

# Oxygen Liquefaction and Storage System for a Lunar Oxygen Production Plant

Eric B. Jenson\*  
*Pacer Works, Ltd, Atlanta, Georgia*

Jerald N. Linsley†  
*Florida Institute of Technology, Melbourne, Florida*

## Abstract

Lunar resource utilization is critical to the economic realization of future space missions. The extraction of oxygen for space vehicles has been given top priority. Recent emphasis has been placed on a process to extract oxygen from lunar ilmenite by reduction with hydrogen. Results from previous studies, based on this process, are used as a baseline for the development of an Oxygen Liquefaction and Storage System. The system encompasses the following tasks: liquefaction of effluent oxygen from the hydrogen reduction reactor, transportation of cryogenic oxygen, and storage of cryogenic oxygen. A baseline system design is presented that requires approximately 8.1 kW to liquefy 200 metric tons/year oxygen. Waste heat from the process is rejected to the lunar regolith by radiation and conduction. The work presented herein represents the current state of an ongoing research and design effort.

## Introduction

Lunar resource utilization is envisioned to be critical to the economic realization of future space missions. NASA has specified a list of priorities for lunar resource utilization<sup>1</sup>. The extraction of propellants for space vehicles has been given top priority. Here, propellants refer to liquid hydrogen and liquid oxygen. While there is relatively little hydrogen (or water) on the moon, there is approximately 40% by weight oxygen in the form of metal oxides of aluminum, iron, titanium, and silicon. A variety of methods have been, or are currently being, studied to extract oxygen from the lunar regolith, some are: hydrogen reduction of ilmenite ( $\text{FeTiO}_3$ ), electrolysis of melted magma, and high temperature separation. Recent emphasis has been placed on the hydrogen reduction of ilmenite process. Therefore, this process is considered here.

The hydrogen reduction of ilmenite process can be broken down into five major processing steps, they are<sup>2,3</sup>:

- 1.) Surface Mining
- 2.) Beneficiation
- 3.)  $\text{H}_2$  Reduction & Electrolysis
- 4.) Cooling and Liquefaction
- 5.) Transportation and Storage

Some work has been completed on the  $\text{H}_2$  Reduction and Electrolysis step<sup>2-5</sup>. In this work, we investigate the Cooling and Liquefaction and Transportation and Storage steps. The following three tasks are identified:

- 1.) Liquefaction of Effluent Oxygen from the Hydrogen Reduction Reactor
- 2.) Transportation of Cryogenic Oxygen
- 3.) Storage of Cryogenic Oxygen

A block diagram for the Oxygen Liquefaction and Storage System is given in Figure 1. The dashed line represents the boundary of the system. Anything outside the boundary is considered to be beyond the scope of this design. Blocks that are on the boundary of the system (crossed by the dashed line) are considered to have a significant impact upon the design of those items within the boundary, and in general represent an interface to another major processing step of the lunar oxygen production plant. The design and specification of these blocks will require a joint effort between the design teams responsible for the processes on both sides of the interface. The vacuum, 1/6 gravity, high radiation, and thermal (diurnal temperature variation of  $-180^\circ\text{C}$  to  $+100^\circ\text{C}$ ) environment found on the moon requires significant innovation in most all aspects of lunar engineering.

Some work on lunar cryogenic systems has been done by NASA, contractors, and others in the 1960's<sup>6-8</sup>. The majority of this work was completed prior to the Apollo 11 lunar landing and was not subject to the data that is available today. This work is being reviewed and re-evaluated taking into account improved lunar surface data, technology advances, and current space systems configurations.

## System Design

To obtain an adequate design, we begin by studying the lunar base system as a whole. Since the majority of the oxygen produced will be used as an oxidizer for space vehicles, an understanding of lunar landing and launch operations is required. Preliminary designs of hydrogen and oxygen storage systems for a lunar landing and launch facility have been completed<sup>9,10</sup>. These designs use a cascade refrigeration scheme to condense oxygen boil-off. In this work, a similar cascade configuration is used. Also, identical oxygen storage tanks with a capacity of 6360 kg and an operational pressure of 1 atm are used. These storage tanks are the oxygen fuel tanks from the lunar lander. Once a tank has been filled at the lunar oxygen plant, it is removed and replaced with an empty or partially empty tank. The full tank is then stored on the lunar surface in a thermally controlled environment with active cooling until needed for launch.

\*Director of Chemical Engineering

†Associate Professor, Chemical and Environmental Engineering

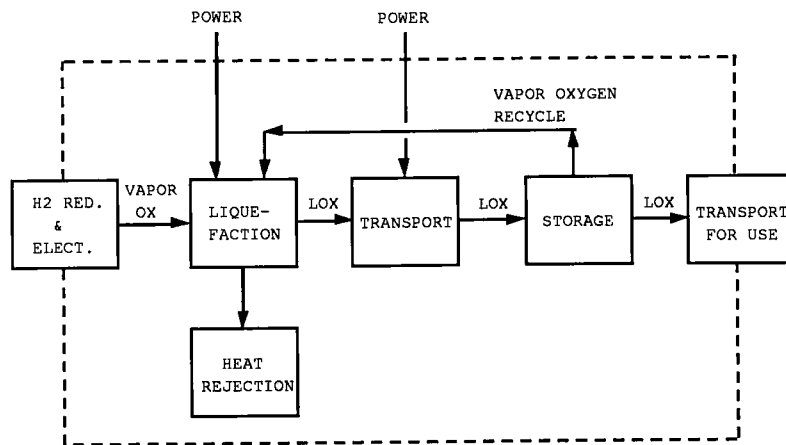


Fig. 1 Oxygen Liquefaction and Storage System Block Diagram

In general, cryogenic liquids are stored at their saturation temperatures at relatively low pressures. This results in relatively low, cryogenic storage temperatures. Therefore, cryogenic storage systems are highly insulated and the major design concern 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 in this paper. However, some comments in regard to the insulation and structural design should be made. 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. Structural members (tension rods) are also in this space. The insulation is designed to protect against heat leaks from both conductive and radiative heat transfer. Unless these vessels will also be used to store cryogenes terrestrially, a vacuum jacket will not be required for cryogenic storage vessels on the moon since they will already be in a vacuum. However, we envision that the storage vessels will at some time be used to store cryogenes terrestrially. Therefore, the storage vessels must be designed to withstand both terrestrial and lunar thermal conditions as well as the stresses of earth launch.

The liquefaction and storage system is designed for an oxygen production rate of 200 metric tons/year (25.3 kg/hr). This is one fifth of the amount envisioned to support a fully operational lunar base and other activities in earth orbit and beyond. Because space systems, in general, must exhibit high operational reliability, five identical modular units will operate in parallel. Thus, greatly increasing the overall reliability of the process. In the event of a malfunction the worst case scenario will be an incremental decrease in productivity. A modular systems design in which subsystems are designed for ease of replacement is recommended.

Power will be required to liquefy oxygen. The liquefaction and storage system is designed for continuous operation, i.e., 24 hours/day, 330 days/year. Assuming that the oxygen plant is constructed at or near the equator of the moon, an energy storage system will be required if solar energy is used. This system must store the energy required for the lengthy 14 day lunar night. Nuclear energy will not require this storage capability and is preferred for continuous plant operation.

An aspect of practically all chemical processes is the removal of waste heat. Terrestrial chemical processing plants typically rely on convection to air (cooling towers). The complexity of this task is greatly increased on the lunar surface due to the lack of an atmosphere and fluids. For space applications, heat removal is generally facilitated by radiating into deep space. This poses a problem in that the efficiency is decreased when the radiator is facing the sun. It was desired that the liquefaction and storage system be designed to remove waste heat without relying on the position of the sun. The proposed mechanism is to use the lunar regolith which has a relatively constant temperature of 240 K at a depth of approximately 0.3 m<sup>11</sup>. For large temperature differences, greater than 250 K, heat will be transferred to the regolith by radiation. For temperature differences less than 250 K heat will be transferred to the regolith by conduction. Conduction will be achieved by transferring the process heat to a cooling fluid which in turn flows through a coil that is buried approximately one meter below the lunar surface. Thus, the regolith acts as the lunar equivalent of the standard cooling tower used in terrestrial processing plants. As for terrestrial plants, the heat removal system is considered a utility and is not included on the process flow diagram.

We begin the analysis by specifying the input and output to the process.

#### Input

The input (or feed) to our process will be the effluent oxygen stream from the H<sub>2</sub> Reduction and Electrolysis step of the lunar oxygen process. This stream will consist of gaseous oxygen at a flow rate of 25.3 kg/hr (T = 1273 K, P = 10 atm) for a 200 metric tons oxygen/year plant. Although this preliminary design assumes the oxygen is pure, the existence of impurities is being investigated. Other inputs to our system will be electric power and, obviously, heat from the surrounding environment.

#### Output

The output from our system will be liquid oxygen at a rate of 25.3 kg/hr (T = 90 K, P = 1 atm) to be used primarily as a propellant for space vehicles. Also, waste heat will result from cooling and liquefaction operations.

For the baseline design we use a cascade liquefaction system with two additional refrigeration loops (methane and ethane). A cascade system was chosen because it enabled the reduction of pressure in the oxygen stream by a factor of ten or more. All refrigerations are based on a Linde-Hampson liquefaction scheme, in which the gas is compressed isentropically, cooled isobarically, and expanded isenthalpically (Joule-Thompson) to give a resulting quality between zero and one<sup>12</sup>. The quality is defined as the fraction of the total fluid that is in the vapor phase. The saturated liquid is pumped to a heat exchanger to perform the isobaric cooling of the previous loop where it exits as a vapor-liquid mixture, at the same pressure. The vapor portion of this stream is combined with the vapor resulting from the expansion and is recycled back to the compressor train. In the case of oxygen, the resulting liquid is transferred to a storage tank and the vapor is recycled and mixed with the precooled feed (stream 3). A process flow diagram, stream table, and equipment table for the Oxygen Liquefaction and Storage System are given in Figures 2-4, respectively.

The first step in the process is to cool the oxygen from the feed temperature of 1273 K (stream 1) to a temperature that is low enough to further cool with the utility coolant. This is accomplished by radiating the heat to the lunar surface, thus decreasing the stream temperature to 500 K (stream 2). The radiator (RA-1) will be inverted with respect to a standard radiator and will radiate to the surface instead of deep space. The advantage gained in doing this is a more consistent operating environment independent of the diurnal cycle.

The next step in the process is to further cool the oxygen against the utility coolant. The oxygen is cooled to 255 K (stream 3) on the hot side of a heat exchanger (CL-1). It is desirable to decrease the temperature of the oxygen stream as low as possible prior to compression because the work required for compression is directly proportional to the input temperature. Stream 3 is then blended with the recycle vapor (stream 14). Stream 14 results from blending the vapor stream from the Joule-Thompson expansion (stream 9) and boil-off (stream 11) from the oxygen storage vessel (STV) and isentropically compressing the gas from 1 atm to 10 atm in two stages (CM-2 & CM-3). Streams 3 and 14 are blended to form stream 4 with a resulting temperature of 225 K. This stream is then cooled against methane on the hot side of a heat exchanger (HX-1) to a temperature of 130 K. The oxygen is compressed isentropically (CM-1) to 20 atm and 161 K (stream 6), and then cooled against methane on the hot side of a heat exchanger (HX-2) to a temperature of 130 K (stream 7). Stream 7 is then expanded isenthalpically to 1.0 atm. This results in a temperature of 90 K and a quality of 0.35 (stream 8). The liquid and vapor portions of stream 8 are separated in the oxygen flash vessel (VE-1). The liquid (stream 10) is pumped (PU-1) to an oxygen storage vessel and the vapor (stream 9) is recycled. The boil-off from the storage vessel (stream 11) is estimated to be 1 kg/hr.

Liquid methane at 3.0 atm and 125 K is pumped (stream 19) from the methane flash vessel (VE-2) to a splitter where the liquid is divided (streams 15 and 17) and fed to the cold sides of heat exchangers HX-1 and HX-2, respectively. Cooling of oxygen in these exchangers results in partially vaporizing the methane. The methane exits the exchangers (streams 16 and 18) with a quality of 0.10 at 3.0 atm and 125 K. Streams 16 and 18 are blended and returned to the

methane flash vessel (stream 20). The vapor from the methane flash vessel is fed to the suction of the methane compressor train (CM-4 and CM-5) which eventually elevates the methane to a pressure of 27 atm and a temperature of 230 K. The compressed methane is condensed isobarically to saturated liquid at 175 K on the hot side of a heat exchanger (HX-3) by ethane at 170 K on the cold side of this exchanger. The resulting condensed methane (stream 24) is expanded isenthalpically to a pressure of 3.0 atm. This results in a temperature of 125 K and a quality of 0.42 (stream 25). The methane is then fed to the methane flash vessel where the liquid and vapor portions are separated.

Liquid ethane at 0.4 atm and 170 K is pumped (stream 26) from the ethane flash vessel (VE-3) through the cold side of heat exchanger HX-3 where the condensing of methane on the hot side partially vaporizes the ethane. The ethane exits the exchanger (stream 27) with a quality of 0.10 at 0.4 atm and 170 K, and is returned to the ethane flash vessel. The vapor from the flash vessel is fed to the suction of the ethane compressor train (CM-6, CM-7, and CM-8) which eventually elevates the methane to a pressure of 25.6 atm and a temperature of 360 K. The compressed ethane is condensed isobarically to sub-cooled liquid at 255 K on the hot side of a heat exchanger (CL-2) by coolant on the cold side of the exchanger. The coolant has input and output temperatures of 250 K and 280 K, respectively. The minimum temperature approach over the entire heat exchanger is set at 5 K. The resulting condensed ethane (stream 32) is expanded isenthalpically to a pressure of 0.4 atm. This results in a temperature of 170 K and a quality of 0.45 (stream 33). The ethane is then fed to the ethane flash vessel where the liquid and vapor portions are separated.

The utility flow sheet, stream table, and equipment list for the Oxygen Liquefaction and Storage System are given in Figure 5. A liquid phase ethylene glycol/water coolant with a working temperature range of 213 K to 523 K and a specific heat of 3.3 kJ/kg·°C at 269 K is used. The coolant is pumped (PU-4) from a holding tank to a regolith exchanger (LR-1) where it rejects heat to the 240 K lunar subsurface by conduction. The regolith exchanger is envisioned to be a coil or a set of parallel pipes buried approximately one meter below the lunar surface. We assume a minimum temperature approach of 10 K at the outlet of the exchanger; i.e., the temperature of the coolant leaving the exchanger (stream U1) is 250 K. We chose a coolant temperature rise of 30 K. This gives a coolant input temperature of 280 K. Knowing the amount of heat that must be removed from the liquefaction process, we calculate the coolant flow rate to be 444 kg/hr. Upon exiting the regolith exchanger, stream U1 is split to form streams U2 and U4. Streams U2 and U4 flow on the cold sides of heat exchangers CL-1 and CL-2, respectively. The flow rates are adjusted so that the outlet temperatures from the heat exchangers are 280 K (streams U3 and U5). Streams U3 and U5 are then blended (stream U6) and returned to the holding tank. Cavitation in the pump (PU-4) is avoided by keeping a minimum operating pressure of 3 atm, which is above the vapor pressure of the coolant at the highest temperature. The utility coolant could also be used to regulate the temperature of electric motors and other equipment by circulating the coolant through specially designed equipment.

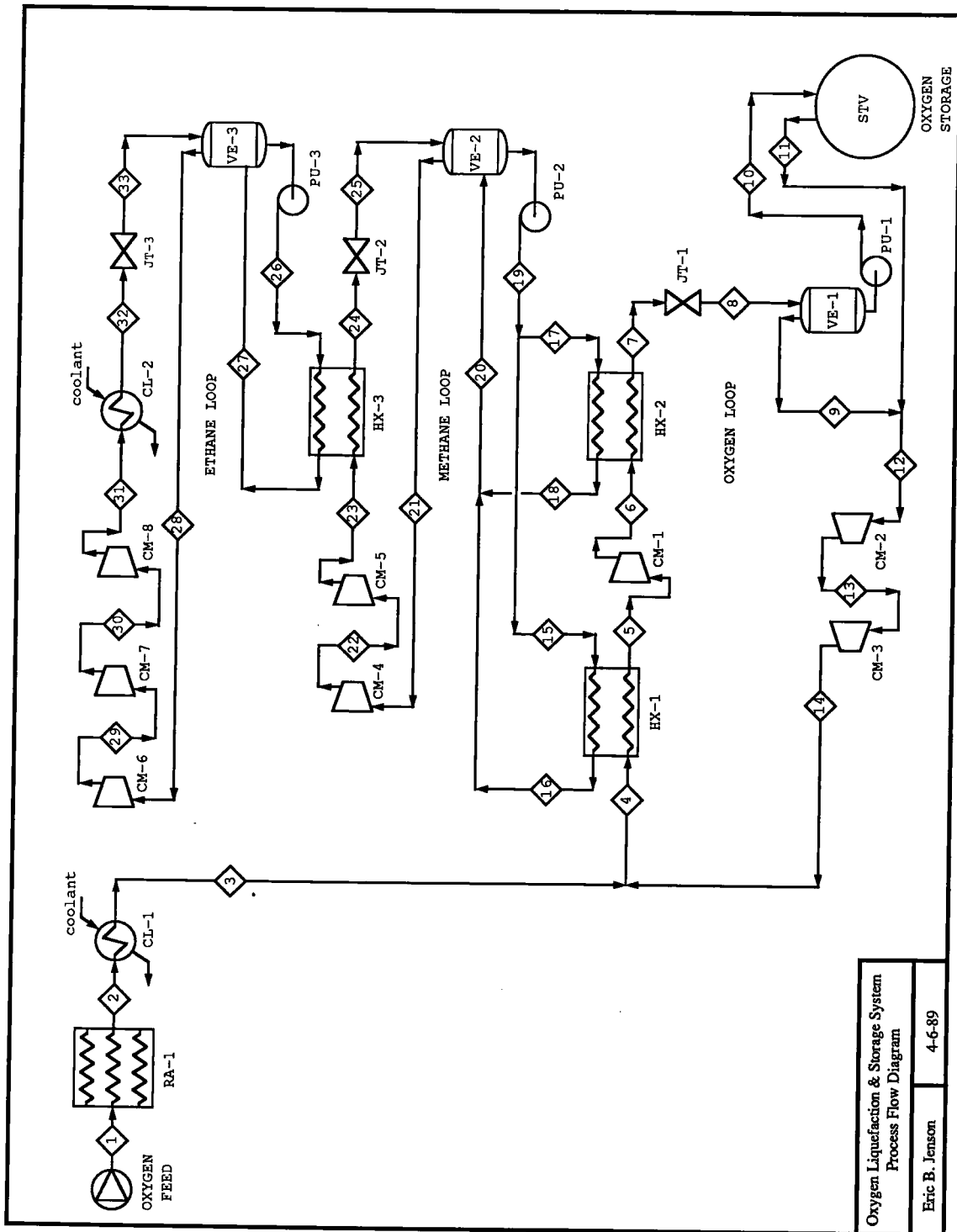
### Future Development

The work presented in this paper represents a baseline design of an Oxygen Liquefaction and Storage System for a lunar oxygen production plant. This design has not undergone extensive optimization. Calculations were performed using Pressure-Enthalpy diagrams for oxygen, methane, and ethane, respectively<sup>13</sup>. Future development will include but is not limited to the following: transfer the calculations to one of the major process simulators, design of equipment, design of process control systems, design overall system configuration emphasizing construction/start-up requirements, optimize to decrease power requirements, mass, and manpower/maintenance requirements, prototyping and testing, and manufacture and delivery of flight hardware.

Near term goals are to obtain equipment designs for the oxygen radiator (RA-1) and the regolith exchanger (LS-1).

### References

- <sup>1</sup>McKay, D.S., "Current Status of Technology to Extract Useful Materials from Lunar and Martian Resources", *Local Section of the AIAA - 13th Annual Technical Symposium*, Houston, Texas, May 11, 1988.
- <sup>2</sup>Christiansen, E.L. and Simonds, C.H., "Conceptual Design of a Lunar Oxygen Pilot Plant", *Symposium on Lunar Bases and Space Activities of the 21st Century*, Paper No. LBS-88-200, Houston, Texas, April 5-7, 1988.
- <sup>3</sup>Eagle Engineering, Inc., *Conceptual Design of a Lunar Oxygen Pilot Plant*, NASA Contract: NAS9-17878, July, 1988.
- <sup>4</sup>Gibson, M.A. and Knudsen, C.W., "Lunar Oxygen Production from Ilmenite", *Symposium on Lunar Bases and Space Activities of the 21st Century*, Paper No. LBS-88-056, Houston, Texas, April 5-7, 1988.
- <sup>5</sup>Briggs, R.A. and Sacco, A., "Oxidation and Reduction of Ilmenite: Application to Oxygen Production on the Moon", *Symposium on Lunar Bases and Space Activities of the 21st Century*, Paper No. LBS-88-170, Houston, Texas, April 5-7, 1988.
- <sup>6</sup>Romero, J.B., Smith, D.W., and Dod, R.E., "Thermal Analysis and Optimization of Cryogenic Tanks for Lunar Storage", *Advances in Cryogenic Engineering: Volume II*, K.D. Timmerhaus (Ed.), Plenum Press, New York, New York, 1965.
- <sup>7</sup>Sedgwick, T.A. and Middleton, R.L., "Extraterrestrial Cryogenic Propellants Reliquefaction", *Advances in Cryogenic Engineering: Volume II*, K.D. Timmerhaus (Ed.), Plenum Press, New York, New York, 1965.
- <sup>8</sup>Glasser, P.E., *Study of Cryogenic Storage on the Moon*, Arthur D. Little, Inc., NASA Contract: NAS8-11377, December, 1965.
- <sup>9</sup>Linsley, J.N., "Studies of Cryogenic Propellant Storage and Handling for the Lunar Landing and Launch Facility (Complex 39L)", Final Report for NASA/ASEE Summer Faculty Research Fellowship Program, Kennedy Space Center, August, 1988.
- <sup>10</sup>Linsley, J., Lind, D., and Altringer, B., "The Design of a Cryogenic Propellant Boil-off Recovery System for the Lunar Landing and Launch Facility (Complex 39L)", Paper 92f, *AIChE Spring National Meeting*, Houston, Texas, April 5, 1989.
- <sup>11</sup>Kopal, Z., *An Introduction to the Study of the Moon*, Gordon and Breach Science Publishers, New York, 1966.
- <sup>12</sup>Barron, R.F., *Cryogenic Systems*, Oxford University Press, New York, 1985.
- <sup>13</sup>*ASHRAE Handbook - 1985 Fundamentals*, SI Edition, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 1985.



Oxygen Liquefaction & Storage System  
Process Flow Diagram

Eric B. Jenson 4-6-89

Fig. 2 Oxygen Liquefaction and Storage System  
Process Flow Diagram

STREAM	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Fluid	O2	O2	O2	O2	O2	O2	O2	O2	O2	O2	O2	O2	O2	O2	CH4
Flow (kg/hr)	25.3	25.3	25.3	40.5	40.5	40.5	40.5	40.5	14.2	26.3	1.0	15.2	15.2	15.2	79
Quality	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.35	1.0	0.0	1.0	1.0	1.0	1.0	0.0
Temperature (K)	1273	500	255	225	130	161	130	90	90	90	90	90	123	175	125
Pressure (atm)	10	10	10	10	10	20	20	1.0	1.0	1.0	1.0	1.0	3.0	10	3.0

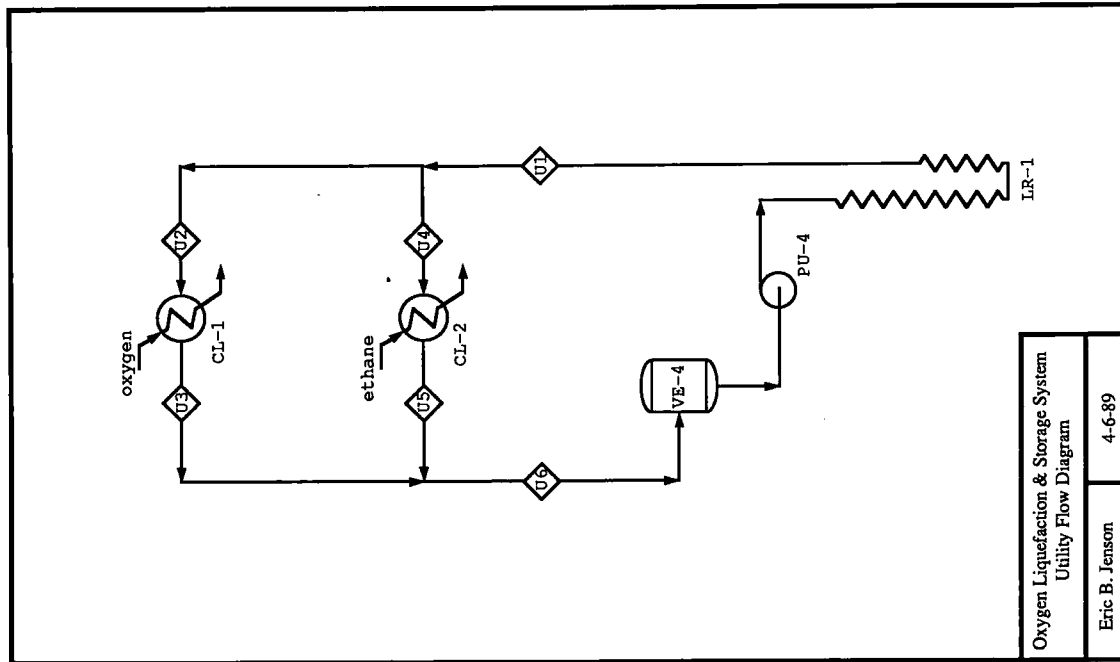
STREAM	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Fluid	CH4	CH4	CH4	CH4	CH4	CH4	CH4	CH4	CH4	CH4	C2H6	C2H6	C2H6	C2H6	C2H6
Flow (kg/hr)	79	162	162	24.1	24.1	41.6	41.6	41.6	41.6	41.6	383	383	69.6	69.6	69.6
Quality	0.10	0.0	0.10	0.0	0.10	1.0	1.0	1.0	0.0	0.42	0.0	0.10	1.0	1.0	1.0
Temperature (K)	125	125	125	125	125	125	172	230	175	125	170	170	170	222	285
Pressure (atm)	3.0	3.0	3.0	3.0	3.0	3.0	9.0	27.0	27.0	3.0	0.4	0.4	0.4	1.6	6.4

STREAM	31	32	33												
Fluid	C2H6	C2H6	C2H6												
Flow (kg/hr)	69.6	69.6	69.6												
Quality	1.0	0.0	0.45												
Temperature (K)	360	255	170												
Pressure (atm)	25.6	25.6	0.4												

Fig. 3 Oxygen Liquefaction and Storage System Process Flow Diagram - Stream Table

COMPRESSORS			HEAT EXCHANGERS		
TAG NO.	NAME	REMARKS	TAG NO.	NAME	REMARKS
CM-1	Oxygen Compressor 1	Work = 259 W	HX-1	Oxygen/Methane Exchanger 1	Duty = 3,770 kJ/hr
CM-2	Oxygen Recycle Compressor 1	Work = 118 W	HX-2	Oxygen/Methane Exchanger 2	Duty = 7,700 kJ/hr
CM-3	Oxygen Recycle Compressor 2	Work = 186 W	HX-3	Methane/Ethane Exchanger	Duty = 19,200 kJ/hr
CM-4	Methane Compressor 1	Work = 924 W	CL-1	Oxygen Cooler	Duty = 5,670 kJ/hr
CM-5	Methane Compressor 2	Work = 1,160 W	CL-2	Ethane Cooler	Duty = 38,300 kJ/hr
CM-6	Ethane Compressor 1	Work = 1,450 W	RA-1	Oxygen Radiator	Duty = 17,700 kJ/hr
CM-7	Ethane Compressor 2	Work = 1,840 W			
CM-8	Ethane Compressor 3	Work = 2,130 W			
		Total = 8,060 W			
PUMPS			VESSELS		
TAG NO.	NAME	REMARKS	TAG NO.	NAME	REMARKS
PU-1	Oxygen Pump		VE-1	Oxygen Flash	
PU-2	Methane Pump		VE-2	Methane Flash	
PU-3	Ethane Pump		VE-3	Ethane Flash	
			STV	Oxygen Storage Vessel	diameter = 2.2 m
VALVES			VALVES		
TAG NO.	NAME	REMARKS	TAG NO.	NAME	REMARKS
JT-1	Oxygen Expansion		JT-1	Oxygen Expansion	
JT-2	Methane Expansion		JT-2	Methane Expansion	
JT-3	Ethane Expansion		JT-3	Ethane Expansion	

Fig. 4 Oxygen Liquefaction and Storage System  
Process Flow Diagram - Equipment List



STREAM	U1	U2	U3	U4	U5	U6
Fluid	Coolant	Coolant	Coolant	Coolant	Coolant	Coolant
Flow (kg/hr)	444	57.0	57.0	387	387	444
Quality	0.0	0.0	0.0	0.0	0.0	0.0
Temperature (K)	250	250	280	250	280	280
Pressure (atm)	4.0	4.0	3.0	4.0	3.0	3.0

HEAT EXCHANGERS		REMARKS
TAG_NO.	NAME	
CL-1	Oxygen Cooler	Duty = 5,670 kJ/hr
CL-2	Ethane Cooler	Duty = 38,300 kJ/hr
LR-1	Regolith Exchanger	Duty = 43,970 kJ/hr
PUMPS		REMARKS
TAG_NO.	NAME	
PU-4	Coolant Pump	
VESSELS		REMARKS
TAG_NO.	NAME	
VE-4	Coolant Holding Tank	

Fig. 5 Oxygen Liquefaction and Storage System Utility Flow Diagram