would be described as a liquid at the end of the second process as well as at the end of the first, for the end points (state point B) of the processes coincide. However, in the second process, the properties of the fluid changed continuously from those associated with a vapor, at state point A, to those associated with a liquid, at state point B. A system whose state point lies above the critical isotherm and critical isobar can exhibit characteristics identical to those described in the second process. Herein lies the advantage of a supercritical storage system. The fluid may be stored at a very high density (normally associated with a liquid) and utilized without ever encountering a two-phase region.

The critical point of helium is at pressure of 33.8 psia (2.26 atms), a temperature of $9.57^{o}R$ ($5.25^{o}K$), and a density of 7.81 lb/ft^3. Thus, the storage of supercritical helium for use on the Lunar Excursion Module presents a unique method of weight reduction because of the high fluid density with the resulting decrease in storage vessel volume.

In pressurization systems there exist many thermodynamic processes which the fluid in the storage vessel may undergo during expulsion. Of course, the most familiar is that of the isentropic expansion. This process is very closely approximated in the very rapid blowdown of high pressure bottles. However, this ideal process cannot be employed for a supercritical helium pressurization system since the rapidly decreasing temperature and pressure would leave an excessive amount of residual fluid in the vessel.

A second process is that of constant pressure expulsion. This is truly the "ideal" process, in that the residuals are a minimum, and the ideal process is time-independent. However, this type expulsion system would require a closely controlled, variable heat input. In a real system, it is highly questionable if the heater could handle the high transients required for maintaining a constant pressure. Further, a system requiring this close control has serious implications from the standpoint of system reliability.

A final system is one of almost constant heat input. This is the method which is utilized in the proposed LEM supercritical helium pressurization system, and will be discussed in depth shortly.

The concept of low temperature, high pressure (supercritical) helium is not new. It was successfully employed in the Titan I, with the helium storage vessel immersed in the LOX tanks. The S-IV & S-IVB stages employ the same method, with the exception that the bottles are immersed in the liquid hydrogen tank. However, there is one basic dissimilarity: the stand-by time of the pressurization system used in these vehicles is not important. In a sense, one could consider that the helium (once temperature equilibrium is attained) is located in an infinite, low-temperature heat sink, i.e., the LH_2 tank at $-423^{o}F$. The LEM does not possess this advantage, and the helium must be stored in a vacuum-jacketed Dewar.

The LEM supercritical helium system is shown schematically in Figure 2. For the sake of brevity, only the LEM descent stage will be discussed. The initial conditions at the time of helium withdrawal are approximately 1500 psia and $38^{o}R$, at a density of approximately 10 lb/ft^3. The helium is withdrawn from the storage vessel, and passed through the primary helium-to-fuel heat exchanger. (The fuel is a blend of equal parts by weight of hydrazine and UDMH.) The temperature of the helium is raised from the storage vessel temperature (initially at approximately $-428^{o}F$) to approximately $-100^{o}F$. The warm helium is then returned to the storage vessel where an internal heat exchanger transfers heat from the effluent helium stream to the stored fluid, raising its temperature and consequently its pressure. The helium, again at very low temperature, exits from the storage vessel and passes through the secondary helium-to-fuel heat exchanger, where the temperature is raised to approximately -50°F. The helium then flows through the regulator package to the propellant tanks.

The maximum helium flow rate is approximately 0.070 lb/sec, compared to a fuel flow rate of approximately 13 lb/sec at full thrust. Because of this wide variance in flow rates, no freezing of the fuel is encountered.

As was pointed out earlier, the helium vessel is a vacuum-jacketed Dewar. The addition of an internal heat exchanger further complicates the design. Figure 3 is a cross-sectional view of one proposed storage Dewar. The inner vessel is approximately 24 inches in diameter; the construction is of titanium - 6Al-4V(ELI). The annular volume contains super insulation. The withdrawal lines are routed circumferentially in the usual manner, to provide long heat conduction paths.

The internal heat exchanger in this design is a hollow copper sphere, with tubes wrapped around it. The sphere is pierced for minimum weight and to provide fluid ingress and egress. The copper sphere acts essentially as an extended surface for the heat exchanger.

The loading conditions place important and significant constraints on the design of a supercritical storage system. The system weight is a direct function of the loading pressure and temperature. Thus, the higher the loading density, the lower the system weight because of a smaller storage vessel.

Figure 4 is the P-v-T surface for helium. Plotted on this figure are the loading conditions for the LEM supercritical helium pressurization system. (The figure is a qualitative representation and the coordinates do not necessarily correspond to the following quoted values.) The critical density (specific volume) is shown for reference. The vessel is loaded with liquid helium at approximately 3 psig and 8°R, shown on Figure 4 as state point 1. Then, chilled, high pressure helium (approximately 400 psia and 10°R) is used to bring the fluid to a supercritical state. The fluid is circulated through a liquid helium boiler, lowering its temperature, hence lowering its specific volume (from v_1 to v_2). When the temperature and pressure stabilize, the system is in a state represented by state point 2. The current LEM system is designed for a 142 hour standby time. During this time, the fluid is subject to a heat leak of approximately 6.5 Btu/hr. This heating, at constant density along the path from state point 2 to state point 3, brings the system to its operating conditions, represented by state point c, viz., 1500 psia and approximately 38°R, (but still at v_2).

Another condition which affects the system weight is the allowable heat leak. If the heat leak requirement is reduced from its present value of 6.5 Btu/hr to a value of 5.0 Btu/hr, the insulation thickness for the Dewar increases approximately two inches. Since the weight is a function of the diameter cubed (D^3), the attendant weight increase is substantial.

Although one may be enthusiastic about the possible weight reduction offered by this method of storage, the magnitude of some of the potential problems associated with the development of a system of this nature should not be underestimated.

One of the most outstanding and pressing problems is the lack of basic thermodynamic properties of helium in the low temperature, high pressure regime. (This is especially true for the LEM ascent stage, which has been proposed as a 3000 psia system.) The size or weight of a Dewar is a function of the required pressure, temperature, and useable fluid mass. In view of the lack of P-v-T data in the regions of interest, the amount (mass) of fluid stored at a given pressure and temperature in a given volume cannot be accurately determined. Further, the weight of residual fluid cannot be easily established. Consequently, an accurate weight prediction is extremely difficult to make. Some preliminary experimental work to determine the required P-v-T data has been accomplished by the LEM contractor.

The passive temperature control of a low-temperature fluid system continues to be a critical area. This must be a very low heat leak system, to prevent over pressurization. As was pointed out earlier, the proposed design will permit a maximum heat leak of 6.5 Btu/hr.

Other programs utilizing supercritical storage systems are having difficulty meeting their stand-by time requirement, which is governed by a heat leak requirement much higher than the one required for the LEM.

Another area of concern is the design of both internal and external heat exchangers. The internal exchanger is a critical item. If the heat rejection rate of the internal exchanger is too high, over pressurization, with subsequent system venting, occurs early in the mission duty cycle. If the heat exchanger is too small, sufficiently high pressure and temperature is not available near the completion of the duty cycle, resulting in an excess of non-useable helium remaining in the storage vessel near the end of the duty cycle. Consequently, close design tolerances must be maintained on the internal heat exchanger. As was seen previously, one proposed design was the use of a spherical heat exchange surface. Another proposed exchanger is merely a pipe coil inside the pressure vessel.

The external heat exchanger appears to present major development problems. The exchangers must operate over a wide range of temperatures (from approximately -430°F to 0°F) at relatively high pressures. They must also be light-weight exchangers or much of the weight reduction potential afforded by this storage concept will be lost. There is, however, cne more serious constraint. Recalling Figure 2, it is noted that the two external heat exchangers operate in series on the fuel side of the exchangers. Since the LEM employs a pressure-fed engine, the propulsion system is quite sensitive to adverse pressure changes. The present LEM propulsion system can tolerate only a 10 psi ΔP increase. Thus, to allow a margin of safety, the external heat exchangers must be designed for a maximum fuel side ΔP of 2.5 psi each, or 5 psi ΔP for the two exchangers in series. For the propellant flow rates encountered on the LEM, this low ΔP requirement may well be a major problem area.

One final area of concern in the development and utilization of this system is in the field of ground support equipment (GSE). Due to its low heat capacity and low temperatures, liquid helium cannot be pumped over long distances without interstage refrigeration. Portable Dewars and a specially designed fill system will be employed for charging the storage vessel. Due to the stand-by time constraint, the system must be loaded just prior to launch; this dictates that the GSE must be at the LEM level, on the mobile arming tower. This introduces considerations of both weight and space on the arming tower.

In conclusion, it should be pointed out that the system is feasible, but that it is not without some problems. As was noted earlier, lack of P-v-T data is a serious shortcoming. The consistent achievement of a very low heat leak will be difficult. The sizing of the internal heat exchanger is critical. The pressure drop on the fuel side of the external exchangers present development problems. The GSE requirements for this system may be pacing items for a flight system that must meet a strict launch schedule.

The seemingly endless number of problems of this system are countered by two great advantages: 1) large potential weight reduction, and 2) a smaller bottle package. This system offers a potential weight reduction of 500 to 1000 pounds (effective or separation weight), depending on whether the system is used on just the descent stage or on both ascent and descent stages. The weight saving is realized primarily in reduced bottle weight, since this constitutes over 80% of the pressurization system weight for an ambient, high pressure storage system. The fact that the volume of the bottle is much smaller (because of the high density), means that a smaller bottle package results. In fact, on the proposed LEM descent stage system, the 3500 psia ambient system, consisting of two storage vessels approximately 33 inches in diameter, is replaced by a supercritical helium pressurization system, consisting of one storage vessel, only 30 inches in diameter (O.D. of the vacuum jacket).

Thus the use of a cryogenic helium pressurization system for the Lunar Excursion Module appears to be an attractive method by which to reduce the overall LEM weight, which in turn increases the potential payload capability of the Lunar Excursion Module.

NASA-S-65-449

P-V-T SURFACE FOR HELIUM

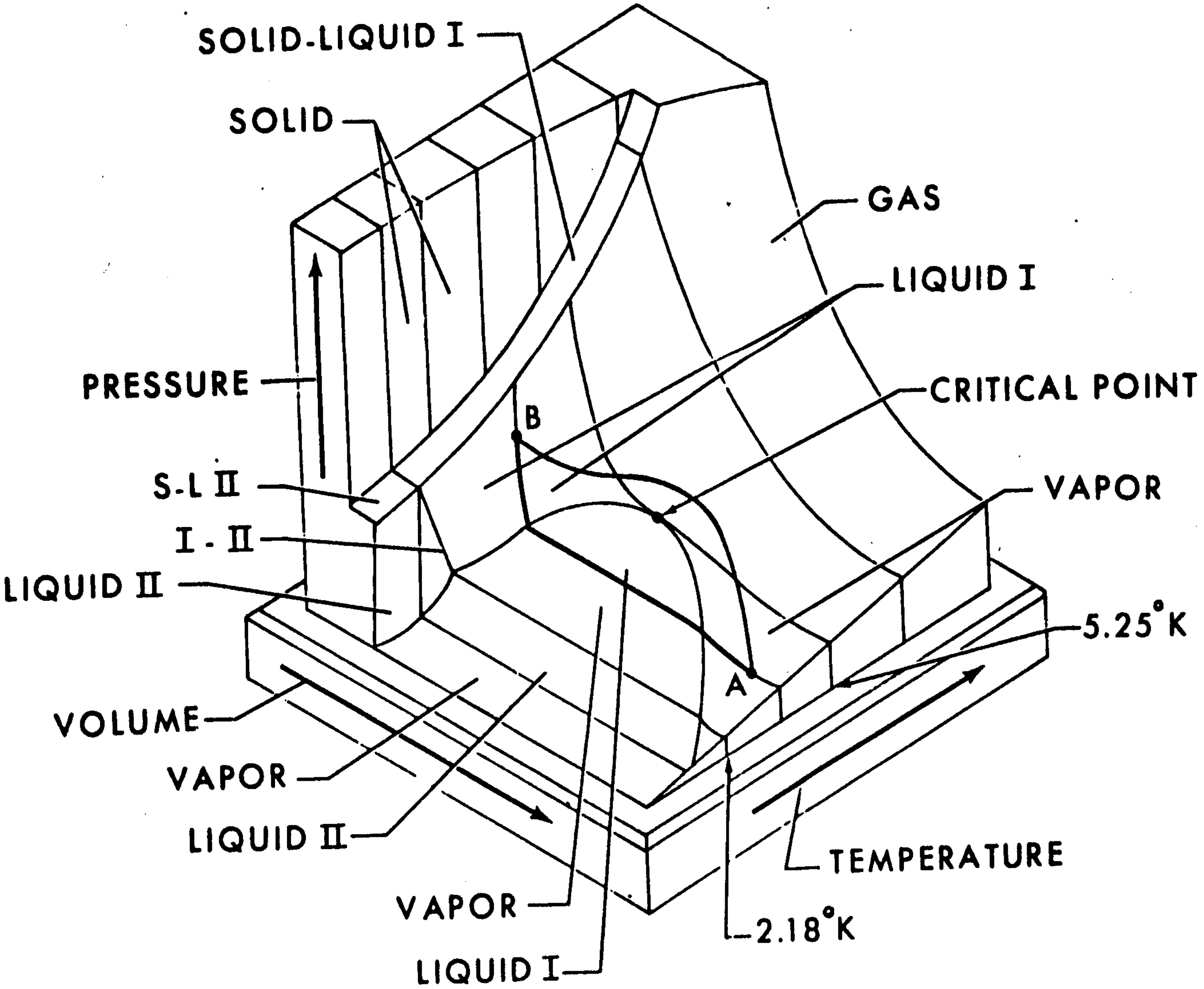

FIGURE 1

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SUPERCRITICAL HELIUM PRESSURIZATION SYSTEM FLOW SCHEMATIC

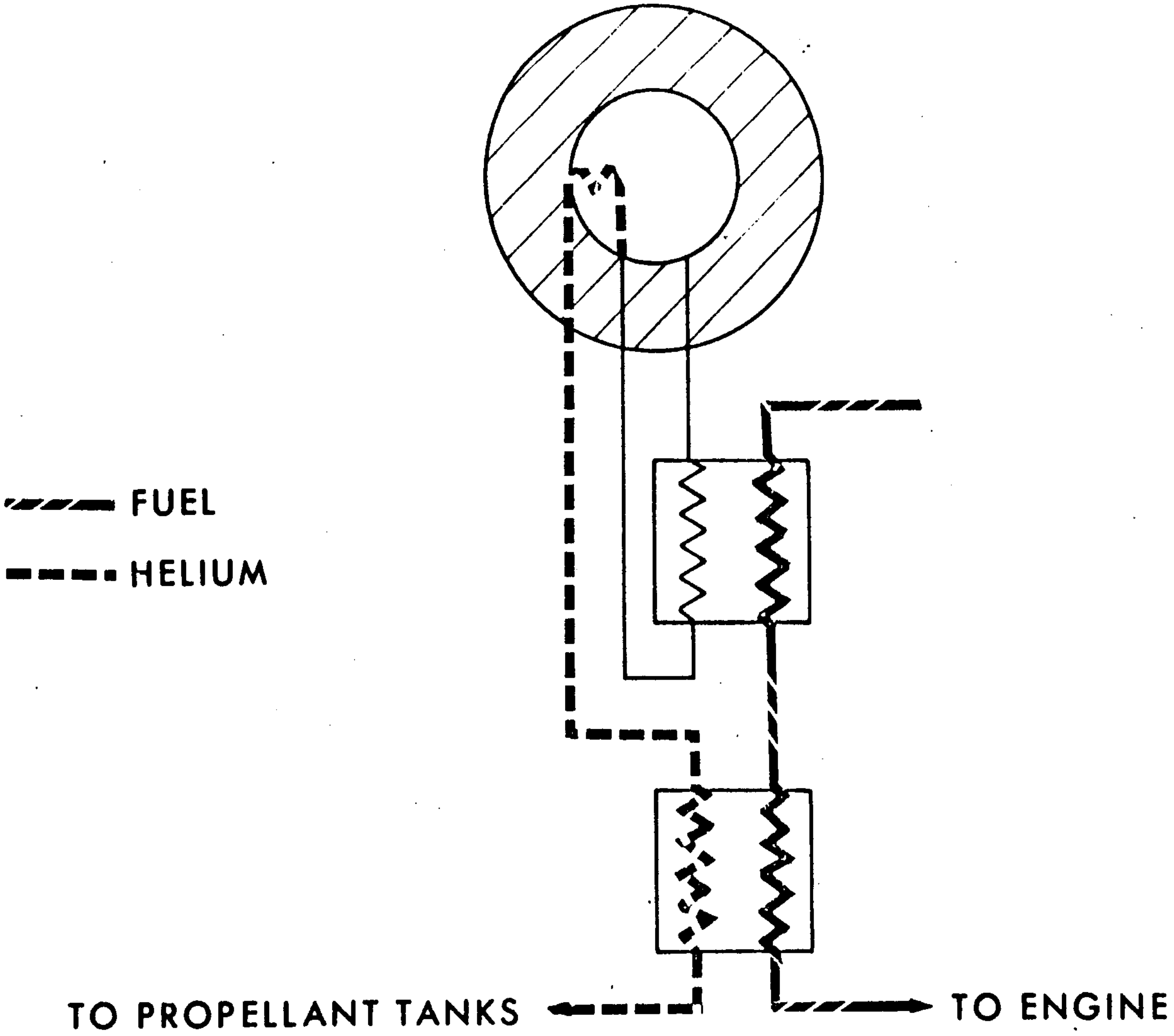

FIGURE 2

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CROSS-SECTIONAL DRAWING OF HELIUM STORAGE VESSEL

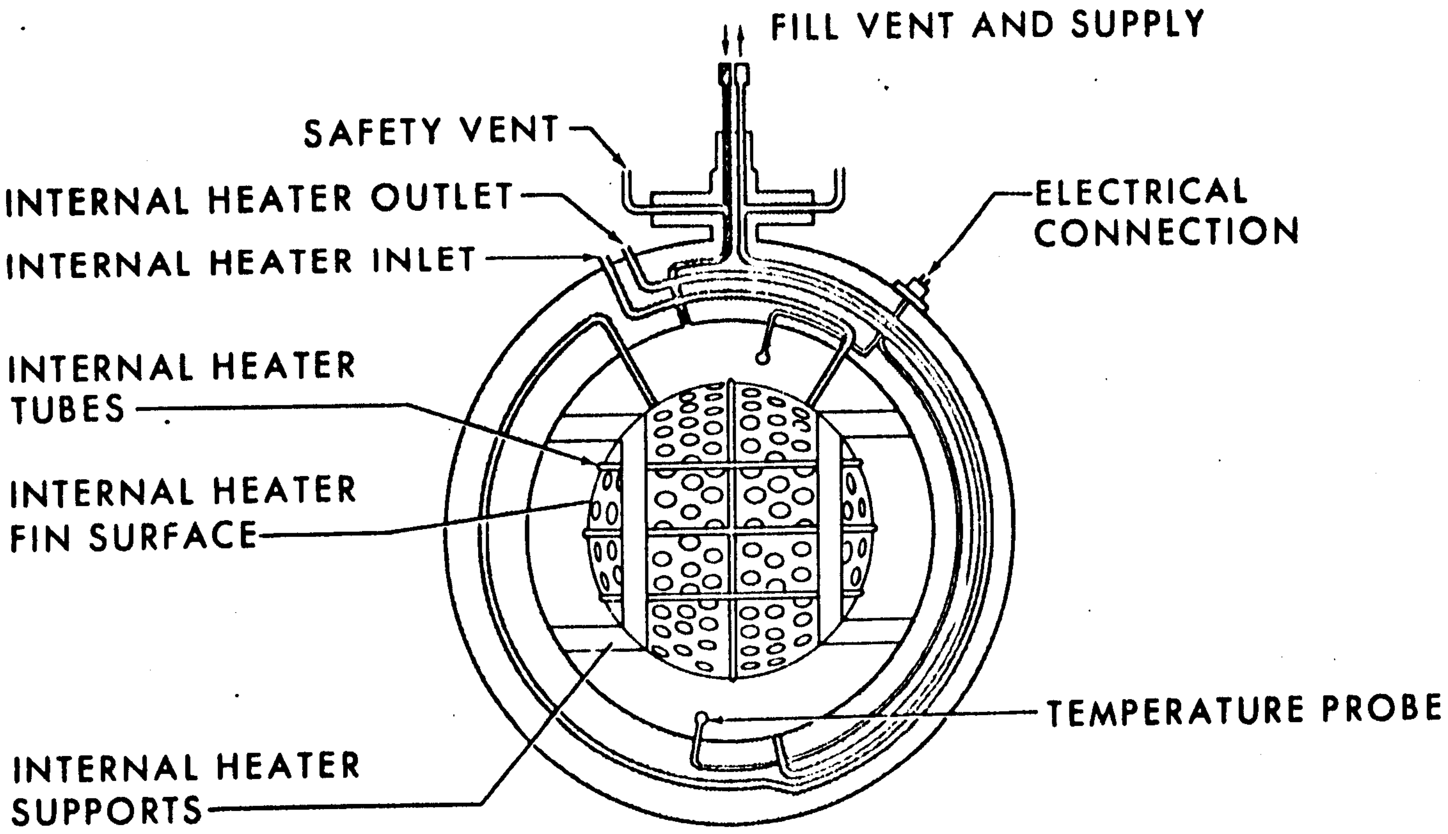

FIGURE 3

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P-V-T SURFACE FOR HELIUM

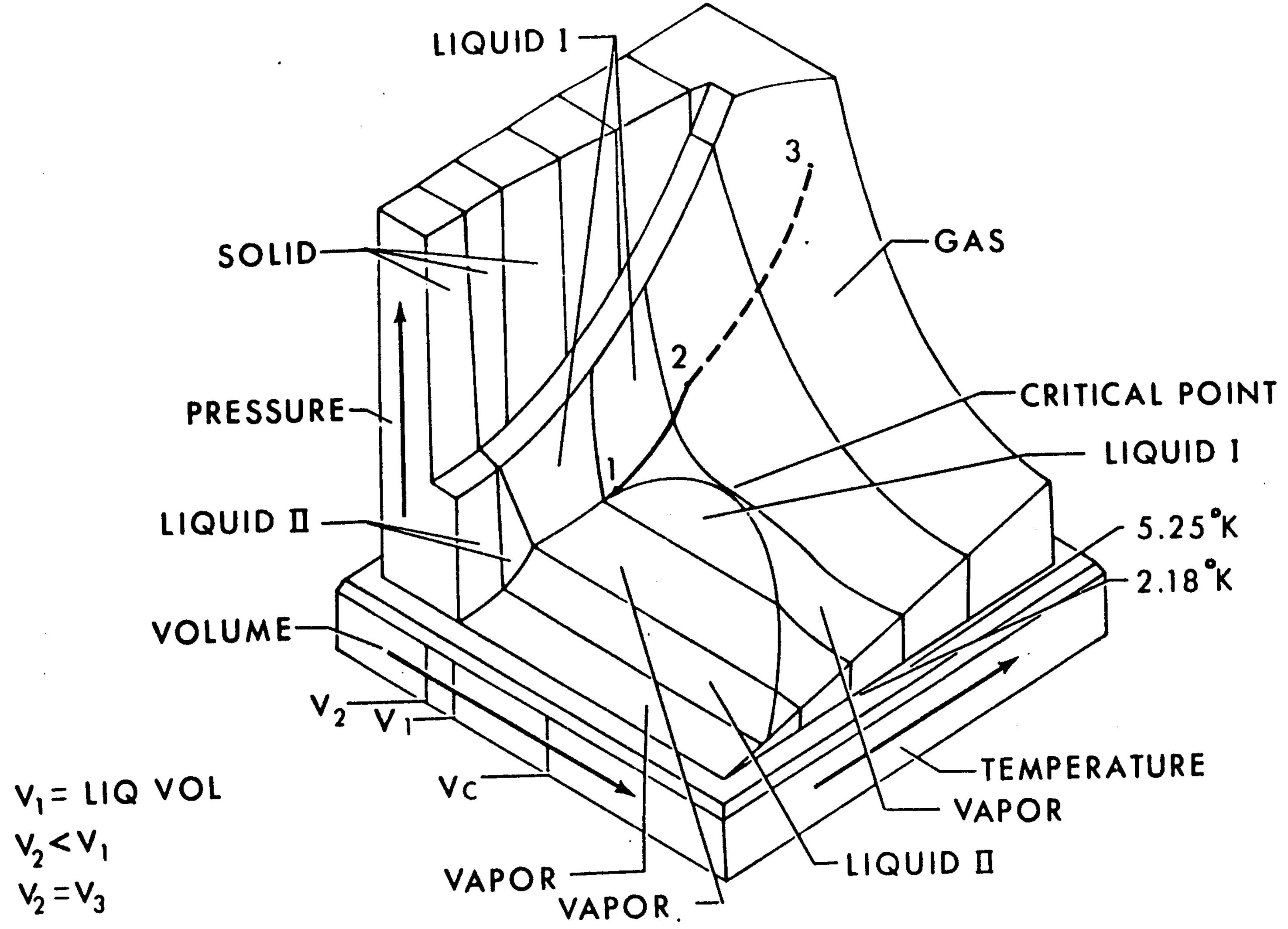

FIGURE 4