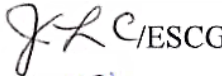**Engineering and Science Contract Group**

2224 Bay Area Boulevard
Houston, Texas 77058

September 23, 2009
ESCG-4470-09-TEAN-DOC-0144

To: M. K. Smith   /NASA

Via: J. L. Cox $\mathcal{JLC}$/ESCG

Reviewed by: A. J. Hanford /AJH/ESCG

From: F. F. Jeng   /ESCG

SUBJECT: Feasibility Analysis of Liquefying Oxygen Generated from Water Electrolysis Units on Lunar Surface

Summary: Concepts for liquefying oxygen (O_2) generated from water electrolysis subsystems on the Lunar surface were explored. Concepts for O_2 liquefaction units capable of generating 1.38 lb/hr (0.63 kg/hr) liquid oxygen (LOX) were developed. Heat and mass balance calculations for the liquefaction concepts were conducted. Stream properties, duties of radiators, heat exchangers and compressors for the selected concepts were calculated and compared.

1.0 Introduction

Oxygen (O_2) supply is essential in future Lunar surface life support systems.   Liquid oxygen (LOX) is one potential oxidant for Lander ascent stage (1) rockets. LOX is projected to be a primary product of Lunar In Situ Resource Utilization (ISRU) system (1). Water will also be generated from ISRU (1). High or moderate pressure O_2 will be generated by a water electrolysis unit using product water from ISRU. High-pressure gaseous oxygen (GOX) can be directly stored for use in Environmental Control and Life Support System and (ECLSS) and ExtraVehicular Activity (EVA), if the GOX pressure is higher than the desirable storage pressures. O_2 at 3,000 psia (20.7 MPa) is now part of the baseline for the Portable Life Support System (PLSS) application (9). GOX generated from ISRU will have to be compressed and stored for filling PLSS O_2 bottles if it is generated at a pressure lower than 3,000 psia (20.7 MPa). Storing GOX between 2,000 and 3,000 psia (13.8 and 20.7 MPa) for use in a regenerative fuel cell power system was suggested for powering the Lunar habitat when Lunar sun light is not available (10).

There are advantages to transferring and storing O_2 in the liquid phase, if GOX could be liquefied at relatively low penalty on the Lunar surface. The density of LOX is much higher than the density of GOX, the storage volume for a fixed mass of LOX will be smaller than the volume for the same mass of GOX. Since the saturated pressure of LOX is low at a cryogenic temperature, the design pressure of storage vessels and therefore the mass of storage vessels could be significantly lower than the mass with high-pressure GOX storage (2). Besides these advantages in storage volume and storage vessel mass, LOX is almost exclusively used as the oxidant in spacecraft engines.

Because of the above reasons, NASA wants to explore the feasibility of liquefying GOX generated from an ISRU water electrolysis unit on the Lunar surface.

1.1 Resources Available for GOX Liquefaction on Lunar Surface
In this study water was assumed as a product of the ISRU Element and GOX will be generated by a water electrolysis system (1). While the operating pressure of the water electrolysis system is not yet determined, an operational pressure range between 200 and 3,000 psia (1.37 and 20.7 MPa) was considered feasible in this analysis.

It was assumed that a GOX liquefaction unit will be located near the ISRU system. Hasan et al. found that temperature around shaded tanks could be between -305 °F (85 K) and -190 °F (150 K). The following cold resource was assumed in this analysis:

Temperature of sinks on the surface: between -305 and -190 °F (85 and 150 K)

1.2 Desirable LOX Generation Rate
A desirable LOX generation rate was estimated based on crew O_2 usage on Small Pressurized Rover (SPR) excursion missions. It was assumed that carrying LOX on SPR excursions is an alternative option in addition to carrying high-pressure GOX. Estimated O_2 usages (8) for the SPR excursions are as follows:

No of Crew	4
Duration	3 – 14 days
Crew member in EVA	4 (2 SPR; 2 CM per SPR)
EVA duration	4 hours
High-pressure O_2 usage in EVA	1.6 lb (0.73 kg)/CM-EVA
Low-pressure O_2 consumption with exercise	1.8 lb (0.82 kg)/CM-d
Low-pressure purge O_2 consumption	0.17 lb (0.077 kg)/CM-EVA
SPR atmosphere	8 psia (55 kPa)
O_2 partial pressure in SPR	3.1 psia (21 kPa)
N_2 partial pressure in SPR	4.9 psia (34 kPa)
Contractable airlock volume	91.8 ft^3 (2.60 m^3)
O_2 loss in each airlock operation	0.16 lb (0.073 kg) (with contractable airlock atmosphere gas recovery)

Total O_2 required in a 14-day excursion	187.4 lb (85.0 kg)
Required O_2 generation rate (assuming LOX will be generated in 7 days before excursions)	1.12 lb/hr (0.51 kg/hr)
Additional LOX required in nominal EVA (for generating high-pressure O_2 from LOX)	0.27 lb/hr (0.12 kg/hr)
Desirable LOX generation rate	1.38 lb/hr (0.63 kg/hr)

2.0 Liquefaction of Gaseous Oxygen

To liquefy O_2 into LOX, the O_2 temperature must be cooled below its critical or saturation temperature and the GOX must be compressed to above its critical or saturation pressure.

The critical conditions (3, 4) for O_2 liquefaction are:

>   Critical temperature   -181.4 °F (155 K)
>   Critical pressure: 731.4 psia (5.04 MPa)

Corresponding saturation temperatures of O_2 at pressures of interest in liquefaction are as follows (4):

Pressure, psia (MPa)	25 (0.17)	50 (0.34)	100 (0.69)	150 (1.03)	200 (1.38)	731 (5.04)
Temperature, °F (K)	-288 (95.4)	-273 (104)	-255 (114)	-243 (120)	-234 (125)	-181 (155)

In addition to utilizing the Lunar cold environment for O_2 liquefaction, further cooling of O_2 can be achieved by flowing cold high-pressure O_2 through a throttling valve (5) in an isenthalpic expansion process or using cryogenic cooling devices.

By utilizing a high-pressure O_2 source from a water electrolysis unit of an ISRU and a cold resource on the Lunar surface or from a cryogenic cooling device, the desired low-temperature LOX can be generated. Some promising technologies for these tasks are discussed in the following sections.

2.1 Liquefaction by Direct Exposing O_2 to Lunar Cold Environment

Figure 1 is the schematic of this concept. Moderate-pressure O_2 generated from a water electrolysis unit is dried first to remove the moisture content carried with GOX during the electrolysis. Molecular sieve desiccant beds were selected to remove the moisture. To take advantage of a higher moisture removal efficiency at a lower desiccant bed temperature, a two-stage moisture removal process was conceptualized to remove essentially all the moisture. Two radiators are used to cool GOX to generate LOX at –240 °F and 165 psia (122 K and 0.84 MPa). A sink temperature of –280 °F (100 K) was assumed. The LOX temperature is limited by the cold environment available on the surface with this concept. However, by adding a pressure let-down valve or a cryogenic-cooler, the temperature and pressure of the generated LOX can be further lowered.

Results from heat and mass balance calculations for this technology are as follows:

Stream	1	2	3	4	5
From	OGA	1st drier	1st radiator	2nd drier	2nd radiator
To	1st drier	1st radiator	2nd drier	2nd radiator	product tank
O_2 flow rate, lb/hr (kg/hr)	1.38 (0.626)	1.38 (0.626)	1.38 (0.626)	1.38 (0.626)	1.38 (0.626)
Moisture flow rate, lb/hr (kg/hr)	0.0024 (0.0011)	1.55×10^{-5} (7.03×10^{-6})	1.55×10^{-5} (7.03×10^{-6})	0	0
Temperature, °F (K)	109 (316)	120 (322)	-25 (241)	-25 (241)	-240 (122)
Pressure, psia (MPa)	225 (1.55)	210 (1.45)	195 (1.34)	180 (1.24)	165 (1.14)
Enthalpy[1], BTU/hr (W)	169 (49)	172 (50)	127 (37)	127 (37)	-45 (-13)

Note: 1) Enthalpies were calculated based on National Institute of Standards and Technology (NIST) data.

Duties of the radiators are as follows:
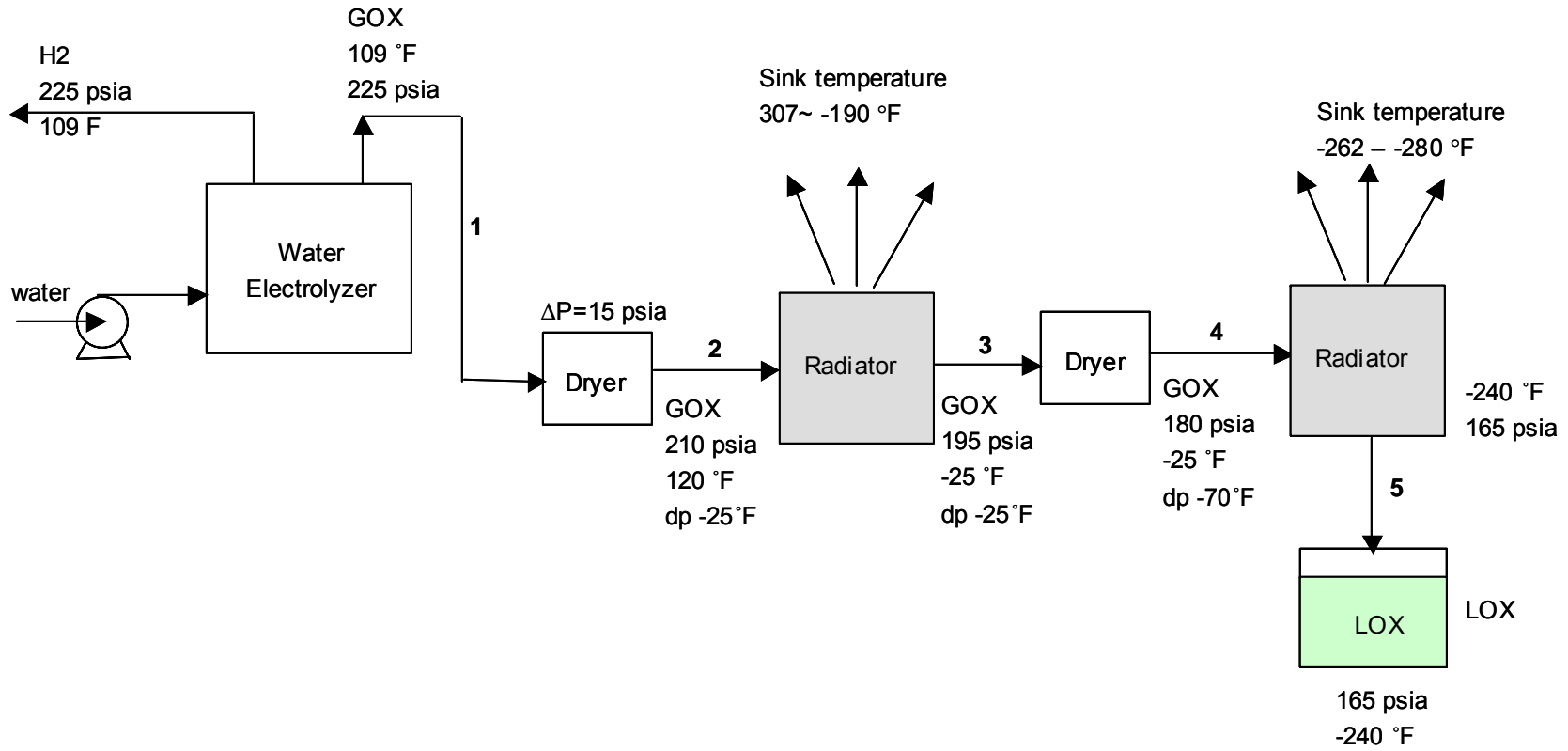
Components	1st Radiator	2nd Radiator
Duty, W	47	173

H2
225 psia
109 F

GOX
109 ˚F
225 psia

Sink temperature
307~ -190 °F

Sink temperature
-262 – -280 °F

water

Water Electrolyzer

1

ΔP=15 psia

Dryer

2

GOX
210 psia
120 ˚F
dp -25˚F

Radiator

3

GOX
195 psia
-25 ˚F
dp -25˚F

Dryer

4

GOX
180 psia
-25 ˚F
dp -70˚F

Radiator

-240 ˚F
165 psia

5

LOX   LOX

165 psia
-240 °F

Figure 1. Schematic of GOX Liquefaction by Direct Cooling

The above information regarding the stream properties and duties of the components can be used for component sizing in future trade studies.

2.2 GOX Liquefaction by Using Radiators, Joule-Thompson (JT) Expansion and Compressors

Using a combination of radiators, heat exchangers, the Joule-Thompson (JT) expansion process, and compressors, colder LOX than those obtained from the previous section can be generated from GOX. By passing a high-pressure, cold GOX stream through a throttling valve, a fraction of the inlet GOX could be liquefied. O_2 flowing through a pressure throttling valve is a constant-enthalpy process. The fraction of an inlet cold O_2 stream liquefied can be calculated by applying an energy balance around the JT valve (5, 7).

Assumptions in the isenthalpic process:

Inlet		Outlet	
GOX	1 lb	GOX	1-x lb
		LOX	x lb
Enthalpy	H_{ig}	GOX	H_{og}
		LOX	H_{ol}

$H_{gi} = (1-x) H_{og} + (x) H_{ol}$
$x = (H_{ig} - H_{og}) / (H_{ol} - H_{og})$

It is assumed that LOX saturated at 50 psia (0.34 MPa) is desirable for propulsion, ECLSS, and EVA applications. Given a GOX stream which has been cooled down to -178 °F (156 K) and the downstream liquefaction equilibrium condition at 50 psia (0.34 MPa) and –272.9 °F (104 K), fractions of inlet GOX liquefied as it passes through the JT valve are listed in the following table:

Pressure, psia (MPa)	800 (5.52)	1000 (6.89)	1200 (8.27)	1400 (9.65)	1500 (10.3)	1600 (11.0)	2000 (13.8)
% liquefied[1]	32.6	42.7	45.3	46.8	47.3	47.7	48.9

Note: 1) Enthalpies from NIST data were used in the calculations.

Figure 2 shows a plot of the fraction of GOX liquefied as a function of the inlet GOX pressure. The plot shows with inlet GOX at –178 °F(156 K) that as GOX pressure increases more inlet GOX will be liquefied. However, the liquefaction fraction approaches a limit of 50% as the GOX pressure increases to 2,000 psia (13.8 MPa). As GOX pressure increases, so will the power penalties associated with the compressor and the Oxygen Generation Assembly (OGA). In addition, the temperature of the inlet GOX stream has a significant impact on the fraction of liquefaction achievable. GOX pressures above 2,000 psia (48.9 MPa) can not be justified in GOX liquefaction.

If generation of LOX is an objective, the optimum OGA operation pressure could be found from a trade among mass of subsystem components, power consumption associated with the OGA and the compressor, and the LOX generation rate.

The following are two liquefaction cases using combinations of radiators, heat exchangers, and compressors.

2.2.1 Case A - Liquefaction with Inlet GOX at 1265 psia (8.72 MPa) and 110 °F (317 K)
Figure 3 is a schematic of a GOX liquefaction case study given an OGA operating pressure at
1,265 psia (8.72 MPa) and a desirable LOX production rate at 1.38 lb/hr (0.63 kg/hr). It was
assumed that LOX saturated at 50 psia (0.34 MPa) is a desirable product. O_2 at 1,265 psia
(8.72 MPa) generated and 110 ˚F (317 K) from a water electrolysis unit passes through desiccant
beds to remove moisture which comes with the O_2 product in the electrolysis unit. The "bone-
dry" O_2 is joined with a recirculating O_2 stream that flows through a radiator. The temperature of
the mixed O_2 stream is cooled to -162 ˚F (165 K) by exposing the mixed O_2 stream to the cold
environment of the Lunar surface. The cold O_2 stream is further cooled to -178 ˚F (157 K) in a
recuperative heat exchanger exchanging heat with a cryogenic O_2 vapor stream venting from a
LOX storage tank. The cold O_2 exiting the recuperative heat exchanger then flows through a
throttling valve and 45.3% of inlet GOX can be liquefied. The LOX product from the JT valve is
collected in a LOX tank. The vaporous GOX is pulled through the recuperative heat exchanger
by a compressor. The compressor compresses the recirculated O_2 stream from 35 psia (0.24
MPa) to 1,250 psia (8.62MPa) to join with O_2 generated from the OGA. An overall cooling load
of 66 W can be obtained with this concept. Stream properties calculated from heat and mass
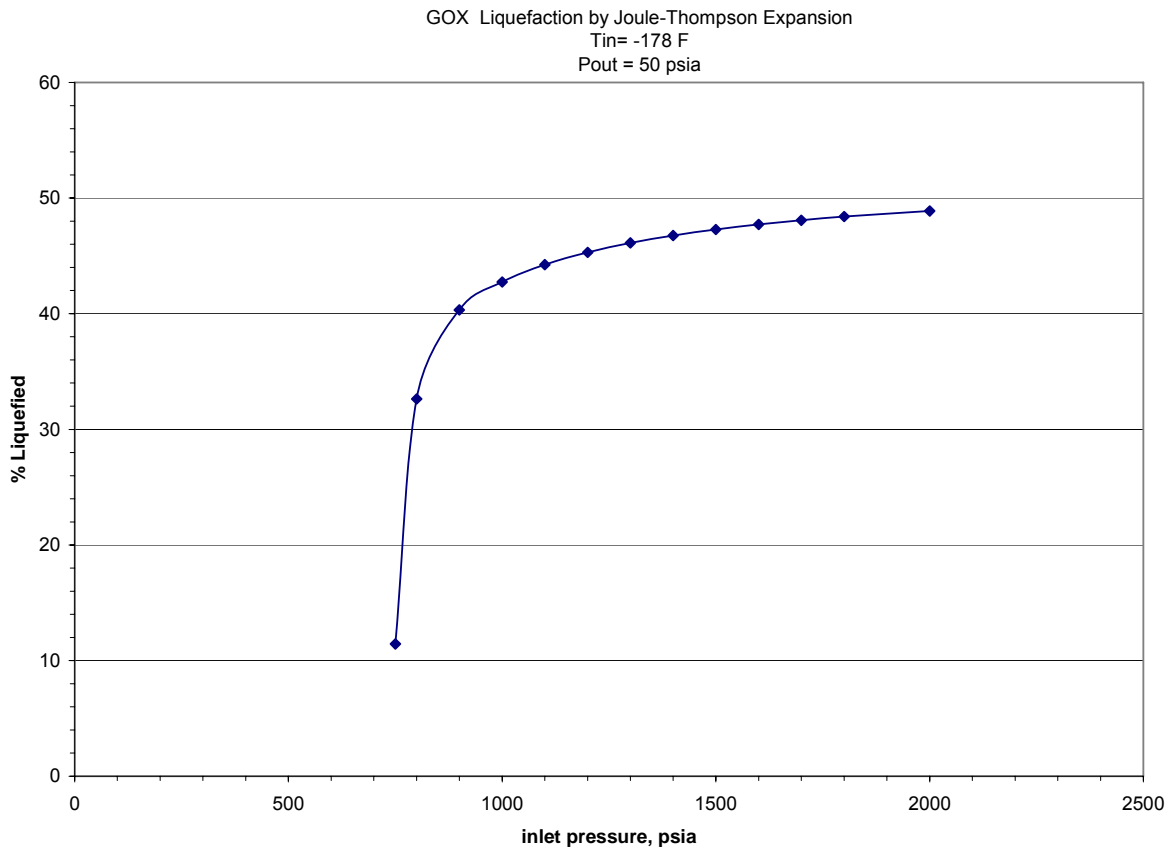balance analyses are summarized in the following table and are also shown in Figure 3.

Figure 2. Percent Inlet GOX Liquefied in Joule-Thompson Process

Stream	1	2	3	4	5	6	7	8	9
From	Compressor and OGA	radiator	heat Ex.	LOX tank	heat ex.	Compressor	OGA	JT valve	LOX tank
To	radiator	Heat Ex.	JT valve	Compressor	compressor		OGA+ Compressor	LOX tank	LOX user
Flow rate, lb/hr (kg/hr)	3.05 (1.38)	3.05 (1.38)	3.05 (1.38)	1.67 (0.76)	1.67 (0.76)	1.67 (0.76)	1.38 (0.63)	3.05 (1.38)	1.38 (0.63)
Temperature, °F (K)	15.5 (264)	-162.0 (165)	-178.0 (156)	-272.9 (104)	-171.7 (160)	-54.9 (225)	110.0 (316)	-272.9 (104)	-272.9 (104)
Pressure, psia (MPa)	1250 (8.62)	1225 (8.45)	1200 (8.27)	50 (0.34)	35 (0.24)	1250 (8.62)	1250 (8.62)	50 (0.34)	50 (0.34)
Enthalpy[1], BTU/hr (W)	91.7 (26.9)	12.4 (3.63)	-0.64 (-0.19)	38.0 (11.1)	61.7 (18.1)	71.5 (20.9)	116.1 (34.0)	-0.64 (-0.19)	-47.2 (-13.8)
Phase	GOX	GOX	GOX	GOX	GOX	GOX	GOX	L + G	LOX
Liquefaction at JT valve: 45.3%									

Note: 1) Enthalpies were calculated based on NIST data.

Duties at the radiator, heat exchanger, and compressor are as follows:

Components	Radiator	Heat Exchanger	Compressor
Theoretical Duty, W	71	12	37
Actual duty, W			122

High efficiencies are expected at the radiator and the recuperative heat exchanger. Thirty percent efficiency was assumed in calculating the power load for the recirculating compressor.

Sizing of the components for this conceptual design has not been conducted because this is beyond the scope of the current task.
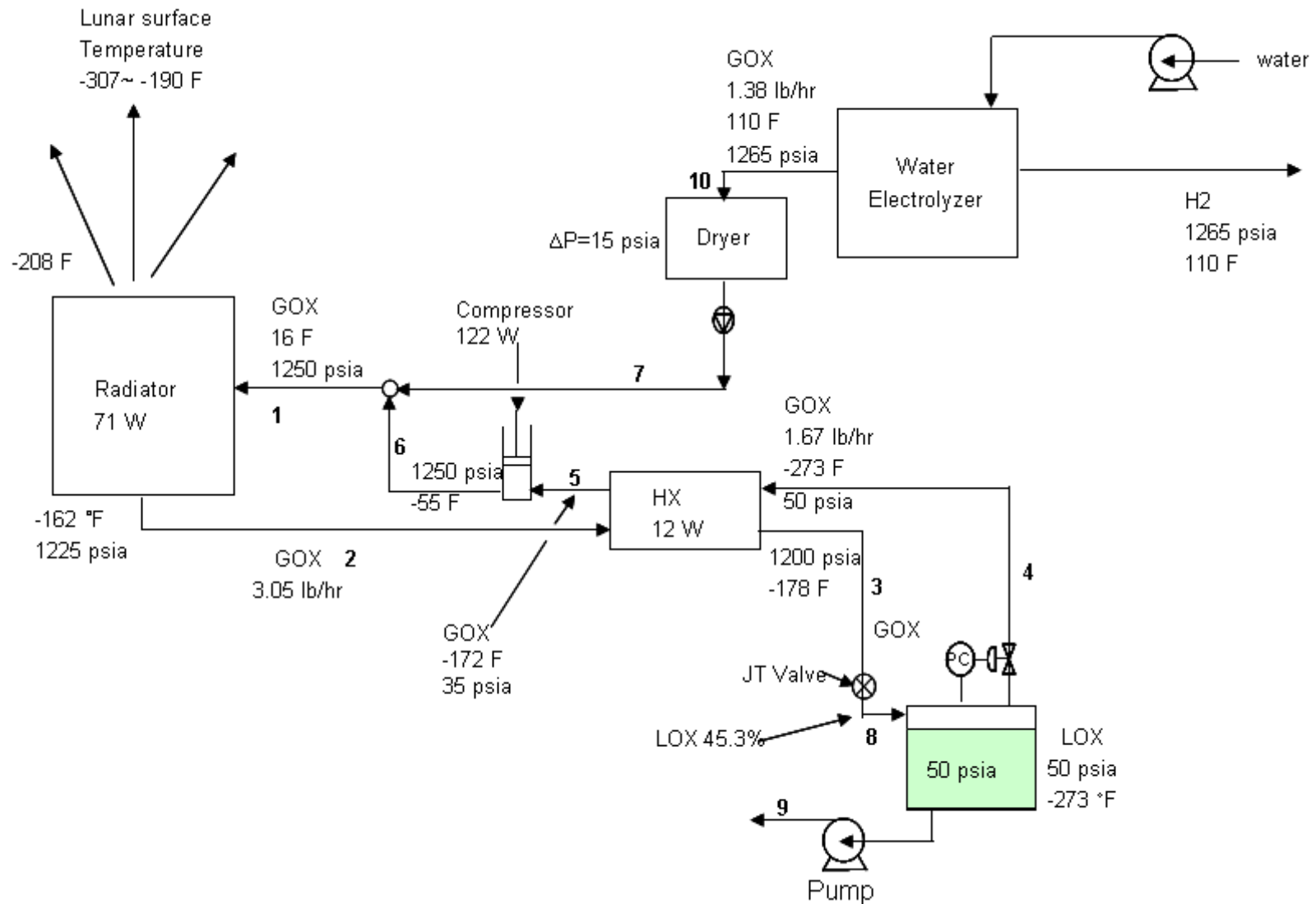
Figure 3. Schematic of GOX Liquefaction Using Radiator, Heat Exchanger and Compressor

2.2.2 Case B - Liquefaction with Inlet GOX at 865 psia (5.96 MPa) and 110 °F (317 K)

To evaluate the impacts of GOX pressure on its liquefaction, heat and mass balance calculations were conducted for an OGA operated at 865 psia and a desired LOX production rate at 1.38 lb/hr (0.63 kg/hr). It was again assumed that LOX saturated at 50 psia (0.34 MPa) is a desirable product. Again, an overall cooling load of 66 W is achievable with this concept. Properties of streams (refer to Figure 3) from heat and mass balance calculations are summarized in the following table:

Stream	1	2	3	4	5	6	7	8	9
From	Compressor and OGA	radiator	heat Ex.	LOX tank	heat ex.	Compressor	OGA	JT valve	LOX tank
To	radiator	Heat Ex.	JT valve	Compressor	compressor		OGA+ Compressor	LOX tank	LOX user
Flow rate, lb/hr (kg/hr)	4.23 (1.92)	4.23 (1.92)	4.23 (1.92)	2.85 (1.29)	2.85 (1.29)	2.85 (1.29)	1.38 (0.63)	4.23 (1.92)	1.38 (0.63)
Temperature, °F (K)	254.4 (397)	159.0 (344)	156.7 (342)	104.0 (313)	153.3 (341)	207.7 (371)	316.7 (431)	104.0 (313)	104.0 (313)
Pressure, psia (MPa)	850 (5.86)	825 (5.69)	800 (5.52)	50 (0.34)	35 (0.24)	850 (5.86)	850 (5.86)	50 (0.34)	50 (0.34)
Enthalpy[1], BTU/hr (W)	384.6 (112)	102.1 (29.9)	42.9 (12.6)	108.8 (31.9)	168.0 (49.2)	221.1 (64.7)	163.6 (47.9)	42.9 (12.6)	-65.2 (-19.1)
Phase	GOX	GOX	GOX	GOX	GOX	GOX	GOX	L + G	LOX
Liquefaction at JT valve: 32.6%									

Note: 1) Enthalpies were calculated based on NIST data.

Duties at the radiator, heat exchanger and compressor are as follows:

Components	Radiator	Heat Exchanger	Compressor
Theoretical Duty, W	82	17	52
Actual duty, W			174

Note: A 3-stage compressor with 30% efficiencies was assumed.

2.3 Liquefaction by Using Pulse Tube Coolers

A single-stage, pulse tube O_2 liquefier has been developed, built and tested by National Institute of Standards and Technology for JSC/NASA in 2000 (6). Figure 4 shows the picture of the system and the schematic illustrating its function. The unit was designed with a cooling load of 15 W and LOX generation rate of 0.29 lb/hr (2.2 g/min) with a sink temperature at 84 °F (302 K). Test data showed that the unit cold end could reach -387 °F (40 K) with no load at its cold end, which is colder than the freezing point of liquid oxygen. LOX with extremely low pressure and low temperature could be generated using this technology. However, the average efficiency of four test runs was low at 8.0% (6). This technology seems appropriate for an application with a low cooling load.

The pulse tube cooler is made of several components: the compressor, connecting lines, aftercooler, regenerator, cold end, cold end heat exchanger, pulse tube, warm end heat exchanger, orifice, inertance tube, reservoir volume, and condensing fins.
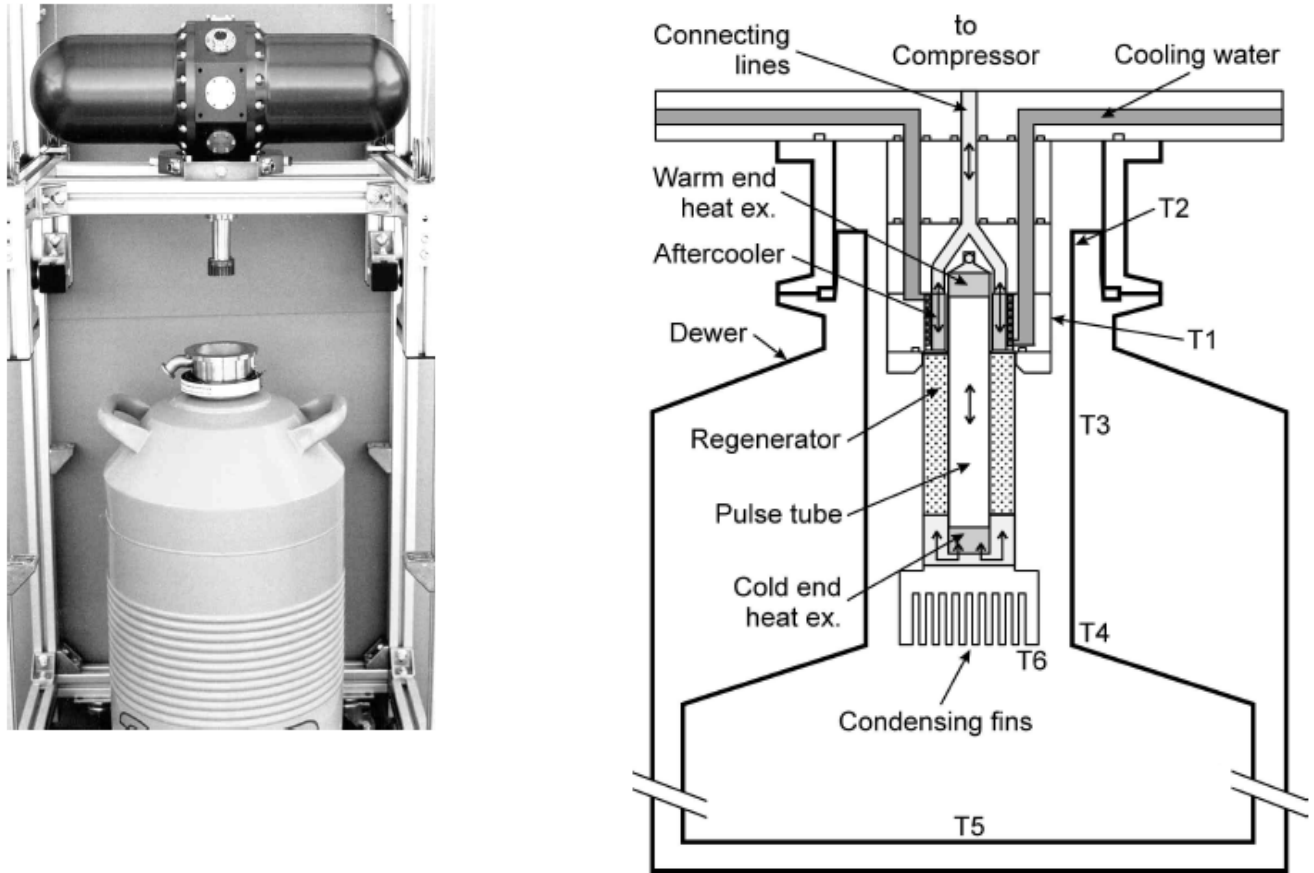
Figure 4. Photo of NIST O$_2$ Liquefier and Schematic of the O$_2$ Liquefier

2.4 Discussions of Liquefaction Technologies

Without detailed sizing and a trade analysis, this discussion is just qualitative. GOX liquefaction by direct cooling using radiators or by using combination of radiators, recuperative heat exchangers, Joule-Thompson expansion processes, and compressors have higher efficiencies and are appropriate for liquefaction applications with higher cooling loads. A pulse tube cooler is appropriate for low cooling load applications, because of its low efficiency.

The analysis cases using inlet GOX from an OGA operated at 865 psia (5.96 MPa) or 1,265 psia (8.72 MPa) show that LOX can be liquefied at either pressure. The compressor power loads are 122 W for an inlet GOX at 1,265 psia and 174 W for an inlet GOX at 865 psia. A more detailed sizing and trade analysis is needed to find out the optimal operating pressure for the water electrolysis unit in a GOX liquefaction subsystem.

An integrated fluid analysis trade comparing storing/transferring high-pressure O$_2$ with storing/transferring LOX for EVA, ECLSS, SPR, and Power is also desirable and suggested.

3.0 Conclusion and Suggestions

A brief thermodynamic analysis of GOX liquefaction processes has been completed.
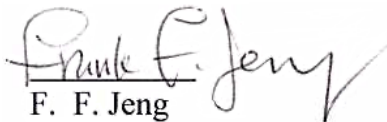
Concepts of O_2 liquefaction units capable of generating 1.38 lb/hr (0.63 kg/hr) LOX were developed. The equivalent cooling load of the concepts is 66 W. These concepts use combinations of radiators, recuperative heat exchangers, Joule-Thompson pressure expansion, and compressors.

Without detailed sizing and a trade analysis of the selected liquefaction technologies, a qualitative comparison indicates that technologies using direct cooling with radiators or by using a combination of radiators, recuperative heat exchangers, and compressors are appropriate for O_2 liquefaction applications with larger cooling loads. A pulse tube O_2 liquefier is good for a unit appropriate for low cooling loads.

GOX pressure and temperature play important roles in the overall system mass and power penalties associated with the GOX liquefaction system. A thermodynamic analysis indicates that pressures above 2,000 psia (13.8 MPa) are not necessary for GOX liquefaction. A detailed trade analysis is needed to determine the optimal water electrolysis pressure for O_2 liquefaction.

An integrated fluid analysis trade comparing strategies between storing/transferring high-pressure O_2 with storing/transferring LOX for EVA, ECLSS, Power, and SPR is also suggested.

A trade study is suggested for comparing liquefaction technologies if LOX is chosen for storing/transferring oxygen.

F. F. Jeng
Thermal and Environmental Analysis Section

References:

1. NASA Lunar Architecture Team report (LAT2), P 19, NASA Lunar Architecture Team, NASA, Aug, 2007.
2. Hasan M. H. and Plachta D. W., "Sub-Critical Liquid Oxygen (LOX) Storage for Exploration Life Support System", Presentation to JSC on Aug. 13, 2008, GRC/ NASA.
3. Perry R.H. and Chilton C.H., "Chemical Engineers' Handbook", 5th edition, McGraw-Hill Book Co., 1973.
4. National Institute of Standards and technology
5. Smith J. M. and Van Ness H.C., "Introduction to Chemical Engineering Thermodynamics", 3rd ed., McGraw-Hill Book Co., 1975.
6. Marquardt E.D. and Radebaugh R., "Pulse Tube Oxygen Liquefier", National Institute of Standards and Technology, Adv. Cryogenic Engineering, Vol. 45, Plenum (2000), pp 457-464., 2000
7. Flynn T.M. and Roth D., "Cryogenic Engineering", a course given at JSC/NASA, Cryoco, Inc, 2009.
8. Bagdigian R., "Small Pressurized Rover (SBR) ECLSS Architecture Study", presentation on 12/15/2008.
9. Phase II Summary Report (draft), NASA Lunar Architecture Team, Sect ion 3.2, Sept., 2007.
10. Freeh J.E., "Analysis of Stationary, Photovoltaic-Based Surface Power System Design at the Lunar South Pole", AIAA paper 2008.

Abbreviations and Acronyms

CM	Crew Member
ECLSS	Environmental Control and Life Support System
EVA	Extravehicular Activity
G	Gas
GOX	gaseous oxygen
H_2	hydrogen
H_2O	water
ISRU	In Situ Resource Utilization
L	Liquid
LOX	liquid oxygen
NIST	National Institute of Standards and Technology
O_2	oxygen
OGA	Oxygen Generation Assembly
PLSS	Portable Life Support System
SPR	Small Pressurized Rover

ELECTRONIC DISTRIBUTION:

J. Collins	/NASA
M. K. Ewert	/NASA
B. C. Conger	/ESCG
J. L. Cox	/ESCG
A. J. Hanford	/ESCG
T. H. Paul	/ESCG
M. K. Smith	/ESCG
F. F. Jeng	/ESCG