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STUDIES OF CRYOGENIC PROPELLANT STORAGE AND HANDLING FOR THE LUNAR LANDING AND LAUNCH FACILITY (COMPLEX 39L)

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1988 NASA/ASEE Summer Faculty Fellow
Research Report

Jerald N. Linsley, Ph.D., P.E.
Department of Chemical Engineering
Florida Institute of Technology
150 W. University Blvd.
Melbourne, FL 32901-6988
(407) 768-8000 x 7560

ABSTRACT

A brief description of Complex 39L as it is currently conceived is presented. A brief discussion of lunar thermal history is then presented. From this follows a discussion of the current lunar thermal environment which will impact the design of cryogenic storage and handling facilities on the moon. Some previous studies are discussed. A conceptual design of liquid oxygen and hydrogen storage facilities is presented. The essential feature of this facility is that cryogens are to be stored in a number of small tanks which can serve as lander propellant tanks rather than as one large storage vessel. These tanks will be placed under a Fuel Inventory Tent (FIT) for shadow shielding. Methods of dealing with propellant boil-off are discussed. A base case cascade refrigeration system for boil-off recovery is designed. Equipment sizes and power requirements are such that it seems very feasible to construct a prototype boil-off recovery system in a laboratory environment.

Outline of the

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1. INTRODUCTION

In addition to reporting on the cryogenics systems engineering work performed this summer, we shall also attempt in this report to explain the larger than usual number of institutional ties upon this work. In addition to the NASA/ASEE (American Society of Engineering Education) Summer Faculty Fellowship program, this project is also intimately tied to the NASA/USRA (University Space Research Association)/UADP (University Advanced Design Program). Further, the Florida Institute of Technology (FIT) has recently established a Space Research Institute (SRI) funded in part by the state of Florida through revenues generated by Challenger memorial license plate sales. A number of possible SRI projects are discussed. An additional institutional tie is past and future participation in proposals for a Space Engineering Research Center. Any space related work by any faculty member from a school aspiring to one of these centers must be viewed as an attempt to strengthen the schools position in this regard.

A preliminary definition of COMPLEX 39L was the topic of a senior engineering advanced space design project during the academic years of 1986-87 and 1987-88 at FIT. This project was part of the UADP sponsored by NASA through the USRA. Over thirty universities participate in this program. Most of the work described herein emanates from this project and extends it. A description of the work done to date on COMPLEX 39L is given in the next section. For the academic year 1988-89, the senior engineering advanced space design project will focus more narrowly on a relatively small subset of the elements which must comprise the facility, namely, the two areas of cryogenic propellant storage systems and guidance systems.

The next section discussed the part of this summer work which was concerned with cryogenic storage. First, lunar site considerations were studied. This entailed a look at the thermal history of the moon. Then, current aspects of the thermal setting on the moon were investigated. From previous work, some base case design criteria were formulated. The problem of the storage of cryogenic propellants on the moon as been studied since the 1960's. Some of these studies are discussed. An estimate of the expected hydrogen boil-off rate was made based upon currently accepted criteria rather than a detailed thermal analysis. From this estimate, a base case cascade refrigeration system for hydrogen boil-off recovery is designed. The bulk of the work described is concerned with this refrigeration system design.

The section on Future Work can be broken into three areas. First, senior design projects to be assigned at FIT during the coming academic year are covered. While this summer research project was primarily concerned with cryogenics, some plans for work on guidance systems during the coming academic year are discussed. Next, some specific recommendations to KSC are promulgated. Finally, some possible research projects for the SRI at FIT are discussed.

2. COMPLEX 39L

As a basis for this work, we consider a preliminary definition of a lunar landing and launch facility (LLLF or Complex 39L). We consider a phase III lunar base (References [3] and [10]). Without specifying specific lunar base scenarios, we envision three traffic levels: 6, 12, and 24 landings/launches per year. We have assumed a single, multipurpose vehicle for the lunar module. The design and specification of the vehicle and of the lunar base will have an impact upon the design of the LLLF. Figure 1 illustrates the Earth-Moon transportation infrastructure. The scope of Complex 39L is graphically illustrated by the Systems Diagram of Figure 2. Here, major functions or facilities are represented by blocks in a block diagram. The dashed line represents the boundary of Complex 39L. This is a simplified version of this diagram. Obviously, other items could be included. Based upon this diagram, we have considered nine major design items or areas. These items are:

[1.] LANDING/LAUNCH SITE CONSIDERATIONS
[2.] STRUCTURE, SHELTER, SAFETY, ENVIRONMENTAL NEEDS
[3.] LANDING/LAUNCH GUIDANCE, COMMUNICATIONS, COMPUTING NEEDS
[4.] LUNAR MODULE SURFACE TRANSPORT SYSTEM
[5.] HEAVY CARGO UNLOADING/LOADING SYSTEMS
[6.] PERSONNEL UNLOADING/LOADING SYSTEMS
[7.] PROPELLANT UNLOADING/LOADING SYSTEMS
[8.] VEHICLE STORAGE
[9.] MAINTENANCE, REPAIR, TEST AND CHECK-OUT REQUIREMENTS

This constitutes a preliminary description of a phase III lunar landing and launch facility. These items are further illustrated on the plot plan of Figure 3.

The senior engineering project of the advanced space design program at FIT for the academic year 1988-89 will consist of subsets of items [3.] and [7.]. Part of the project will be concerned with guidance and communications. These functions and others will be housed in the modules to the left of the VAT (Vehicle Assembly Tent) as depicted on the plot plan. Another part of the project will be concerned with cryogenic propellant storage and handling. These functions will be housed in the FIT (Fuel Inventory Tent) to the right of the VAT, again, as depicted on the plot plan.

Figure 4 presents a preliminary sketch of the VAT. We envision using similar structures for the FIT's. The fuel and oxidant (liquid hydrogen and liquid oxygen) will be housed in separate tents for safety. The purpose of the tents is to provide shadow shielding and, hence, a near constant thermal environment for the cryogenic fuel tanks. More detailed descriptions of Complex 39L and the tents are presented elsewhere (References [3] and [10]).

3. CRYOGENIC SYSTEMS

3.1. Lunar Thermal History

To evaluate the thermal environment for cryogenic propellant storage on the moon, some aspects of lunar thermal history were studied. A surprisingly large body of literature exists on this topic (References [8], [9], and [13]). Most of our knowledge comes from theoretical calculations. Direct observation is difficult. Mathematical models in the form of an energy balance are formulated from the following partial differential equation.

(1) $$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r}\left(r^2 k \frac{\partial T}{\partial r}\right) + A$$

Here, the term, A, is a radioactive decay heat source term. Other nomenclature is standard. An initial condition expressing the initial temperature as a function of the radius is written as

(2) $$T(r,0) = f(r)$$

Initial time is taken as 4.5 billion years ago. Boundary conditions used are

(3) $$\frac{\partial T(0,t)}{\partial r} = 0$$

(4) $$T(R,t) = g(t)$$

The first condition states that the temperature is symmetrical about the center of the moon. This, of course, assumes that spatial variations in the properties, density, heat capacity, and thermal conductivity are negligible. The second condition gives surface temperature as a function of time. This is usually taken as some constant average temperature in the neighborhood of 273 K. A surface heat flux boundary condition could also be used.

Many studies have been performed using such models. A number of variations on the model can be imposed. Some studies differ in the treatment of the temperature variation of the physical properties : density, heat capacity, and thermal conductivity. In most cases, the density and heat capacity are taken as constant while the thermal conductivity is taken as a function of temperature cubed.

Another variation is in the assumed abundance of radioactive elements in the moon. Given an abundance (set of concentrations), the heat source term is a summation of the energy release upon decay of each radioactive element considered. Some studies also assume a spatial distribution of these elements. If the possibility of melting of the lunar material is considered, then the boundary value problem becomes a moving boundary problem and another physical constant, the heat of fusion, is introduced. This parameter may also vary with temperature and position. Two major initial conditions are used. One can assume that the moon was initially cold and has been heated up by radioactive decay or one can assume that the moon was initially hot and has been cooling. Since the current surface temperature variation is fairly well known, a good average surface temperature can be estimated. The effects of convection of a molten core have also been studied.

All but the simplest of these variations produce boundary value problems that cannot be solved analytically. Finite difference techniques have been used. Spatial steps are on the order of 10's of kilometers (e.g., 20 km). Time steps are on the order of millions or tens of millions of years. Thus, an average surface temperature or flux is used instead of the diurnal (daily) variations. A time step of a million years would require 4500 time steps for the 4.5 billion year life of the moon. The 20 km radial step would require 87 space steps.

The resulting solution for such problems is a time and radial variation of lunar temperatures over the history of the moon. In addition, one can calculate an average lunar surface heat flux. The results of many of these studies show that the moon is currently near a thermal steady-state. Further, the variations in temperatures at shallow depths (0 to 100 km) from one model to the next are not very significant. Also, the calculated surface heat flux is on the order of 10^{-7} times the maximum (ecliptic) daytime solar insolation of 1400 W/m^2. This means two things for our studies:

1.) We can assume constant subsurface temperatures.
2.) We can neglect the "net: surface heat flux.

3. 2. Lunar Thermal Environment

A similar hierarchy of boundary value problems can be posed for the lunar surface down to shallow depths over a period of one lunar day (about 28 earth days). For a period of one lunar day, we can ignore the radioactive heat source term so that the problem becomes a purely heat conduction problem. The surface boundary condition will be a function of time. During lunar daytime, the surface will receive solar energy. The surface will also radiate to outer space according to the Stefan-Boltzman law. At night, only the radiation term will be present. Other variations that could be imposed upon this surface boundary condition are whether or not to approximate the nonlinear radiation term by a linear function and, if so, one could vary the choice of the points about which to linearize this term, depending upon the time of day one wants the resulting approximate solution to be most accurate. Since the heat conduction equation is second order, another boundary condition is required. The most common conditions are that the temperature is constant at infinite depth. This can be posed in various ways, depending upon the geometry of the problem. The problem can be posed as a one dimensional problem. The one dimension would be along a radius from the equator at high noon. Other radii could be chosen and the only change required would be boundary condition. Another possible boundary condition is that the heat flux, i.e., the first partial derivative of temperature with respect to the depth coordinate be zero at infinite depth. For spherical geometry, these two boundary conditions would be constant temperature or zero derivative at the center of the moon. The problem can be posed with static moon or a rotating moon. While the moon does actually rotate, the solutions of the static problems are often sufficient to answer various questions pertaining to the lunar thermal setting. For the one dimensional problem, temporal variations are handled by the time varying surface boundary condition and one need only pose an initial condition. For the rotating sphere problem, the time boundary condition is periodic. That is neglecting the net thermal flux predicted by lunar thermal history studies, the solution of the rotating sphere problem should repeat itself every lunar day. A number of the one dimensional problems have been solved for various boundary conditions (References [8] and [13]). We have not encountered a solution to the rotating sphere problem.

The result of these various heat conduction problems using the best available estimates of lunar thermal properties is that the constant temperature that is attained at "infinite" depth is 240 K + or - 6 K (Reference [8]). Furthermore, this temperature is attained at a depth of about one foot!

So, while the lunar surface temperatures vary much more than terrestrial temperatures - from a scorching 373 K to a chilling 120 K, this variation occurs only over a relatively shallow portion of the moon and that at very shallow depths, the constant temperature of 240 K (-28 °F) prevails. We will use this in our designs. We shall consider this the temperature at which we can reject heat from heat engines. On earth, this temperature is ambient, i.e., about 100 °F, via cooling water or air. We shall reject heat on the moon by conduction to the regolith.

3.3 Previous Studies

Studies of lunar cryogenic storage have been performed since the 1960's and, perhaps, before. We will cite only three here. One of the more useful that we found was performed by P. Glaser, et al, of the Authur D. Little and Co. (Reference [7]). A basic cryogenic storage vessel design is found therein. Some fundamental aspects of radiation heat transfer on the moon are developed in this report. Bell of Boeing (Reference [6]) studied no-loss storage of solid hydrogen on the moon. However, to date, solid hydrogen has only been produced as a slush of up to a maximum of 40 % solid in liquid. A recent study was performed under the auspices of the USRA program (Reference [2]).

As mentioned above, there are many other similar studies. Most of these studies focus on the vessel design and the attendant radiation heat transfer. Almost all of these studies consider only a single (or perhaps, two) storage vessels. Almost all studies consider the vessel to be sitting "bare" on the lunar surface and, therefore, subject the the wide diurnal temperature variations. Thus, some of the fundamental bases of this study, namely, storage in small, vehicle tank sized vessels and the use of a tent for shadow shielding and constant thermal environment, make an exhaustive literature search less than useful. Nevertheless, a more exhaustive review of the literature is planned elsewhere.

3.4. Propellant Storage

For inventory purposes, we shall base our design upon a fully developed Phase III lunar base. The levels of development of the various levels of lunar base scenarios have been defined elsewhere (Reference [12]). The important thing for our purposes is the maximum population level of 30 people. We shall specify that our propellant inventory be of such a magnitude that all 30 people could be evacuated from the lunar surface without additional propellant resupply. Our base case lander (Reference [1] and [11]) will transport 6 people. The propellant requirements are 12500 kg of LOX, 2175 kg of LH2, at an O/F of 5.75. We multiply these numbers by 5 for the 5 required launches for evacuation. We allow 10 % for chill-down requirements. This aspect needs further study. We allow 5 % for boil-off. Again this figure needs additional work. This gives a total inventory of 72000 kg for LOX and 12500 kg for LH2. If these inventories were stored in single spherical tanks, the resulting diameters would be: LOX - 4.9 m; LH2 - 7.0 m. Most lander designs use twin spherical tanks for both oxidant and fuel. Both are used simultaneously. This maintains a relatively constant center of gravity for the vehicle. We shall store our inventories in twelve tanks, two for each of the five launches and two extra for the chill-down requirements, boil-off losses, if any, and other contingencies. Each of the twelve tanks will have a diameter of 2.2 m for LOX and 3.1 m for LH2. These tanks will be stored in two rows of six tanks per row. Each propellant, LOX and LH2 will have its own FIT (Fuel Inventory Tent). We envision transport of propellant to and from the vehicle to be performed by transport of the entire fuel tank. The lander is assumed to have a modular design so that the fuel tanks can be removed and replaced easily. These tanks will be manifolded together in several ways. First, we would envision a vapor manifold to gather boil-off losses. Secondly, we would envision a liquid manifold for both removal and replenishment of liquid propellant to and from the tanks. Finally, there will probably be an instrumentation manifold. A detailed thermal analysis of the FIT's has yet to be performed. However, preliminary analyses of the shadow problem from other sources (Reference [7]) indicate that wide diurnal temperature variations on the lunar surface would extend into the tent only to the extent of about one foot, just as they do in the vertical direction. Thus, most of the tent floor would be at the subsurface temperature of 240 K.

3.5 Hydrogen Boil-off Recovery

In general, cryogenic liquids are stored at their saturation temperatures at relatively low pressures. This results in relatively low, cryogenic storage temperatures. Storage at ambient conditions is prohibitive because of the increased storage pressure requirements and, hence, increased vessel thickness and weight. Therefore, cryogenic storage tanks are highly insulated and major design concerns for cryogenic vessels is the minimization of heat leaks. There are three major sources of heat leaks for cryogenic vessels: through the insulation, through structural members, and through piping. Detailed vessel design is not considered here. However, a word should be said in regard to the insulation and structural design. Cryogenic vessels are normally designed with two concentric shells. The space between the inner and outer shells is filled with multilayer insulation and is usually evacuated. This handles the insulation part of the design. However, structural members are also present between the shells to hold the shells apart. Commonly used structural members are tension rods to hold the two shells in place. These rods should be strategically placed. They should have high tensile strength and low thermal conductivity. This is the nature of the structural design problem to minimize heat leaks. The piping design problem is similar. It could be argued that a vacuum jacket is not needed for cryogenic storage vessels on the moon since they will already be in a vacuum. While we eventually plan to produce oxygen from lunar materials and extraterrestrial hydrogen sources will be exploited as soon as possible, we must design for the case where these storage tanks will be coming from earth. Therefore, they must withstand terrestrial thermal conditions. Furthermore, these propellant tanks must be designed structurally to be able to withstand the stresses of earth launch while being fully or nearly fully loaded. In this section we shall study the recovery of hydrogen boil-off with the idea that if we can recover hydrogen boil-off, some of the resulting subsystems can be relatively easily used to recover the oxygen boil-off.

Hydrogen boil-off can be handled several different ways. First, we could just design to minimize the boil-off or hold it at or below some minimum acceptable level and live with it. This boil-off would have to be made-up from resupply just as we will have to do for much of the chill-down LH2 and the inevitable leaks in the system. The boil-off can be minimized, of course, by heavier thermal design, i.e., better insulation, better structural design, better designed piping, etc. LH2 boil-off can be minimized by storing the hydrogen as a slush at its triple point. This would mean that the heat of fusion would have to be leaked into the system before heat of vaporization would result in boil-off. Other ways to handle the boil-off would be to use an active refrigeration system to condense and return the boil-off. Some candidate refrigeration systems are: cascade compression refrigeration, helium refrigeration, magnetic refrigeration, thermoelectric refrigeration, or some combination of the above. Metal hydride storage of the hydrogen at or near ambient conditions could also be utilized in the hydrogen storage scheme.

For a base case, the cascade refrigeration system was chosen for study. Cascade refrigeration systems are among the more thermodynamically efficient systems (Reference [5]). Perhaps one of the more exotic systems mentioned above or something entirely new will finally be used on the moon, but for study purposes, this system should be considered so as to provide a target to improve from. We start by storing hydrogen at 1 atm (20 K). There is no compelling reason to use this pressure on the moon. However, we have a lot of terrestrial experience designing for this pressure. Unless we are going to use another pressure for thermodynamic purposes (e.g., the triple point pressure of 1 psia) it is felt that use of standard terrestrial conditions would result in design efficiencies. In this cascade refrigeration, a number of design guidelines were imposed to improve the reliability of the system. An effort was made to keep refrigerant pressures as low as possible. Even so, the Neon loop has a pressure of near 3000 psia. Compression ratios were kept low (3 to 6) This may turn out to be a constraint that can be relaxed at final, detailed design stage. However, in industrial practice, it is found that this guideline results in more reliable compressor systems. For this base case study, ideal (isentropic) compressors and expanders were used. Known efficiencies can always be imposed at a more detailed design stage. A minimum temperature approach of 3 K or 5 °F was assumed for most of the heat exchangers in the system. Low temperature approaches such as these are commonly used in cryogenic work. One exception to this low temperature approach was made for the exchangers which reject heat to the 240 K lunar subsurface. Here, we chose a temperature approach of 10 K or 18 °F. So, the latent heat from the hydrogen boil-off at 20 K is to be rejected at 250 K. For estimating the areas of the heat exchangers, we used a constant, overall heat transfer coefficient of 100 BTU/hr/sq ft/°F or, in the units used mostly in this study, 2000 kJ/hr/sq m/K. Refined estimates of the heat transfer coefficient would, of course, be made at a more detailed stage of design. Finally, as a basis, we first design a hydrogen boil-off recovery system based upon a unit capacity of 1.0 kg of hydrogen per hour.

A five loop cascade refrigeration system has been formulated for boil-off recovery. This system is depicted in Figure 5. The five refrigerants are: hydrogen at the first level, then neon, nitrogen, methane, and ethane. Properties of these refrigerants are listed in the refrigerant table of Figure 6. One aspect of these data that should be pointed out is the relatively large, 150 °F gap between the critical temperatures of neon and nitrogen. Life would be simpler if there existed another refrigerant with a critical temperature intermediate to these two temperatures. Perhaps this would be a area in which to consider mixed refrigerants.

Following the overall flow diagram of the five loop cascade refrigeration system is a series of five flow diagrams for the individual loops. A pressure-enthalpy (P-H) diagram for each of the loops is also presented. The overall stream table is presented in Figure 7.

The hydrogen loop is depicted on Figure 8 and its P-H diagram is given by Figure 9. As mentioned previously, the gaseous hydrogen boil-off from the various tanks will be gathered into a common manifold. From this manifold, the hydrogen vapor at 1 atm and 20 K (stream 1) will mix with recycle hydrogen vapor (stream 7) coming from the hydrogen flash vessel, VE1,at the same conditions. The mixed stream (stream 2) serves as suction to the first compressor, CM1. The CM1 discharge conditions (stream 3) are currently set at 3.9 atm and 35 K. These and other interstage conditions could be changed in a more final design. Second stage, CM2, discharge conditions (stream 4) are 15 atm and 61 K. This compressed hydrogen stream is cooled to 33 K (stream 5) isobarically and supercritically on the hot side of the heat exchanger, HX1, by neon at 30 K on the cold side on the same exchanger. This stream then passes through a valve (JT1) where the supercritical hydrogen experiences a Joule-Thompson (isenthalpic) expansion. This results in partial liquifaction (about 40 %) of the hydrogen (stream 6). The two phase stream is separated in an adiabatic flash vessel, VE1. The resulting liquid, recovered hydrogen boil-off, is pumped (stream 8) to the LH2 manifold to be returned to storage in on of our LH2 tanks. The vapor is recycled (stream 7) to mix with additional hydrogen boil-off (stream 1) to begin the cycle over again.

Liquid neon, saturated at 2.2 atm and 30 K, is pumped (stream 9) from the neon flash vessel, VE2, to the cold side of HX1. Cooling of the hydrogen stream on the hot side of this exchanger results in partial vaporization of the neon (stream 10). This vapor along with that from the two phase stream 19 serves as suction (stream 11) to a compressor train which eventually elevates the neon pressure to 64.8 atm and 117 K. This compressed neon stream is cooled to 75 K isobarically on the hot side of HX2 by nitrogen at 72 K on the cold side of this exchanger. The resulting cooled neon (stream 15) serves as CM6 suction and is compressed to 200 atm and 117 K. Again, this compressed neon stream is cooled to 75 K isobarically on the hot side of HX3 by nitrogen at 72 K on the cold side of this exchanger. The resulting cooled neon stream (stream 17) is fed to an expander, EX1, where the neon expands isentropically to a pressure of 27 atm and 44 K (stream 18) This supercritical stream passes through a valve, JT2, and experiences a Joule-Thompson (isenthalpic) expansion to 2.2 atm and 30 K. This expansion valve produced partial liquifaction (about 10 %) of the neon (stream 19). This two phase stream is separated in the adiabatic flash vessel, VE2, and the cycle begins again.

Liquid nitrogen at 0.5 atm and 72 K from the nitrogen flash vessel, VE3, is pumped (stream 24) to a splitter and divided into two streams which pass through the cold sides of the neon coolers, HX2 and HX3. The resulting partially vaporized nitrogen streams are rejoined and returned (stream

25) to the flash vessel. The vapor from this stream and stream 33 is separated and fed (stream 26) to a nitrogen compressor train. Nitrogen is compressed in several stages (3, here) to 13.4 atm and 192 K. This compressed nitrogen is cooled isobarically to 128 K on the hot side of HX4 by saturated liquid methane at 125 K on the cold side of this exchanger. The resulting cooled nitrogen (stream 30) serves as the suction to CM10 which compresses the nitrogen to 40 atm and 178 K. Again, this compressed nitrogen is cooled isobarically to 128 K on the hot side of HX5 by saturated liquid methane at 125 K on the cold side of this exchanger. This supercritical nitrogen stream passes through an expansion valve, JT3, expands isenthalpically to 0.5 atm and 72 K. The resulting stream 33 is partially liquified (about 30 %). This two phase stream passes to the nitrogen flash vessel, VE3, to begin the cycle again.

Liquid methane at 2.65 atm and 125 K is pumped (stream 38) from the methane flash vessel, VE4, to a splitter where the liquid is divided and fed to the cold sides of exchangers HX4 and HX5. Cooling of nitrogen in these exchangers results in partial vaporization of the methane. These two streams are rejoined (stream 39) and returned to the flash vessel. The vapor from this stream and stream 44 are separated in VE4 and fed to the suction of the methane compressor train which eventually elevates the methane to a pressure of 24.76 atm and a temperature of 222 K. This compressed methane is condensed isobarically at 172 K on the hot side of HX6 by saturated liquid ethane at 169 K on the cold side of this exchanger. The resulting condensed nitrogen (stream 43) is expanded through a valve, JT4, to 2.65 atm. This partially (about 40 %) vaporizes the previously saturated liquid stream. This two phase mixture (stream 44) passes to the adiabatic flash vessel, VE4, to begin the cycle again.

Liquid ethane at 0.41 atm and 169 K is pumped (stream 45) from the ethane flash vessel, VE5, through the cold side of HX6 where the condensing of methane on the hot side partially vaporizes the ethane. This partially vaporized ethane (stream 46) returns to the flash vessel where the vapor, along with that from stream 53, are separated and fed (stream 47) to an ethane compressor train. Compressed ethane at 6.8 atm and 288 K (stream 49) is cooled to 250 K in the hot side of a heat exchanger, LS1, which has as its cold side, the 240 K lunar subsurface. This cooled ethane (stream 50) is further compressed (CM15) to 13.6 atm and 283 K (stream 51). Again, this compressed ethane at 6.8 atm and 288 K (stream 49) is cooled to 250 K in the hot side of a heat exchanger, LS2, which has as its cold side, the 240 K lunar subsurface. The ethane is condensed to saturated liquid in this latter exchanger (stream 52) and this liquid stream subsequently passes through an expansion valve, JT5, and expands isenthalpically to 0.41 atm and 169 K. In this expansion, the liquid stream is partially vaporized (about 40 %) and the resulting two phase stream 53 is sent to the flash vessel to begin the cycle again.

An interesting equipment design problem for this cycle will be the heat exchanger which are to reject heat to the lunar regolith heat sink.

As mentioned previously, the major process results of this design are to be found on the Stream Table, Figure 7. A preliminary Equipment List is also presented. Again this list is very preliminary and based upon the 1.0 kg/hr hydrogen boil-off rate. Again, the compressor and expander work terms are calculated on a 100% isentropic efficiency basis. The heat exchangers are based upon the previously-mentioned overall heat transfer coefficient. The vessel volumes were based upon a ten minute holding time while operating half full. These criteria are, of course, subject to refinement.

Another result table is given as a Summary Table, Figure 19. Here, for each loop, we have listed the heat rejected from this loop to the next higher loop and ultimately to the lunar regolith. we have also listed the compression work in kilowatts and in horsepower. The flash vessel volumes are listed in liters and gallons. This shows that such a unit would not be unusually large.

While no detailed thermal analysis of the cryogenic propellant storage tanks was performed, some criteria have been found (Reference [4]). It has been estimated that boil-off rates of 0.3 % per month for hydrogen and 0.1 % per month for oxygen are achievable by good thermal design. If we use the hydrogen criterion for our system, this turns out to be a boil-off rate of about 0.05 kg/hr. Thus, the system presented is over designed by a factor of 20. If we allow ourselves only a 100% safety factor, we could reduce the volumes, areas, power requirements, and other capacity related factors for our design by a factor of ten. Such as system would be fairly small. It would be very feasible to build a prototype of such a system.

6. FUTURE WORK

First, class projects for the 1988-89 academic year at FIT will be discussed. These NASA\USRA sponsored University Advanced Design Projects for mostly senior engineering students will fall into two categories: cryogenic propellants and guidance.

Guidance projects will be mentioned first. Some possible projects are:

* An altimeter to measure the lunar module's altitude and vertical velocity. A Ku-band carrier is envisioned.

* Ground based computing systems for control of the lunar module landing and launch operations, including navigation, control and systems test and check-out.

* Microwave communication link for sensing and control.

* Lunar ground based tracking system for navigation and detection of nearby spacecraft.

* Multiple beacons for spacecraft guidance and navigation.

These projects will be addressed primarily by the electrical engineering students.

For projects in the area of cryogenic storage and handling, we can follow the outline of this report. There exist some possibly interesting lunar thermal history projects but these would be given low priority. Perhaps a space scientist would tackle such a problem. Some of the diurnal thermal analysis problems would be of more immediate engineering interest. We anticipate projects in this area. A detailed radiation heat transfer analysis of the various tents proposed for Complex 39L is a high priority project for this year. Three aspects of the design of cryogenic storage vessels will be pursued. First, a design of the double walled multilayer insulated vessel should be performed. Next, a combination structural and thermal design of the support members between the two walls will be tackled. This problem of utilizing a material with a high tensile strength and low thermal conductivity should be a good project for our composite materials group. Finally, the thermal analysis of the piping to and from the vessel will be of interest. More work will be done on the proposed base case cascade refrigeration system. In addition, it is anticipated that work will be performed on the other systems enumerated in the prefatory discussions of the hydrogen boil-off recovery systems. These are: storing the hydrogen as a slush at its triple point, helium refrigeration, magnetic refrigeration, thermoelectric refrigeration, or some combination of the above. Metal hydride storage of the hydrogen at or near ambient conditions could also be utilized in the hydrogen storage scheme.

This list of possible projects is not meant to be exhaustive. It is anticipated that faculty and students will formulate other meaningful projects within the scope of our assignment.

A few words should be said about the status of process simulation at KSC. The author is a specialist with many years of experience in the use of process simulation software. Nevertheless, it was not possible to utilize ASPEN on the engineering VAX in a timely manner on the cascade refrigeration system studied herein. It is suggested that a new look be given to process simulation software at KSC. A good strong software specification should be written with respect to the technical features of a possibly new software package and also with respect to the usability or user-friendliness of the package. Currently, the help of the package implementor and a VAX systems person is required to successfully utilize ASPEN as it currently exists on the engineering VAX. There exist other packages with the same or sufficient technical capability and that can be easily utilized by a casual engineering user. This does not mean that the current ASPEN package could not be upgraded to this level. However, this upgrade should be compared to other packages.

Finally, some possible R&D projects that seem to be good candidates for FIT's new Space Research Institute (SRI). First, given the scale of lunar cryogenic boil-off recovery systems, it is proposed that KSC consider having someone such as the above mentioned SRI build a prototype of such a system. Terrestrial operations as opposed to lunar operations should not pose insurmountable problems for such a prototype. This would be a good way to evaluate designs, reliability, operability, maintainability, and leak-worthiness of such a system. Another possible project which the author learned of this summer is the kinetics of the chemical reaction between silver and hydrogen sulfide gas. This is currently a problem in the LCC. The materials division of design engineering is working on a test bed to simulate conditions in the LCC. It seems that a solid, scientific study of this heterogeneous chemical kinetics problem would permit the calculation of the consequences this problem for the LCC. It also seems to be the sort of problem that would be better performed in a university research environment rather than the KSC operations environment. Lastly, since KSC is becoming a center of excellence in the application of robotics to launch systems, it seems logical to extend this area of research to Complex 39L.

7. CLOSURE

In closing, the author wants to acknowledge NASA, ASEE, USRA, KSC, and the new PT-AST group for the opportunity to work at KSC this summer in particular and over the past year in general. This has been a very pleasant, enlightening, and inspiring association and it is to be hoped that this will continue through the USRA program and other projects. One project which has not yet been mentioned in this report is the author's electrophoresis research which he hopes to develop into a payload for the STS. Should this payload project come to fruition, the author hopes tap the lode of payload expertise in the Advanced Systems Group at KSC. Again, the author is grateful for the opportunity to serve.

6. REFERENCES

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8. LIST OF FIGURES

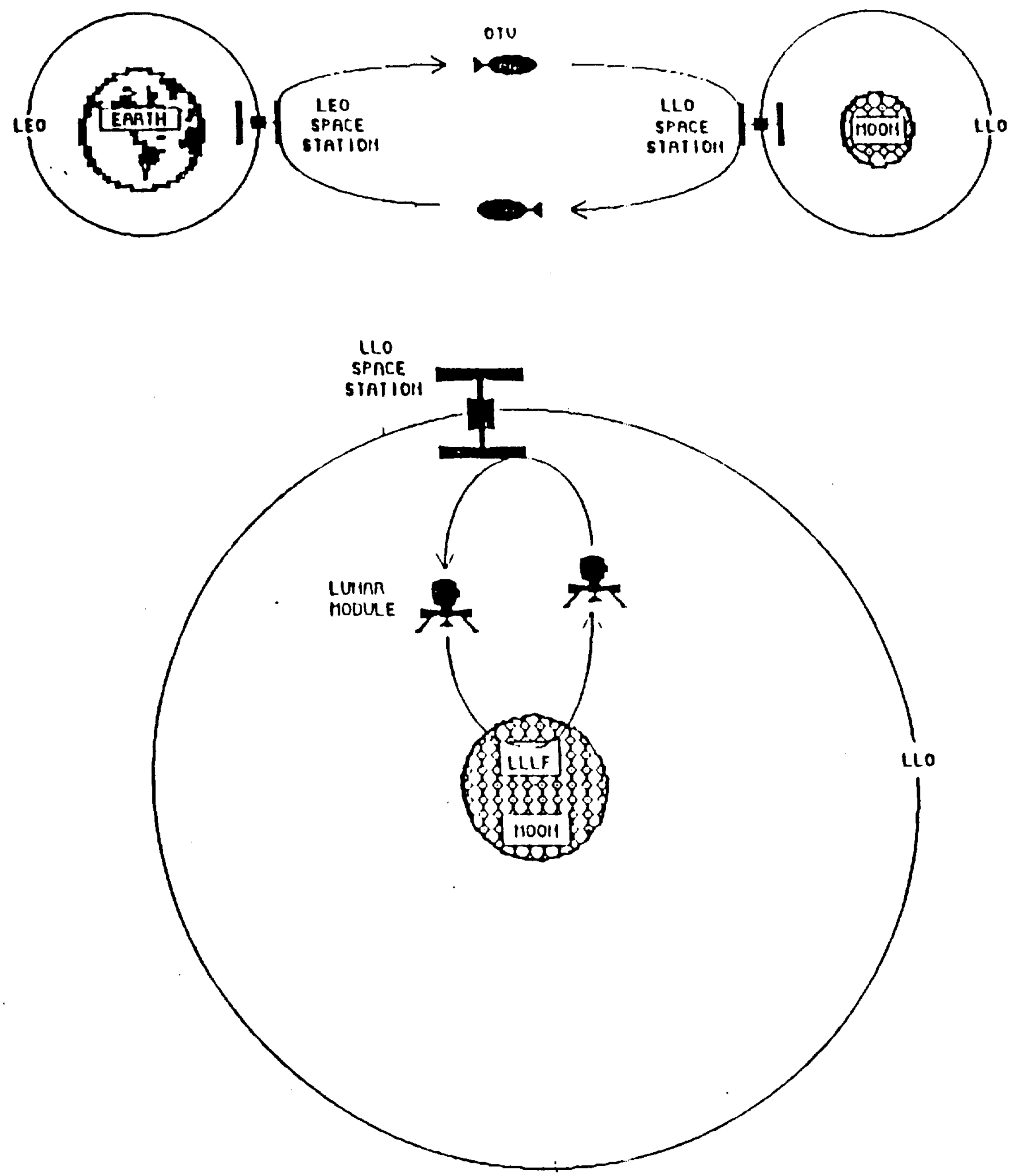


Figure 1 Earth -- Moon Transportation Infrastructure

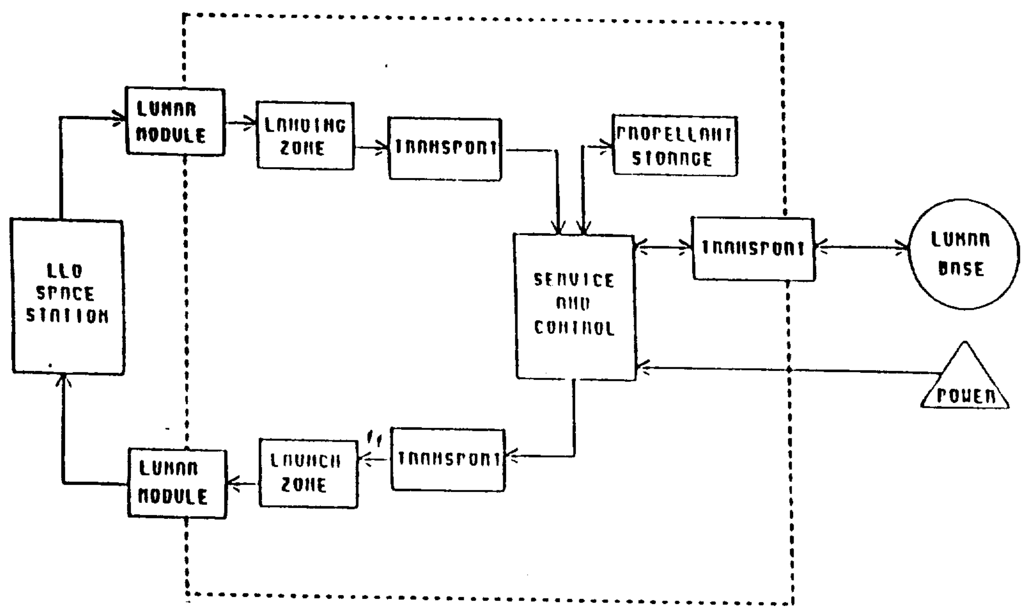


Figure 2 Lunar Landing and Launch Facility

(LLLF or Complex 39L) Systems Diagram

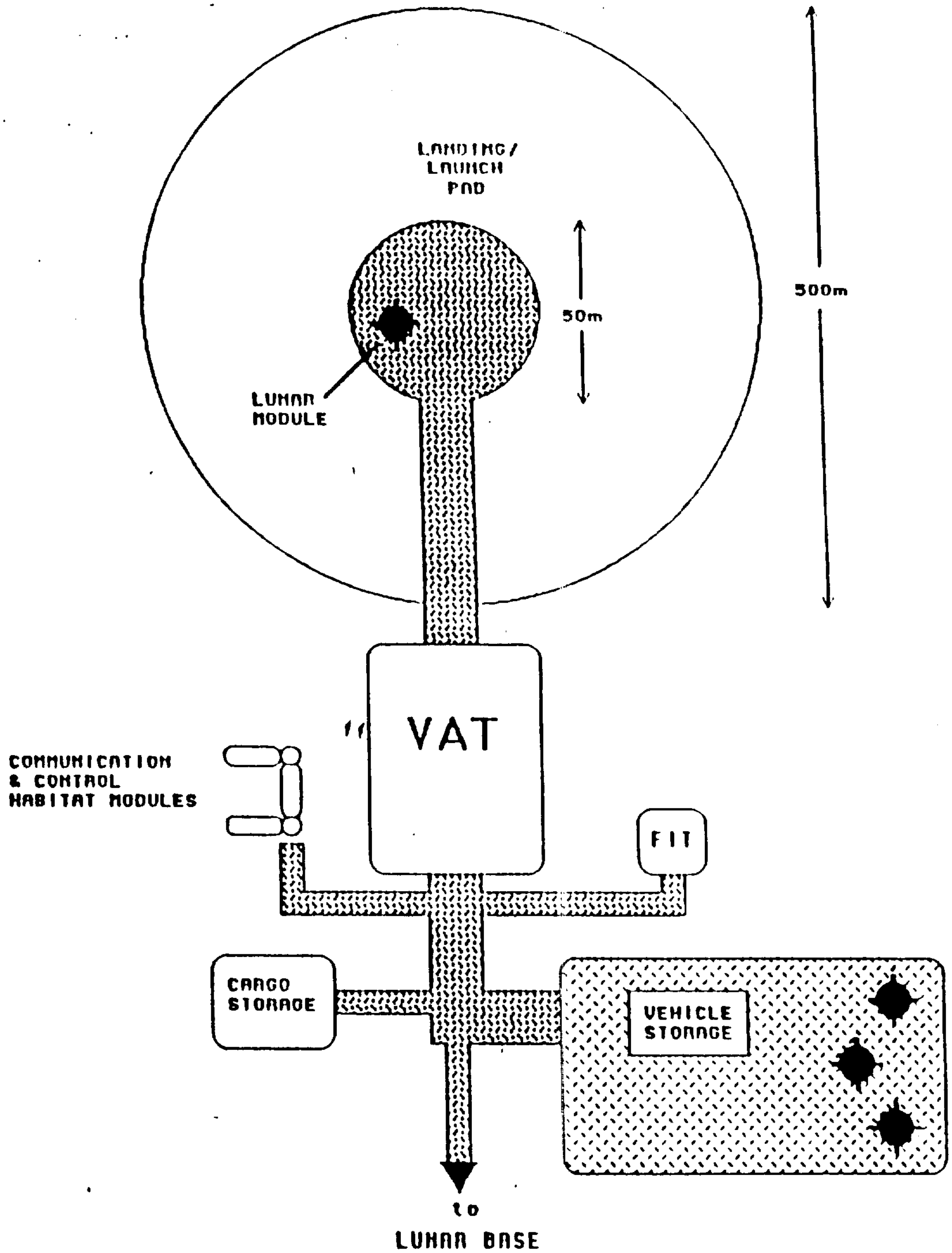


Figure 3 Complex 39L Plot Plan

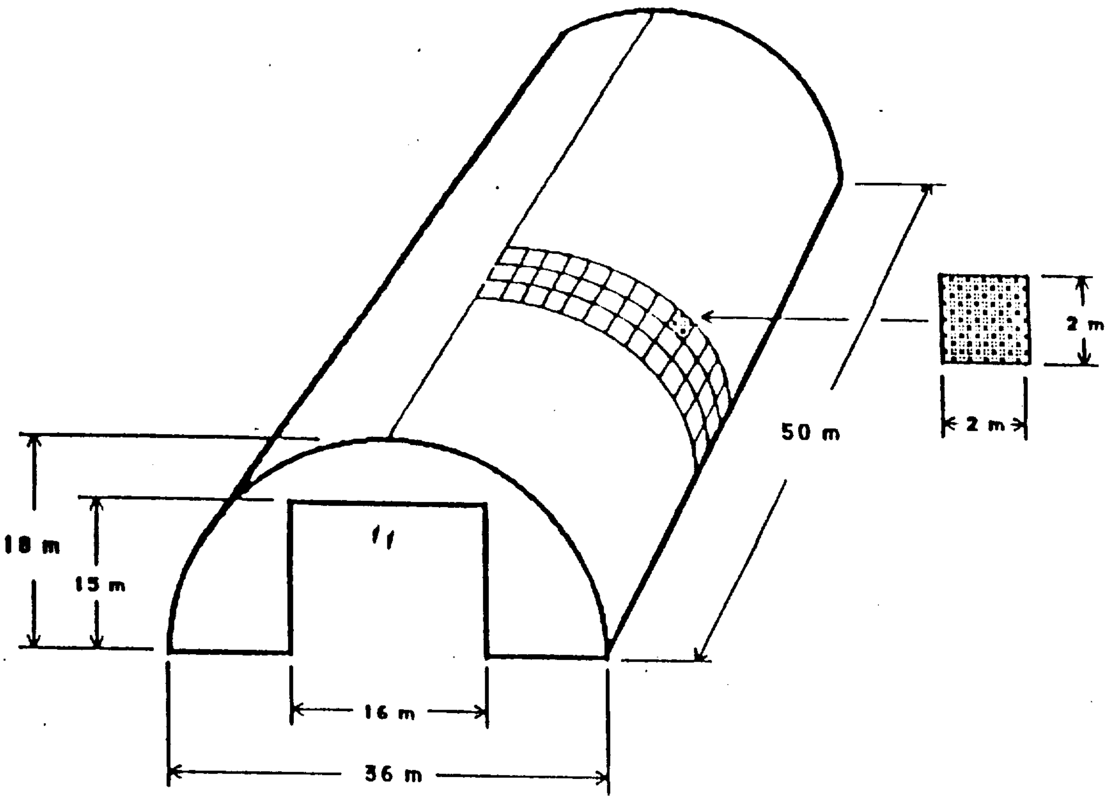


Figure 4 Complex 39L -- Vehicle Assembly Tent (VAT)

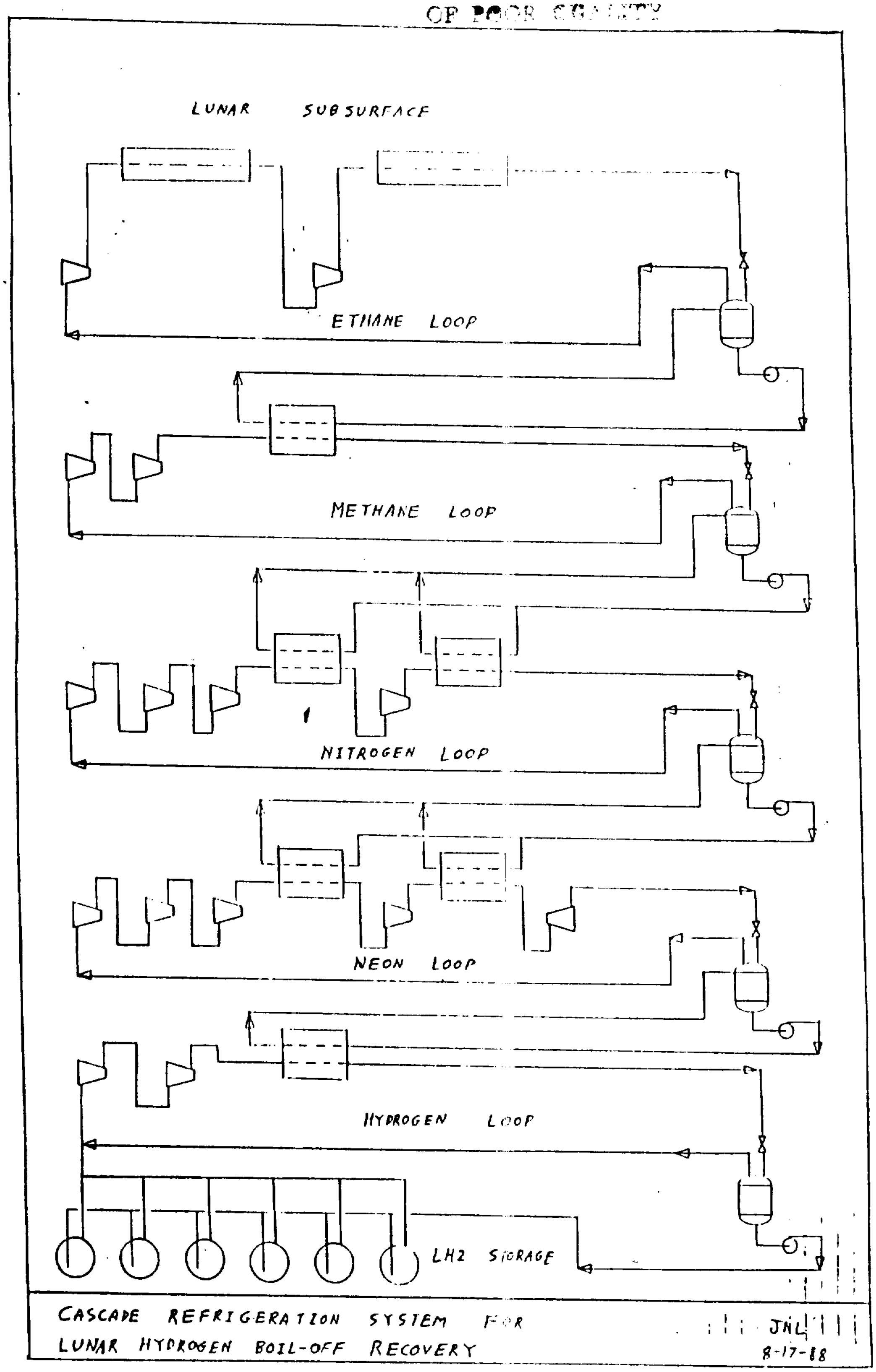

LUNAR SUBSURFACE
ETHANE LOOP
METHANE LOOP
NITROGEN LOOP
NEON LOOP
HYDROGEN LOOP
LH2 STORAGE
CASCADE REFRIGERATION SYSTEM FOR
LUNAR HYDROGEN BOIL-OFF RECOVERY
JNL
8-17-88

Figure 5

Table 2 Physical Properties of Refrigerants*

Refrigerant Name	Chemical Formula	Molecular Mass	Boiling Point at F[k]	Freezing Point, F	Critical Temperature, F	Critical Pressure, psia
Hydrogen (para)	H_2	2.0159	−423.2	−434.8	−400.3	187.5
Neon	Ne	20.183	−410.9	−415.5	−379.7	493.1
Nitrogen	N_2	28.013	−320.4	−346.0	−232.4	492.9
Methane	CH_4	16.04	−258.7	−296	−116.5	673.1
Ethane	C_2H_6	30.07	−127.85	−297	90.0	709.8

Figure 6

CASCADE REFRIGERATION SYSTEM — STREAM TABLE

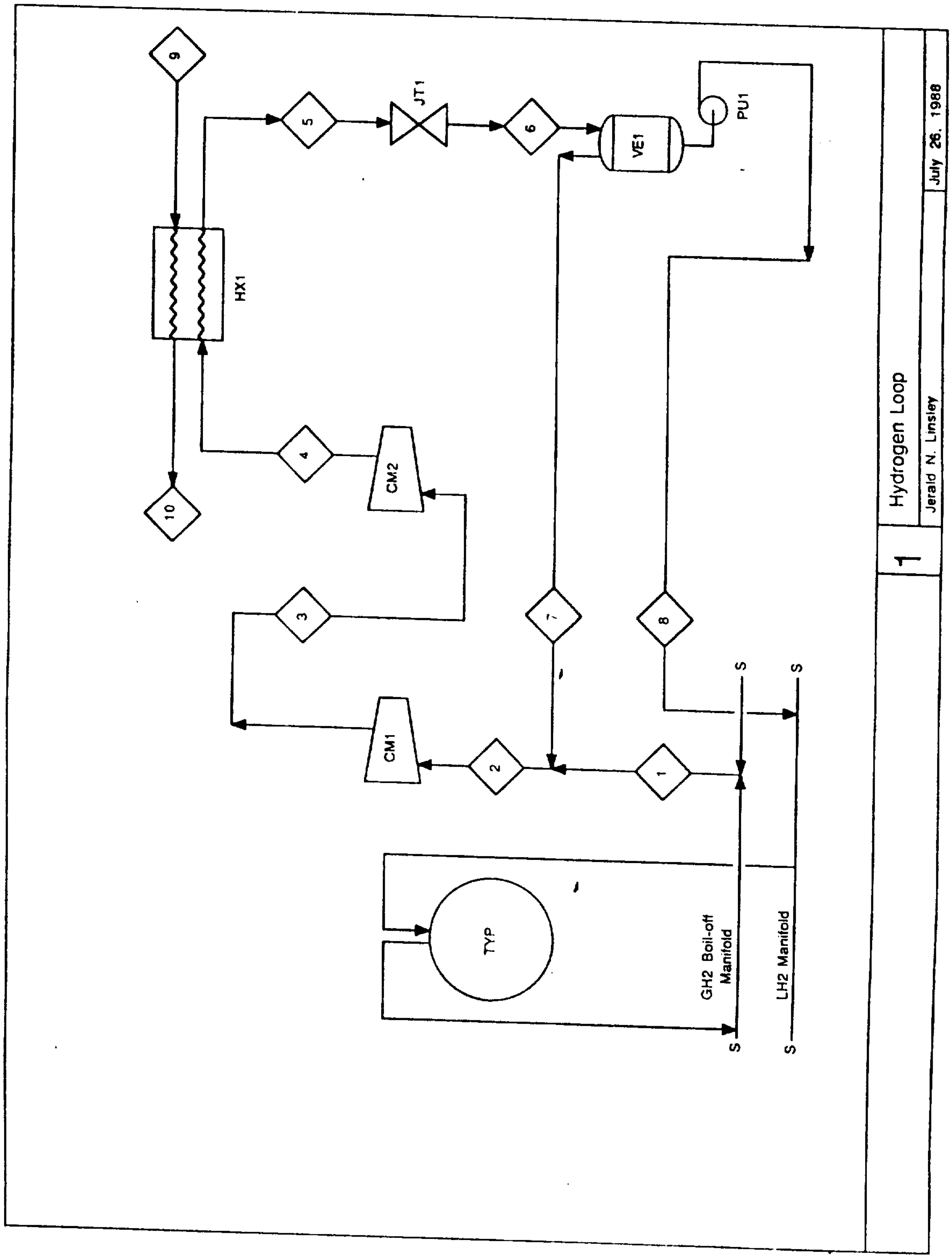
STREAM	1	2	3	4	5	6	7	8	9	10	11	12	13
FLUID	H_2	H_2	H_2	H_2	H_2	H_2	H_2	H_2	Ne	Ne	Ne	Ne	Ne
FLOW (KG/HR)	1.0	3.33	3.33	3.33	3.33	3.33	2.33	1.0	110.4	110.4	88.4	88.4	88.4
QUALITY	0.0	1.0	1.0	1.0	1.0	6.70	1.0	0.0	0.0	0.2	1.0	1.0	1.0
PRESS (ATM)	1.0	1.0	3.9	15.0	15.0	1.0	1.0	1.0	2.2	2.2	2.2	6.8	21.0
TEMP (K)	20	20	35	61	313	20	20	20	30	30	30	48	75

STREAM	14	15	16	17	18	19	20	21	22	23	24	25	26	27
FLUID	Ne	Ne	Ne	Ne	Ne	Ne	N_2	N_2	N_2	N_2	N_2	N_2	N_2	N_2
FLOW (KG/HR)	88.4	88.4	88.4	88.9	88.4	88.4	123.3	123.4	123.3	123.4	246.7	246.7	71.5	71.5
QUALITY	1.0	1.0	1.0	1.0	1.0	0.75	0.0	0.0	0.2	0.2	1.0	0.2	1.0	1.0
PRESS (ATM)	69.8	64.8	200	200	27	2.2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1.5
TEMP (K)	117	75	117	75	44	30	72	72	72	72	72	72	72	95

STREAM	28	29	30	31	32	33	34	35	36	37	38	39	40	41
FLUID	N_2	N_2	N_2	N_2	N_2	N_2	CH_4	CH_4	CH_4	CH_4	CH_4	CH_4	CH_4	CH_4
FLOW (KG/HR)	71.5	71.5	71.5	71.5	71.5	71.5	541	274	541	274	815	815	268	268
QUALITY	1.0	1.0	1.0	1.0	1.0	0.311	10.0	0.0	0.20	0.20	0.0	0.20	1.0	1.0
PRESS (ATM)	4.5	13.4	13.9	40.0	40.0	0.5	2.65	2.65	2.65	2.65	2.65	2.65	2.65	8.16
TEMP (K)	140	192	128	178	128	72	125	125	125	125	125	125	125	166

STREAM	42	43	44	45	46	47	48	49	50	51	52	53
FLUID	CH_4	CH_4	CH_4	C_2H_6	C_2H_6	C_2H_6	C_2H_6	C_2H_6	C_2H_6	C_2H_6	C_2H_6	C_2H_6
FLOW (KG/HR)	268	268	268	256.3	256.3	872	872	872	872	872	872	872
QUALITY	1.0	1.0	0.39	0.01	0.20	1.0	1.0	1.0	1.0	1.01	1.01	0.141
PRESS (ATM)	24.76	24.76	2.165	0.141	0.141	0.141	1.170	6.89	6.80	18.6	13.6	0.141
TEMP (K)	222	172	125	169	169	169	227	218.8	250	283	250	169

Figure 7



Hydrogen Loop
1
Jerald N. Linsley
July 26, 1988
HX1
JT1
VE1
PU1
CM1
CM2
TYP
GH2 Boil-off Manifold
LH2 Manifold
S
S
S
S
1
2
3
4
5
6
7
8
9
10

Figure 8

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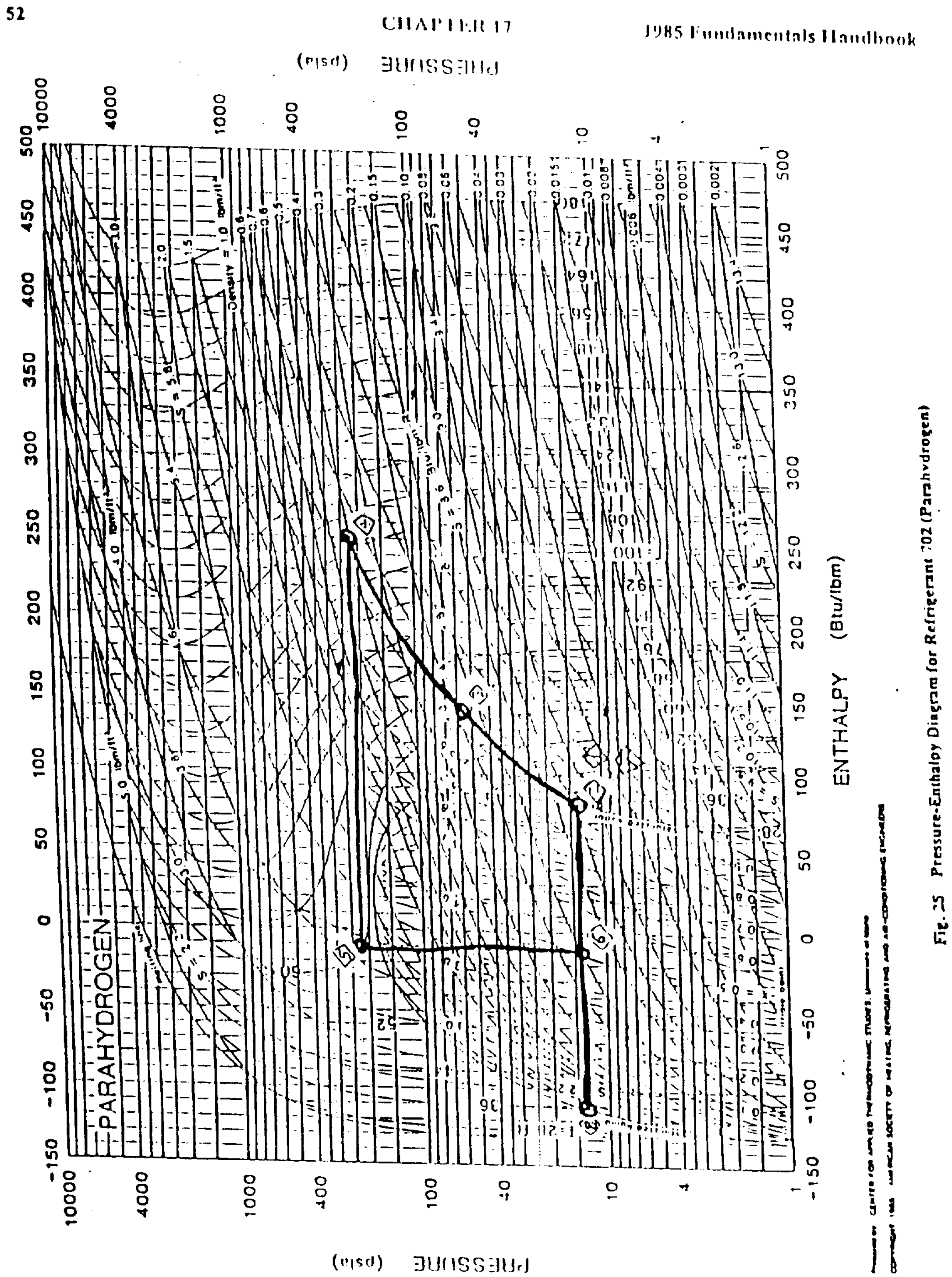

Figure 9

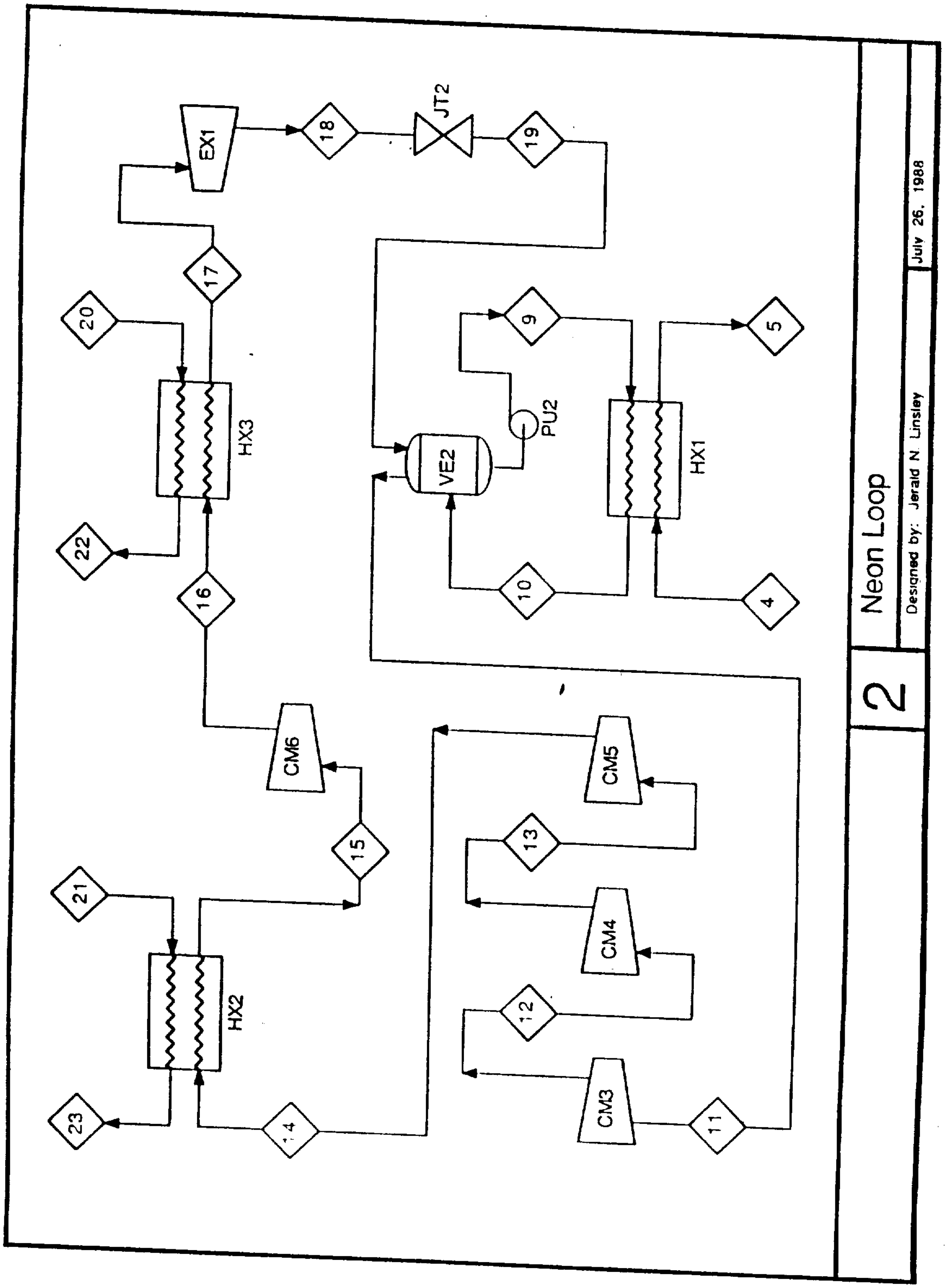
Neon Loop
Designed by: Jerald N Linsley
July 26, 1988
2
EX1
JT2
HX1
HX2
HX3
VE2
PU2
CM3
CM4
CM5
CM6
4
5
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23

Figure 10

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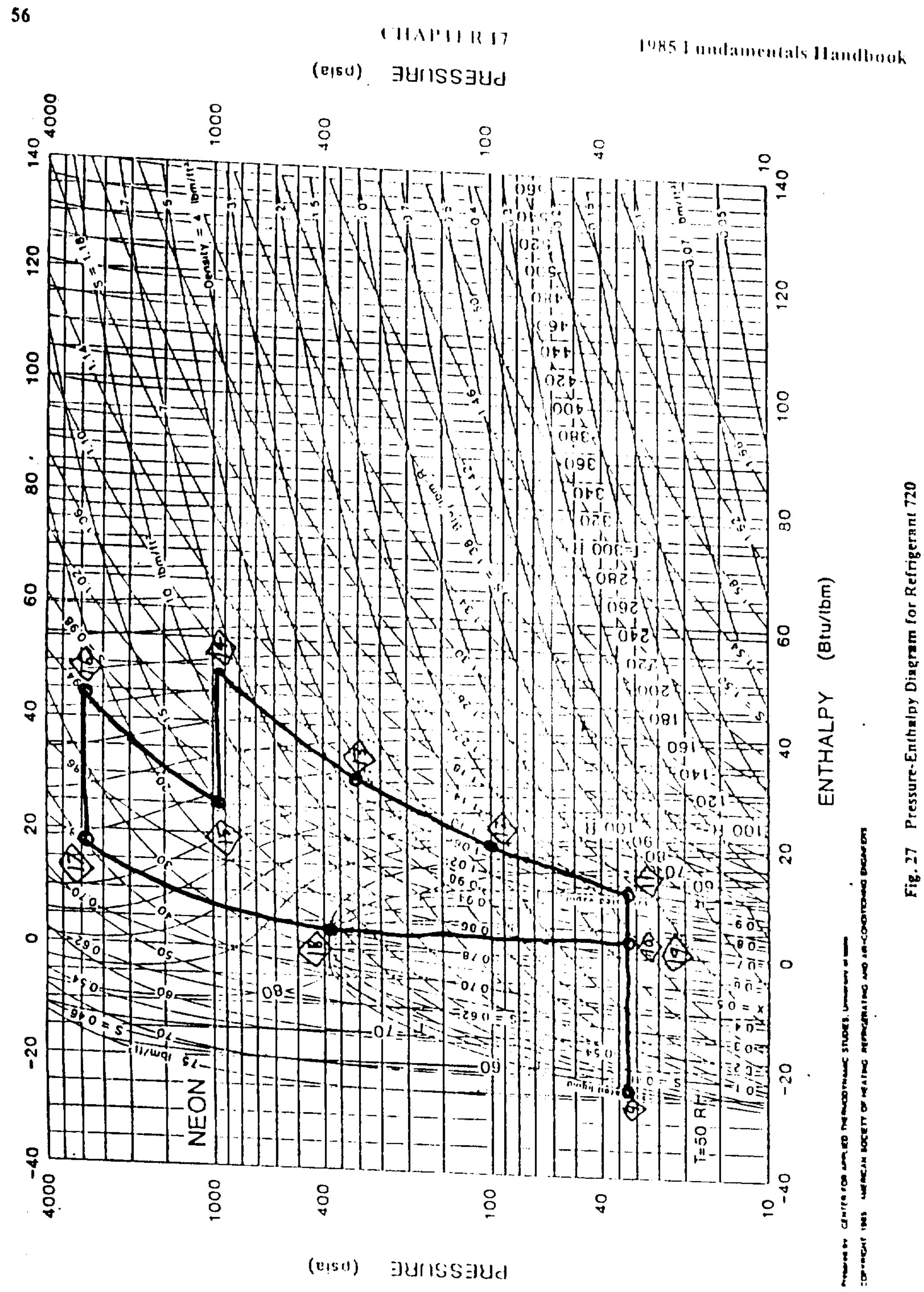
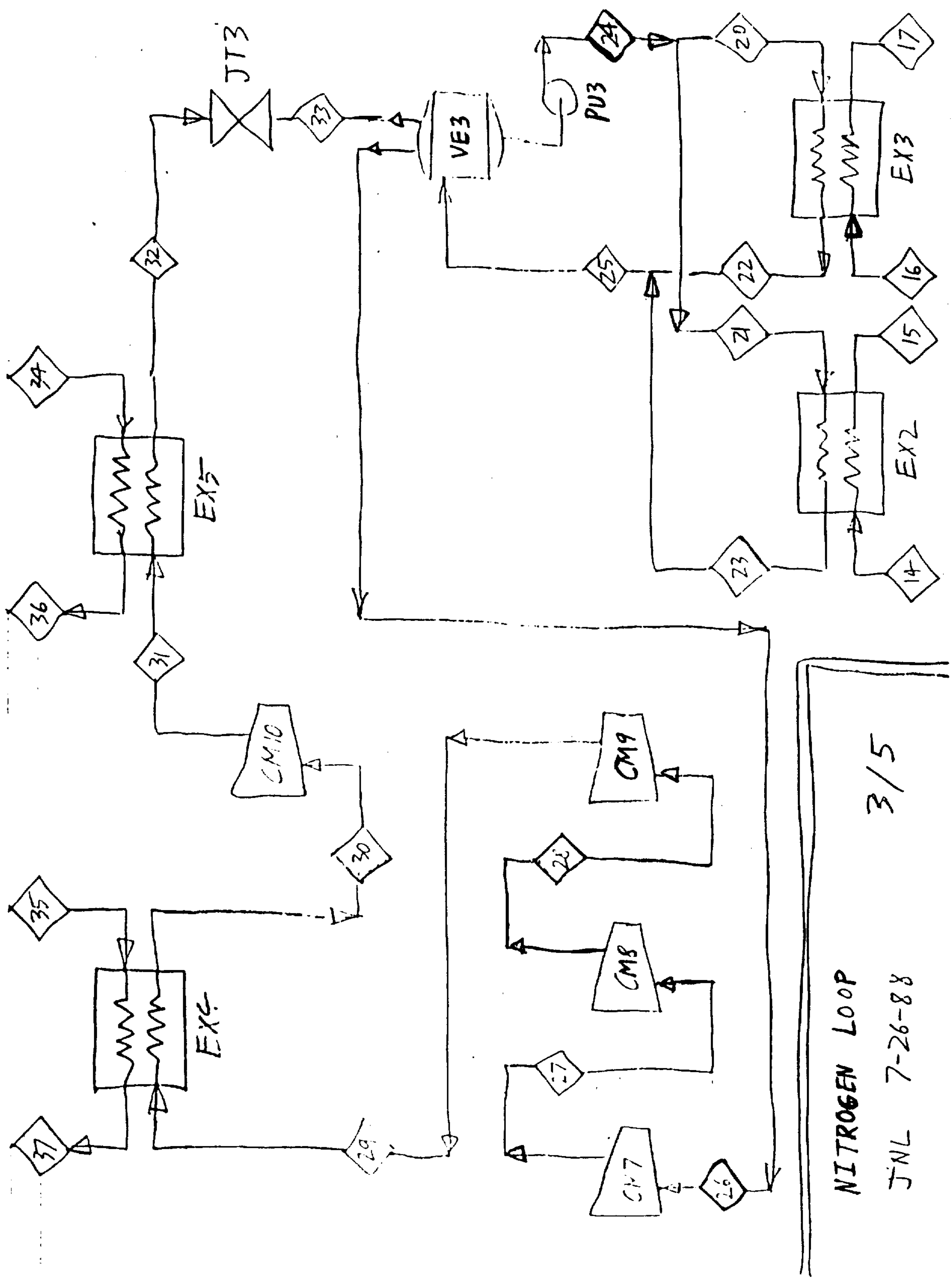


Figure 11



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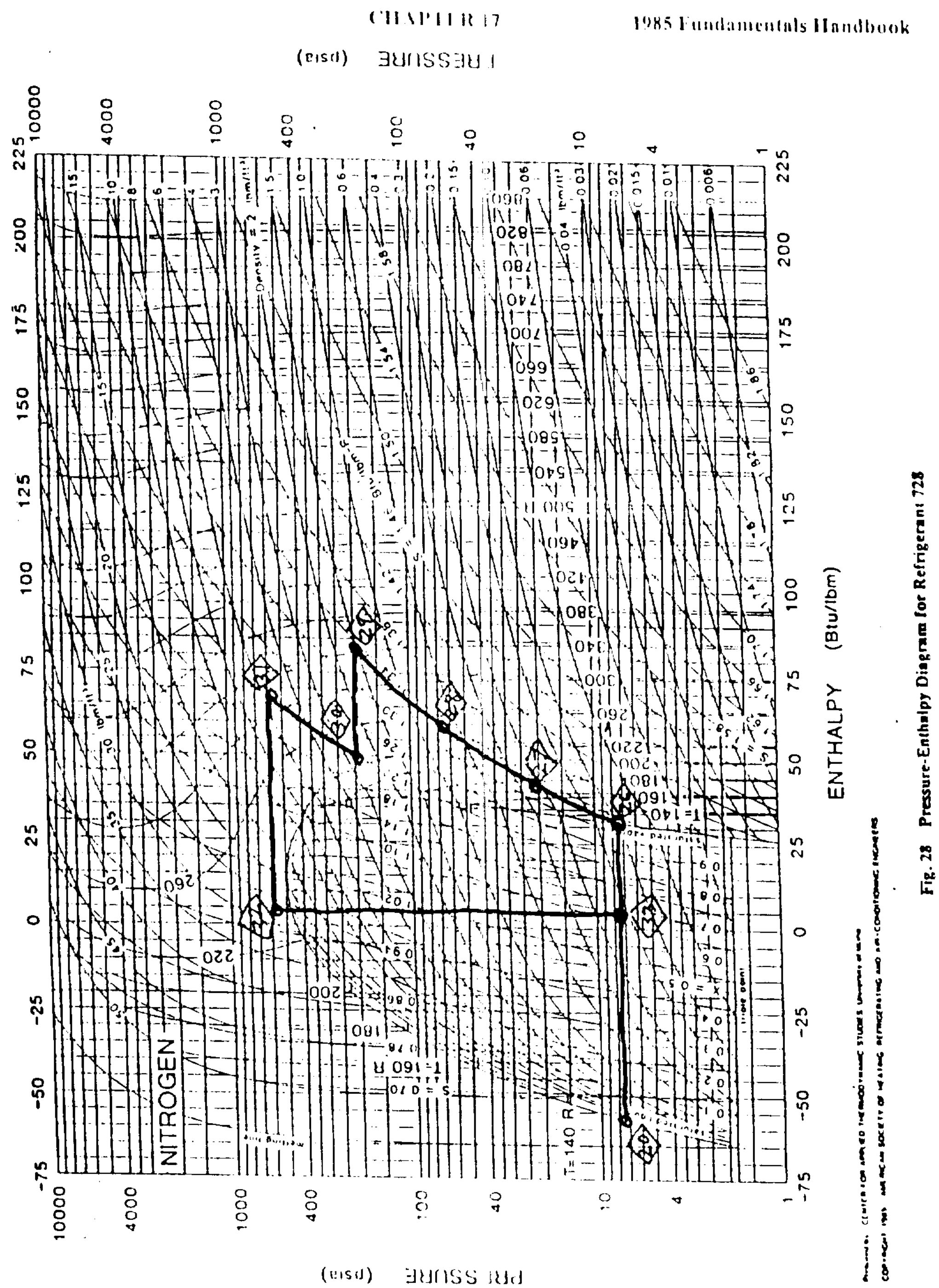

Figure 13

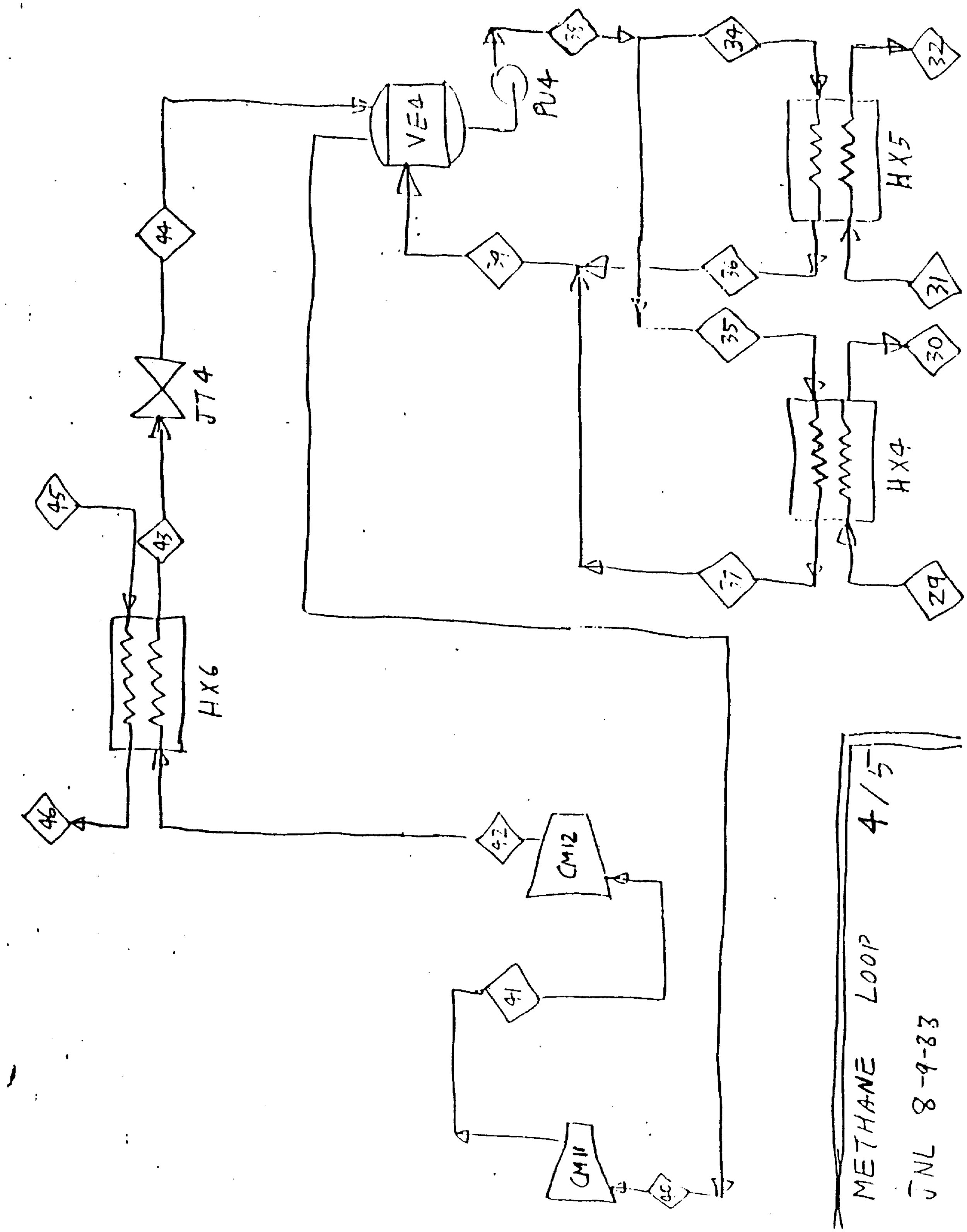

Figure 14

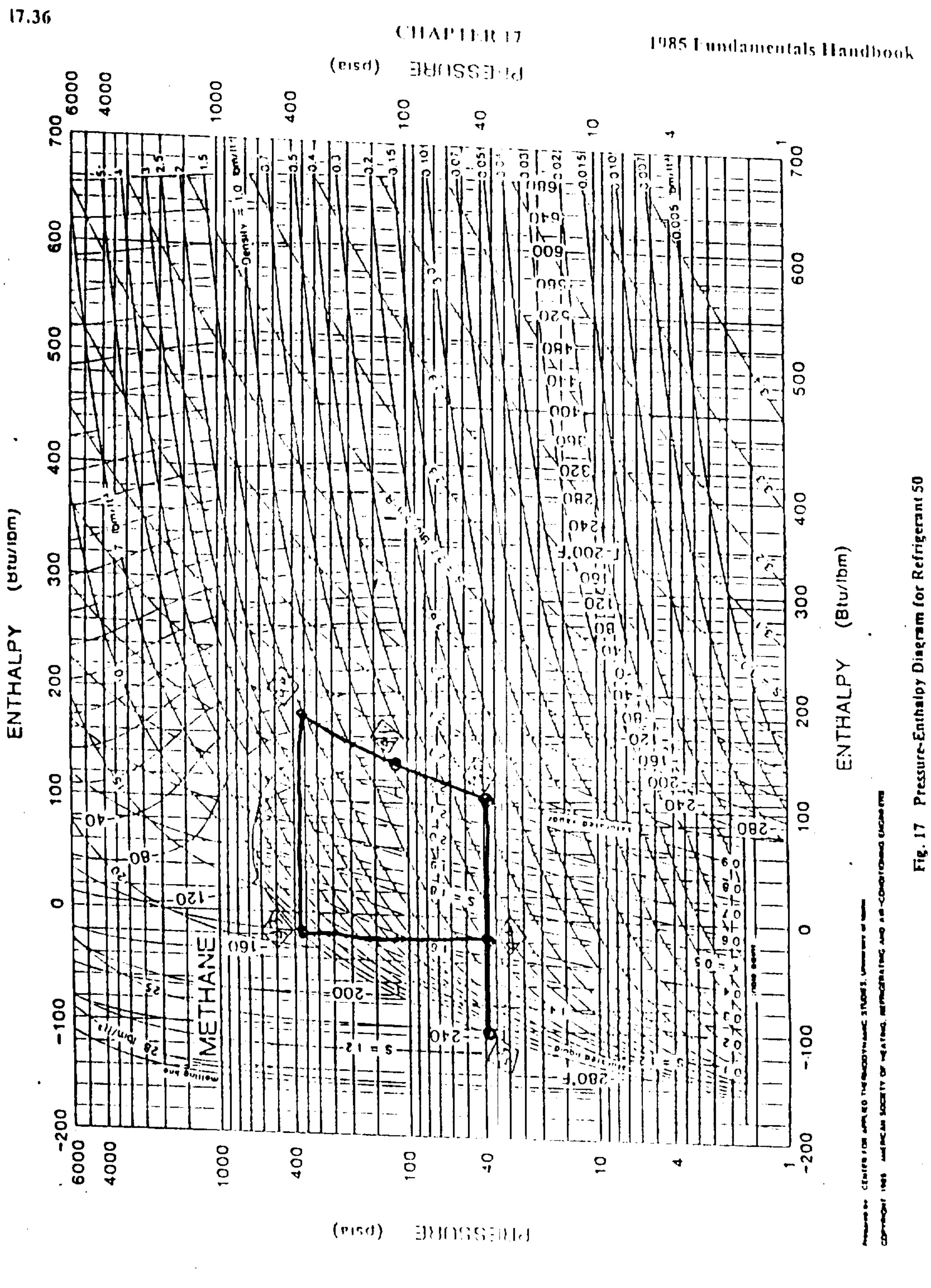
17.36
CHAPTER 17
1985 Fundamentals Handbook
PRESSURE (psia)
ENTHALPY (Btu/lbm)
METHANE
Fig. 17 Pressure-Enthalpy Diagram for Refrigerant 50

Figure 15

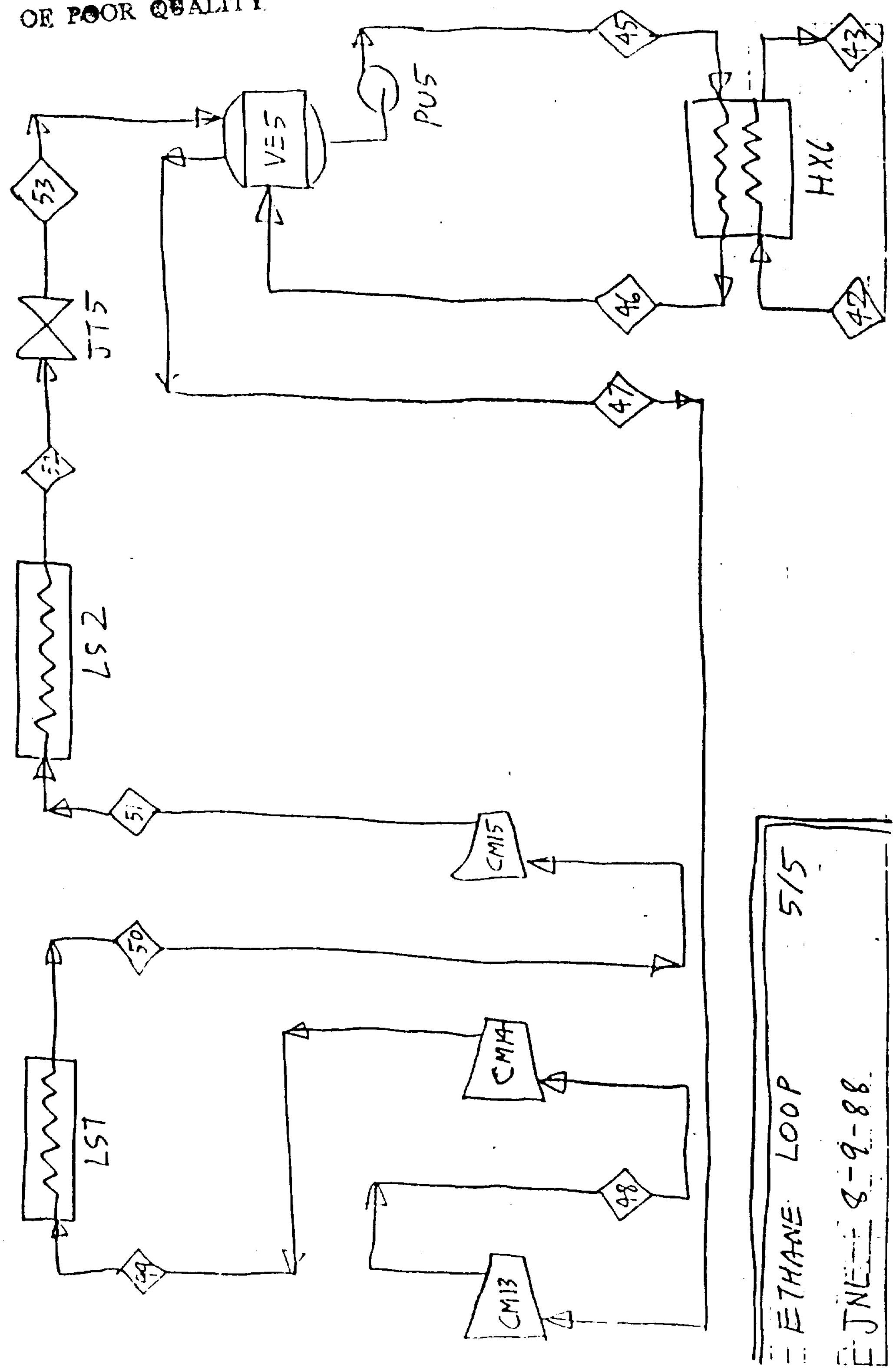
VES
PUS
HX6
JT5
LS2
LS1
CM15
CM14
CM13
53
45
43
46
42
47
51
50
48
ETHANE LOOP 5/5
9-9-88

Figure 16

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.38 CHAPTER 17 1985 Fundamentals Handbook

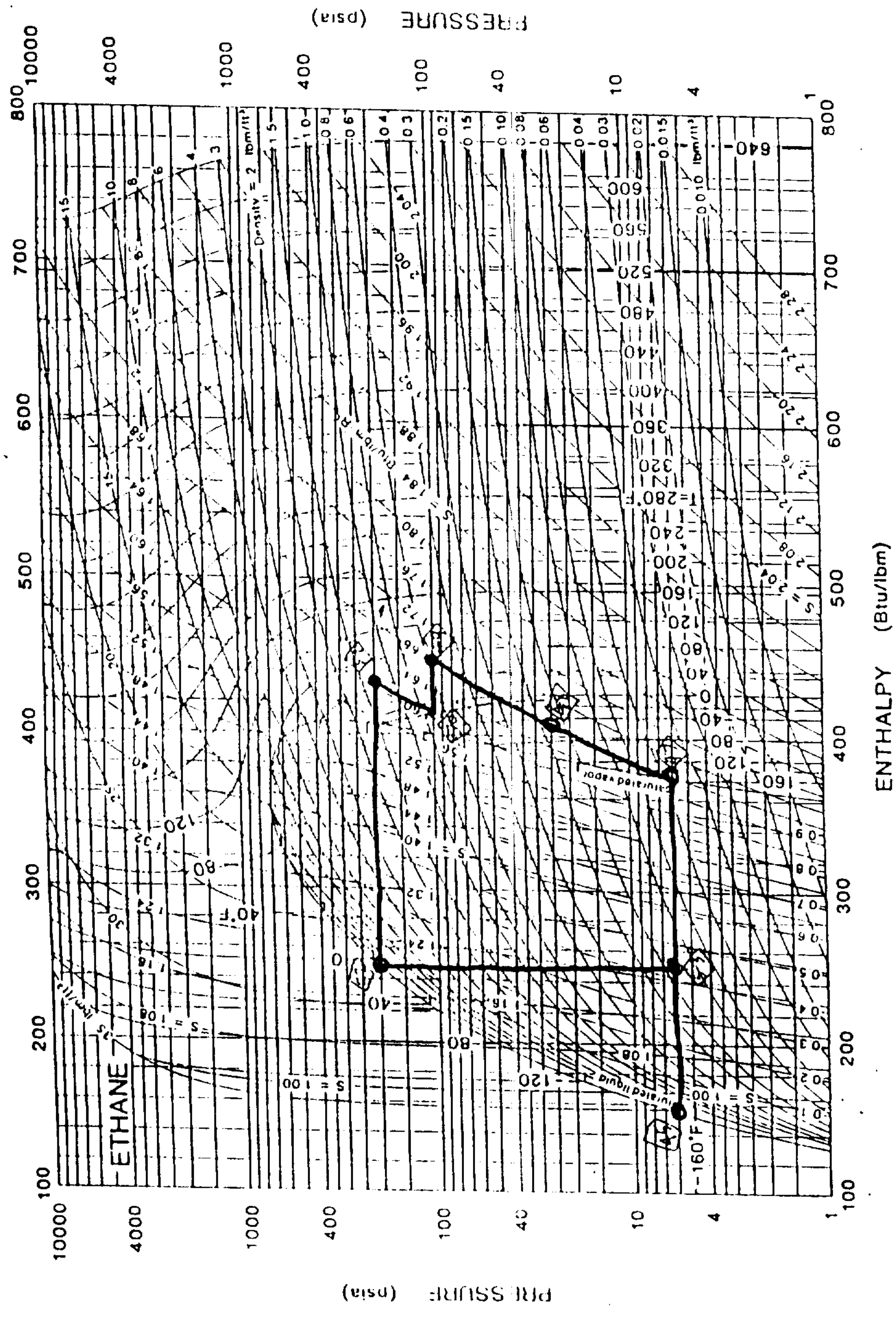

Fig. 18 Pressure-Enthalpy Diagram for Refrigerant 170

Figure 17

BY JNL DATE 8-19-88 SUBJECT CASCADE REFRIGERATION SYSTEM SHEET NO 1 OF 2
CHKD BY ____ DATE ____ JOB NO ____

EQUIPMENT LIST

TAG No.	NAME	REMARKS
	COMPRESSORS AND EXPANDERS	
CM1	HYDROGEN STAGE 1	
CM2	HYDROGEN STAGE 2	
CM3	NEON STAGE 1	
CM4	NEON STAGE 2	
CM5	NEON STAGE 3	
CM6	NEON STAGE 4	
EX 1	NEON EXPANDER	
CM7	NITROGEN STAGE 1	
CM8	NITROGEN STAGE 2	
CM9	NITROGEN STAGE 3	
CM10	NITROGEN STAGE 4	
CM 11	METHANE STAGE 1	
CM 12	METHANE STAGE 2	
CM 13	ETHANE STAGE 1	
CM 14	ETHANE STAGE 2	
CM 15	ETHANE STAGE 3	
	PUMPS	
PU1	HYDROGEN PUMP	
PU2	NEON PUMP	
PU3	NITROGEN PUMP	
PU4	METHANE PUMP	
PU5	ETHANE PUMP	

BY JNL DATE 8-19-88 SUBJECT ____ SHEET NO 2 OF 2
CHKD BY ____ DATE ____ JOB NO ____

TAG NO.	NAME	REMARKS
	VESSELS	
VE1	HYDROGEN FLASH	
VE2	NEON FLASH	
VE3	NITROGEN FLASH	
VE4	METHANE FLASH	
VE5	ETHANE FLASH	
	HEAT EXCHANGERS	
HX1	HYDROGEN COOLER	
HX2	NEON COOLER 1	
HX3	NEON COOLER 2	
HX4	NITROGEN COOLER 1	
HX5	NITROGEN COOLER 2	
HX6	METHANE COOLER 1	
LS1	ETHANE COOLER 1	
LS2	ETHANE COOLER 2	
	VALVES	
JT1	HYDROGEN EXPANSION	
JT2	NEON EXPANSION	
JT3	NITROGEN EXPANSION	
JT4	METHANE EXPANSION	
JT5	ETHANE EXPANSION	

Figure 18

Figure 19

SUMMARY TABLE

LOOP	REJECTED HEAT (kJ/hr)	Compression Work (kW)	(hp)	Vessel Volume (l)
Hydrogen	1767	0.22	0.30	4
Neon	10166	2.8	3.8	30
Nitrogen	16160	3.2	4.3	100
Methane	53600	5.4	7.3	600
Ethane	88900	9.9	13.3	1600
			29.0	

Neon Expander: 0.81 kW or 1.1 hp