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Cryogenic Reactant Storage for Lunar Base Regenerative Fuel Cells

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Lisa L. Kohout
Lewis Research Center
Cleveland, Ohio

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CRYOGENIC REACTANT STORAGE FOR LUNAR BASE REGENERATIVE FUEL CELLS

Lisa L. Kohout
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

There are major advantages to be gained by integrating a cryogenic reactant storage system with a hydrogen-oxygen regenerative fuel cell (RFC) to provide on-site electrical power during the lunar night. Although applicable to any power system using hydrogen-oxygen RFC's for energy storage, cryogenic reactant storage offers a significant benefit whenever the sun/shade cycle and energy storage period approach hundreds of hours. For solar power installations on the moon, cryogenic reactant storage reduces overall specific mass and meteoroid vulnerability of the system. In addition, it offers synergistic benefits to on-site users, such as availability of primary fuel cell reactants for surface rover vehicles and cryogenic propellants for OTV's. The integration involves processing and storing the RFC reactant streams as cryogenic liquids rather than pressurized gases, so that reactant containment (tankage per unit mass of reactants) can be greatly reduced. Hydrogen-oxygen alkaline RFC's, GaAs photovoltaic (PV) arrays, and space cryogenic processing/ refrigeration technologies are assumed to be available for the conceptual system design. Advantages are demonstrated by comparing the characteristics of two power system concepts: (1) a conventional lunar surface PV/RFC power system using pressurized gas storage in SOA filament wound pressure vessels and, (2) that same system with gas liquefaction and storage replacing the pressurized storage. Comparisons are made at 20 and 250 kWe. Although cryogenic storage adds a processing plant (drying and liquefaction) to the system plus 30 percent more solar array to provide processing power, the approximate order of magnitude reduction in tankage mass, confirmed by this analysis, results in a reduction in overall total system mass of approximately 50 percent.

INTRODUCTION

Solar photovoltaic power systems have provided reliable power for the majority of the United States space missions. At present, these systems have been confined to earth orbit domains. However, as the U.S. space program moves into the 21st century, solar photovoltaic systems will also be applied to lunar surface missions. These systems will use a PV array to gather solar energy during the sunlight portion of the orbit and an energy storage subsystem to accumulate energy for release during solar eclipse. A primary candidate for the energy storage subsystem is the hydrogen-oxygen regenerative fuel cell, which exhibits the highest energy density of all the nonnuclear systems for storage periods exceeding 2 hr.

The primary components of the conventional RFC subsystem (Fig. 1) include a fuel cell unit, an electrolysis unit, reactants, and reactant tankage. The fuel cell and electrolysis unit masses scale with power level, which is a function of electrode area, while the reactant and associated tankage masses scale with energy, which is a function of reactant volume. During the eclipse portion of a mission, gaseous hydrogen and oxygen are delivered to the fuel cell unit at regulated pressure. Electrical power and heat are generated as the hydrogen and oxygen reactants are combined to form water. The water leaves the fuel cell stack and is stored in a tank. During the daylight portion of the mission, the stored water is pumped to an electrolysis unit, which is supplied with electrical power from an outside source (the photovoltaic array) to electrolyze the water and regenerate the gaseous hydrogen and oxygen reactants.

Conventional RFC's store the reactants as gases in pressurized tanks, typically in the range of 0.7 to 2.4 MPa (100 to 350 psia). Common tank materials include Inconel (a nickel-base alloy) and lightweight filament-wound materials such as Kevlar/epoxy. It was determined during the course of this study that, for short storage periods such as those associated with a low earth orbit application (~0.5 hr storage), tankage accounts for only 5.5 percent of the total power system mass (Fig. 2) for reactants stored in Inconel tanks. However, as the storage time increases, an increasing percentage of the RFC subsystem mass lies in tankage. For lunar missions, where the storage requirements approach 350 hours, the tankage comprises an overwhelming 82.5 percent of the total system mass. Substitution of lightweight Kevlar/epoxy tanks for Inconel tanks reduces this percentage only slightly, from 82.5 to 64.6 percent (Fig. 3). Since the tankage does not directly contribute to the power and energy output of the system, any reduction in its mass would be advantageous. This is especially significant considering the high cost of delivering a payload to the lunar surface.

One option for reducing tankage mass is to liquefy and store the reactant streams as cryogens rather than pressurized gases. However, cryogenic storage requires a refrigeration plant and increased solar array area to provide power to that plant. For an orbital application, the refrigeration plant and additional solar array would outweigh any resulting savings in tankage. However, since the tankage for a lunar application is such a large portion of the overall system mass, the savings realized by cryogenic storage might easily pay for the added components and complexity.

To determine if a net advantage does exist, two "lunar base" PV/RFC conceptual designs were generated and characterized as follows: A baseline case using conventional (gaseous reactant) storage, similar to the lunar base solar power plant design developed by Eagle Engineering [1], was established using a well-known modeling code [2]. This baseline was then modified to reflect the implementation of cryogenic storage. The cryogenic system was defined and the mass of each component determined for both a 20 and a 250 kWe output power level. The resultant total power system mass was compared to the mass of the baseline system.

SYSTEM MODELING

A conventional RFC was modeled as a baseline system. For this system, the reactant gases were assumed to be stored at the electrolyzer operating pressure of 2.2 MPa (315 psia) in tanks made from filament-wound Kevlar 49/epoxy matrix. Based on data from the Lawrence Livermore Laboratory [3], the rupture stress of this type of material is approximately 931 MPa (135 000 psi). The working stress used for modeling the tanks was 233 MPa (33 750 psi). A 10-mil titanium liner was included in each tank to reduce the diffusion of gas through the tank wall. The tanks were sized for the volume of reacting gas plus approximately 28 percent residual gas needed to maintain the tank pressures at the fuel cell operating pressure of 0.4 MPa (60 psia) to the end of the cycle. The water storage tank was also assumed to be constructed of filament-wound Kevlar 49/epoxy matrix and was designed for a storage pressure of 2.2 MPa (315 psia).

In modeling the cryogenic system, the gaseous reactant storage tanks were removed from the baseline system, as indicated by the dashed line in Fig. 1, and replaced with a refrigeration plant and storage facility, including driers for the reactant gas streams, liquefaction units, and cryogen storage tanks (Fig. 4). Additional PV array area was also included to provide power to the refrigeration plant. A 250 kWe system was chosen as the initial design point because of a previous study [4] which addressed the definition and preliminary design, including component mass estimates, of space-based cryogenic processing for an on-orbit fuel depot. The process flow rate for the depot corresponded to the flow rate required for a 250 kWe RFC. After the 250 kWe system was defined, the system was scaled down to 20 kWe. This lower power level is representative of the minimum power level envisioned for an installation such as a lunar observatory. A brief description of each subsystem as well as the methods employed for subsystem scaling are given below.

Fuel Cell/Electrolyzer Subsystem

The fuel cell/electrolyzer (FC/EU) subsystem was modeled using a code that was developed at the NASA Lewis Research Center [2]. The code calculates mass and performance characteristics based on input design parameters which, for this study, were set to state-of-the-art values (Table 1). These parameters were the same for both the 250 and 20 kWe systems.

Gaseous Hydrogen/Oxygen Drying Subsystem

The hydrogen and oxygen gas streams leaving the electrolysis unit contain water vapor that must be removed before the gases are liquefied so as to prevent ice formation. A drying subsystem (Fig. 5) is used to remove the water vapor. Wet gas leaving the electrolyzer at operating temperature enters a heat exchanger and rejects some of its heat to the drying radiator. The cooled gas stream then enters a cold trap where 99.9 percent of the water content of the stream is removed through condensation. A sorption dryer, consisting of a rotor built up of corrugated sheets impregnated with a hygroscopic salt, removes the remaining water from the stream. Drying takes place in approximately three-quarters of the rotor with regeneration of the sorption material taking place in the remaining quarter section. Regeneration is accomplished by reheating a portion of the gas stream exiting the cold trap and passing it through the rotor. All water removed in the drying process is sent back to the electrolysis unit [4].

The drying subsystem equipment mass for the 250 kWe system was taken directly from Ref. 4. The 20 kWe drying subsystem mass was scaled linearly based on the total mass flow of wet gas into the driers.

Hydrogen/Oxygen Liquefaction Subsystem

After leaving the drier, the hydrogen and oxygen streams enter liquefaction units. A reversed Brayton cycle is used to liquefy the gases. A diagram of the cycle is shown in Fig. 6. The equipment for the liquefaction of the hydrogen and oxygen streams is similar except that two refrigeration stages are required for hydrogen due to the extremely low temperature that must be achieved. Approximately 15 kW is removed from the hydrogen stream at an efficiency of 9.5 percent; 9 kW is removed from the oxygen stream at an efficiency of 12.5 percent. The liquefaction units are also used to liquefy boiloff from the storage tanks [4].

The masses and efficiencies for the 250 kWe hydrogen and oxygen liquefaction subsystems were taken directly from Ref. 4. To determine the mass of the liquefaction subsystems for the 20 kWe system, the 250 kWe subsystem masses were scaled down based on specific power requirements given in the reference along with the mass flows of hydrogen and oxygen to the respective liquefaction units.

It should be noted that the in-space liquefaction technology assumed for this study is based on long-range projections. Current technology addresses cooling requirements on the order of a few watts. Considerable development would be needed to achieve the system described in this study.

Reactant Storage Tanks

The design of the cryogenic hydrogen and oxygen storage tanks is based on a Beechcraft design [5] as shown in Fig. 7. The tanks consist of a spherical aluminum inner pressure vessel and a concentric aluminum outer shell with 90 layers of multilayer insulation and two vapor-cooled shields placed between the inner and outer spheres. The vapor cooled shields together with the Joule-Thomson valve and pressure vessel wall heat exchanger comprise a thermodynamic vent system which provides thermal protection from radiant heat flux. For purposes of characterization, the tank volumes for both the 250 and 20 kWe systems were determined based on the volume of required reactants plus a 5 percent reactant residual. An additional 10 percent tank volume was also added to accommodate the maximum filling level achievable [6]. Fluid expulsion techniques were not considered in the scope of this study. However, a couple of options have been identified. A pressurized line running from the dry gas streams to the respective cryogen tanks could be used to provide pressurized expulsion of the fluid from the tank. Another option is to utilize fuel cell waste heat to provide the energy required for fluid expulsion. A comparison of the tank dimensions for both the baseline gaseous system and the cryogen system is given in Table 2.

As for the gaseous system, the reactant water was stored at 2.2 MPa (315 psia) in tanks made from filament-wound Kevlar 49/ epoxy matrix. A working stress of 233 MPa (33 750 psi) was assumed in modeling the tank.

Radiators

Radiators are required for the fuel cell, drying, and hydrogen and oxygen liquefaction subsystems. Radiator characteristics for both the 250 and 20 kWe systems are listed in Table 3. The effective emissivity accounts for the actual surface emissivity at end-of-life as well as for the nonisothermal nature of the radiating surface and redundancy. The rejection temperature given in Table 3 is a log mean effective rejection temperature. The fuel cell radiator, operating during the lunar night, was sized for a 20 K sink temperature. However, both the drying and liquefaction subsystem radiators operate during the lunar day and, consequently, must reject heat to a significantly higher sink temperature, on the order of 330 K. Since both of these subsystems are characterized by low effective rejection temperatures in relation to the sink temperature, it was desired to make the sink temperature on the lunar surface as low as possible so as to reduce the radiator area and, therefore, the radiator mass. In order to reduce the lunar sink temperature, the radiator panels were oriented vertically with an aluminized plastic sheet spread as a cover over the lunar soil in the area immediately surrounding the radiator. The vertical orientation of the panels ensures that the radiator sees no direct solar energy, while the cover sheet, having a lower solar absorptivity and thermal emissivity than the lunar soil, reduces the effect of reflected solar and thermal energy from the lunar surface. The configuration reduces the daytime equivalent sink temperature on the lunar surface from 330 to approximately 220 K [7].

For the 250 kWe system, the drying and liquefaction subsystem radiators were sized based on heat loads derived from the data presented in Ref. 4. In order to size the 20 kWe system radiators, the heat load from the drying system was scaled down based on total wet gas mass flow through the driers, while the liquefaction heat loads were scaled based on the mass flows of hydrogen and oxygen to the respective liquefaction units. The radiators were then sized for these heat loads. The fuel cell radiator for both power levels was sized based on the fuel cell heat load calculated in the RFC code.

Cryogen-to-Gas Conversion Subsystem

The cryogenic reactants must be vaporized and heated prior to being fed to the fuel cell. Approximately 25 kW of heat are required for reactant conversion for the 250 kWe system while approximately 2 kW of heat are required for the 20 kWe system. Although a detailed analysis of this subsystem has not been done to date, it is envisioned that the subsystem would utilize waste heat from the fuel cell to accomplish the conversion. One additional heat exchanger loop would be required which would not contribute significantly to the total system mass.

Photovoltaic Array

A GaAs sun-tracking array was a chosen for use in this system. The specific power of the array is 123 W/kg at 22.512 percent efficiency and 383 K. The specific mass is 2.48 kg/m^2 [8 to 10]. These numbers include the array blanket, support frame, pivots, tracking mount, and wiring harness. The solar array was sized to provide power to the cryogen plant as well as to the lunar installation during the day. The breakdown of the power requirements for both the 250 and 20 kWe systems are given in Table 4. The final array area required to provide this amount of power was 2780 and 221 m^2 for the 250 and 20 kWe systems, respectively. For comparison, the baseline gaseous systems required 2134 and 170 m^2 of array area.

Power Conditioning

During the lunar day, power flows from the PV array to: (a) the electrolyzer, (b) the reactant driers and liquefaction units, and (c) the user. During the lunar night, power flows from the fuel cell unit to the user. The electrical loads associated with each subsystem have been estimated, but, since a detailed design has not yet been developed, the actual power conditioning requirements are not known. Therefore, a specific mass of 10 kg/kw was used to characterize the power conditioning subsystem.

RESULTS

A schematic layout of the complete RFC system with cryogenic storage, including radiators and PV array, is shown in Fig. 8. The mass breakdowns for the 250 kWe baseline and cryogenic systems are presented in Table 5. A comparison of the cryogenic system with the baseline system shows that the cryogen plant (drying and liquefaction equipment and associated radiators) accounts for an additional 7218 kg not present in the baseline system. The PV array mass is increased by 1601 kg over the baseline system reflecting the additional power required to operate the cryogen plant. Similarly, the power conditioning mass is also increased by 1968 kg.

Although the cryogen plant and augmented PV array and power conditioning requirements result in the addition of 10 787 kg to the baseline system, the total cryogenic system mass was found to be less than half of the mass of the gaseous system. The primary reason for the significant decrease in total system mass lies in the hydrogen and oxygen reactant tank mass. A savings of 81 072 kg is realized by replacing the pressurized gas storage tanks with cryogen storage tanks. This is due to the decrease in tank volume when storing the reactants as cryogens as opposed to pressurized gases. As shown graphically in Fig. 9, the additional mass associated with the implementation of the cryogenic storage system is more than compensated by the decrease in hydrogen and oxygen reactant tank mass alone. A secondary reason for the significant reduction in mass, as is shown in Table 5, is a 7210 kg decrease in reactant mass, reflecting the reduction in hydrogen and oxygen residuals as compared to gaseous storage.

It should be noted that the mass of the FC/EU plant (fuel cell and electrolyzer stacks and associated mechanical ancillaries and radiators) is the same for both the gaseous and cryogenic systems. This reflects the fact that only the subsystems within the established boundaries were changed during the course of the analysis (Figs. 1 and 4).

A detailed mass breakdown for the 20 kWe system is given in Table 6 and depicted graphically in Fig. 10. Again, the total cryogenic system mass was found to be less than half of the mass of the gaseous system. A similar discussion holds for this system as was presented for the 250 kWe system.

An artist's rendition of a 50 kWe PV-RFC power system with cryogenic storage for a lunar observatory is shown in Fig. 11. In addition to providing reactants for the regenerative fuel cells, the cryogenic hydrogen and oxygen can also be used as reactants for primary fuel cells to power surface rovers or as propellants for cargo/crew ascent vehicles, as is depicted in this rendition. Thus, the system can provide synergistic benefits for on-site users as well as offer a significant reduction in total mass.

CONCLUDING REMARKS

Cryogenic reactant storage appears to have a major benefit for lunar surface regenerative fuel cell energy storage systems. The reduction in tank mass realized by going to cryogenic storage more than compensates for the additional mass due to liquefaction plants and increased solar array and power conditioning requirements. For solar photovoltaic power systems utilizing cryogenic storage, the resulting overall mass reduction is approximately 50 percent as compared with a system utilizing gas storage in filament-wound pressure vessels. With an approximate 5:1 propellant-to-payload mass ratio to deliver a payload to the lunar surface, the power system mass savings translates into a considerable propellant mass savings as well. The total lower mass results in fewer launches required for delivery, and therefore, a significant reduction in launch cost. This is not the only benefit, however. Synergistic user benefits also exist.

The cryogenic regenerative fuel cell system can provide a ready supply of liquid hydrogen and oxygen on-site for other uses such as primary fuel cell reactants and cryogenic propellants. However, the added complexity of the proposed system over that of a conventional RFC system must be weighed against these benefits to determine its applicability to a specific mission. Future work on this system will address such issues as the scalability of the liquefaction process components, the impact of advanced technology on liquefaction subsystem mass and performance, subsystem optimization, the cryogen-fuel cell interface, and reliability/ redundancy trade-offs.

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TABLE 1. - RFC OPERATING CONDITIONS

Fuel cell/electrolyzer operating temperature, K	355
Fuel cell operating pressure, MPa	0.4
Electrolyzer operating pressure, MPa	2.2
Fuel cell/electrolyzer current density, mA/cm^2	161

TABLE 2. - COMPARISON OF REACTANT STORAGE TANK SIZES

[Based on single tank per reactant.]

	250 kWe		20 kWe	
	Gaseous storage (Kevlar)	Cryogenic storage	Gaseous storage (Kevlar)	Cryogenic storage
Hydrogen tank				
Mass of H_2, M.T.	4.40	3.59	0.35	0.29
Radius, M	9.0	[a]2.4 [b]2.6	3.9	[a]1.0 [b]1.2
Volume, m^3	2969	56	236.8	4.5
Oxygen tank				
Mass of O_2, M.T.	34.9	28.5	2.79	2.28
Radius, M	7.1	[a]1.9 [b]2.0	3.1	[a]0.8 [b]1.0
Volume, m^3	1485	27	118.4	2.2

[a] Inner shell.

[b] Outer shell.

TABLE 3. - RADIATOR CHARACTERISTICS

Subsystem radiator	Emissivity (Effective)	Specific mass, kg/m^2	Rejection temperature, (Effective) K	Sink temper- ture, K	Required area, m^2	
					250 kWe	20 kWe
Fuel cell	0.595	5	359	20	267	21
Drying	0.595	5	320	220	53	3
Hydrogen liquefaction	0.595	5	330	220	574	47
Oxygen liquefaction	0.595	5	340	220	164	13

TABLE 4. - SYSTEM POWER REQUIREMENTS

Component	Power to be supplied by PV array, kW	
	250 kWe	20 kWe
Electrolyzer	400.0	31.7
H_2/O_2 Driers	2.0	.2
H_2 liquefaction unit	123.5	9.8
O_2 liquefaction unit	71.3	5.7
Baseline power to user	250.0	20.0
Total power to be delivered by PV array	846.8	67.4

TABLE 5. - WEIGHT SUMMARY - 250 kW SYSTEM

Component	Gas storage, (Kevlar) kg	Cryo storage, kg
Fuel cell stack	2 903	2 903
Ancillaries	140	140
Electrolyzer stack	3 993	3 993
Ancillaries	782	782
FC radiator system	1 334	1 334
H_2 tank	57 866	3 850
O_2 tank	29 091	2 035
H_2O tank	594	594
Reactants:		
H_2O	30 591	30 591
H_2 residual	978	171
O_2 residual	7 762	1 359
Gaseous drying equipment	-------	138
Drying radiator	-------	264
H_2 liquefaction unit	-------	2 336
H_2 liquefaction radiator system	-------	2 967
O_2 liquefaction unit	-------	599
O_2 liquefaction radiator system	-------	914
Solar array	5 284	6 885
Power conditioning	6 500	8 468
Total	147 818	70 323

TABLE 6. - WEIGHT SUMMARY - 20 kW SYSTEM

Component	Gas storage, (Kevlar) kg	Cryo storage, kg
Fuel cell stack	252	252
Ancillaries	23	23
Electrolyzer stack	323	323
Ancillaries	112	112
FC radiator system	106	106
H_2 tank	4 737	449
O_2 tank	2 395	258
H_2O tank	47	47
Reactants:		
H_2O	2 439	2439
H_2 residual	78	14
O_2 residual	619	108
Gaseous drying equipment	------	9
Drying radiator	------	17
H_2 liquefaction unit	------	141
H_2 liquefaction radiator system	------	241
O_2 liquefaction unit	------	45
O_2 liquefaction radiator system	------	74
Solar array	420	547
Power conditioning	517	674
Total	12 068	5879

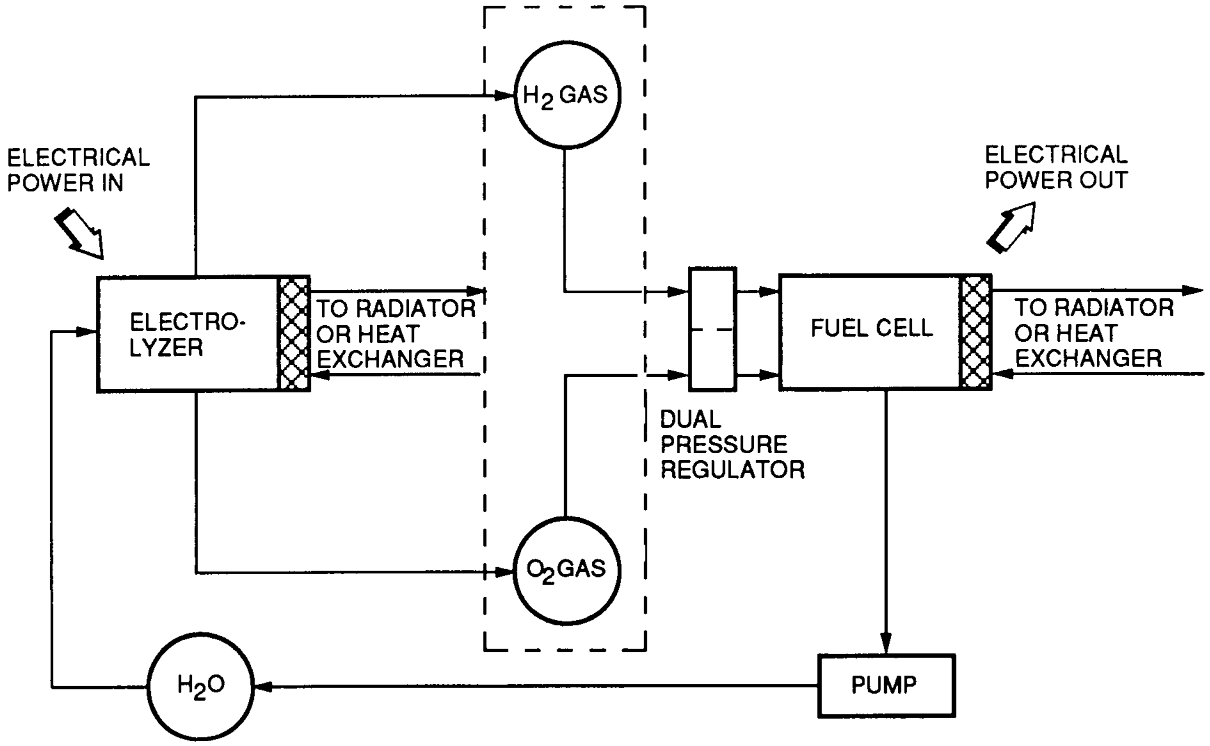

Figure 1. - Conventional regenerative fuel cell system (reactants stored as pressurized gases).

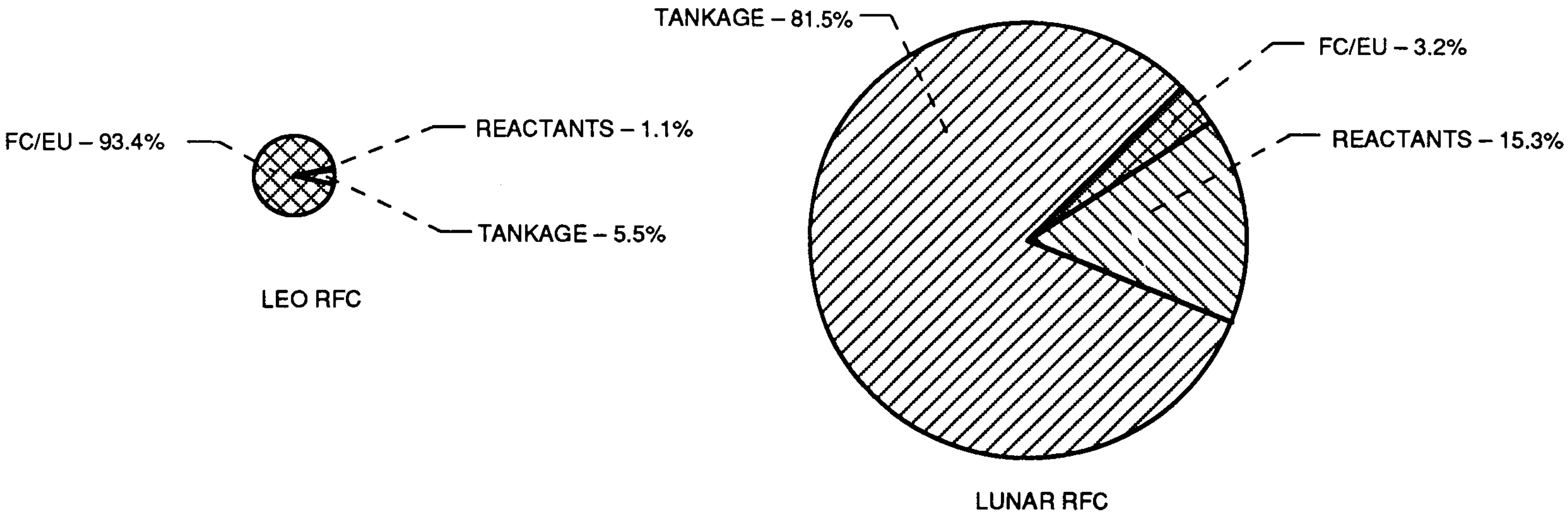

Figure 2. - Comparison of mass breakdowns for a 250 kW regenerative fuel cell system. (Inconel tank material)

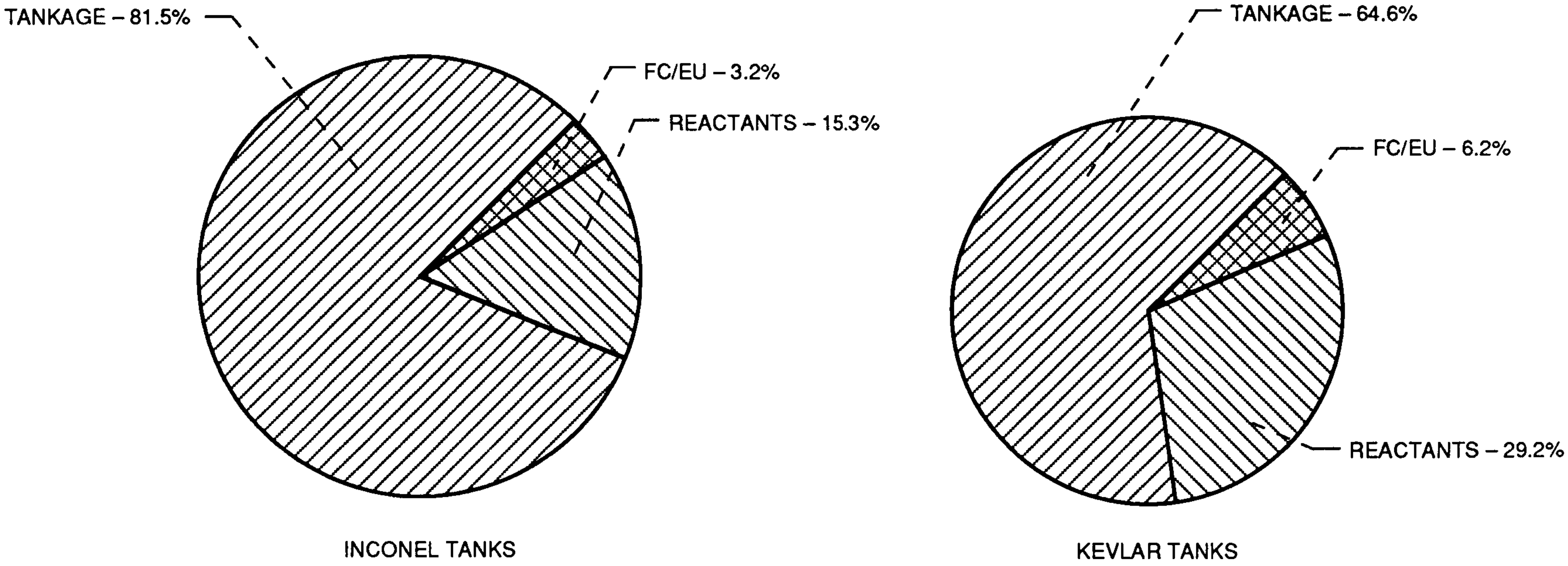

Figure 3. - Mass breakdown for a 250 kW lunar regenerative fuel cell system.

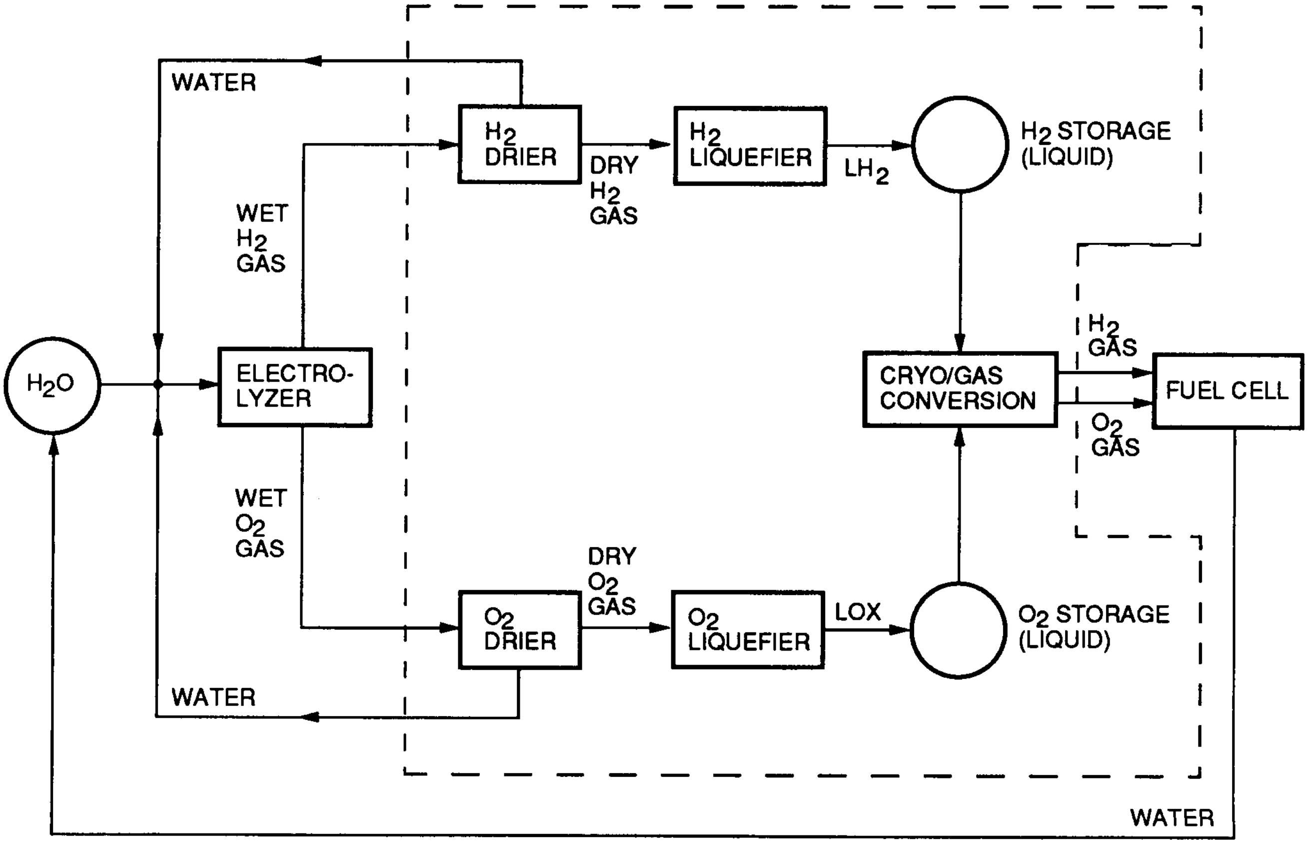

Figure 4. - Regenerative fuel cell system (reactants stored as cryogenic fluids).

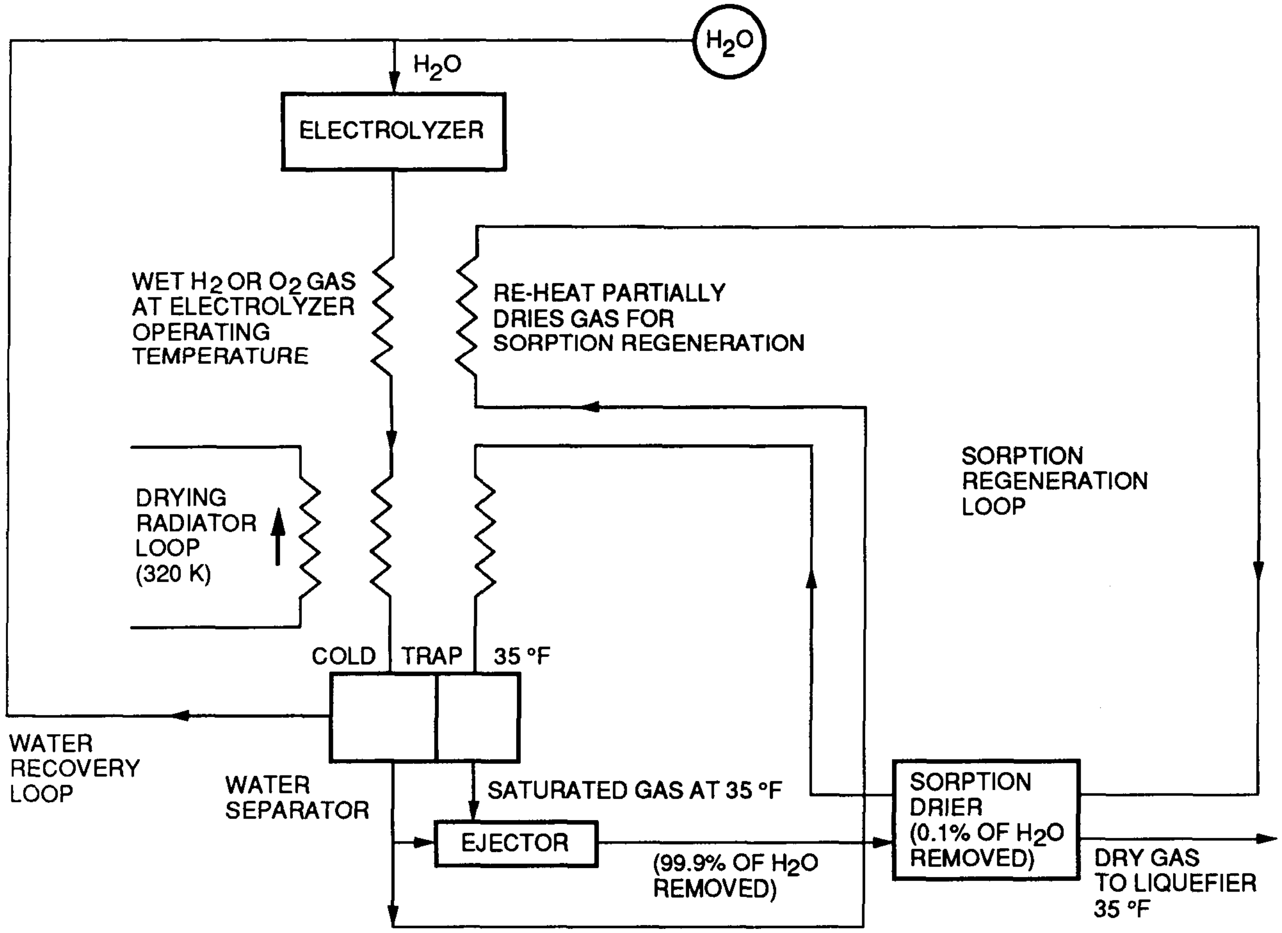

Figure 5. - Gaseous hydrogen/oxygen drying system (from Bock and Fisher).

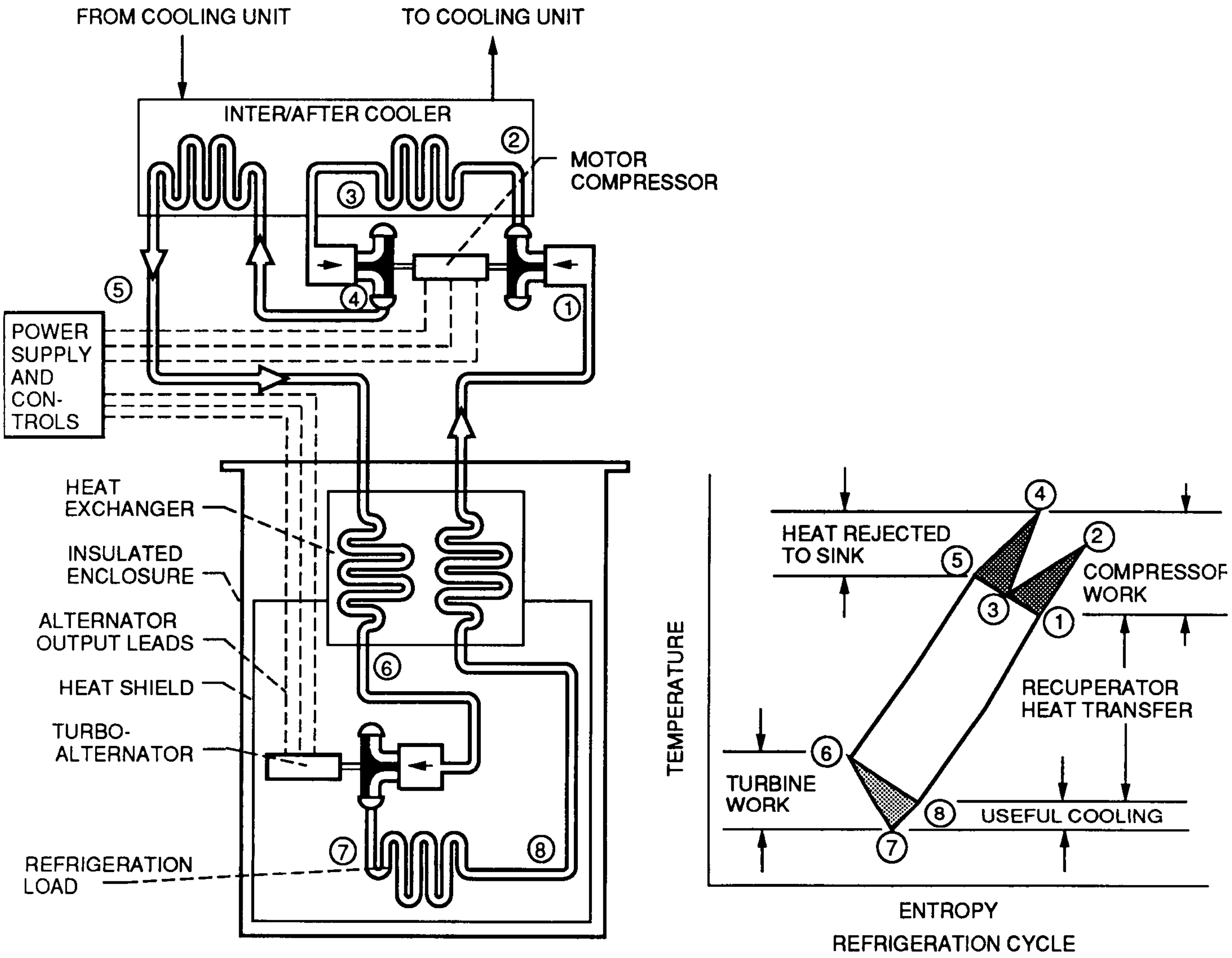

Figure 6. - Reversed Brayton liquefaction cycle (from Bock and Fisher).

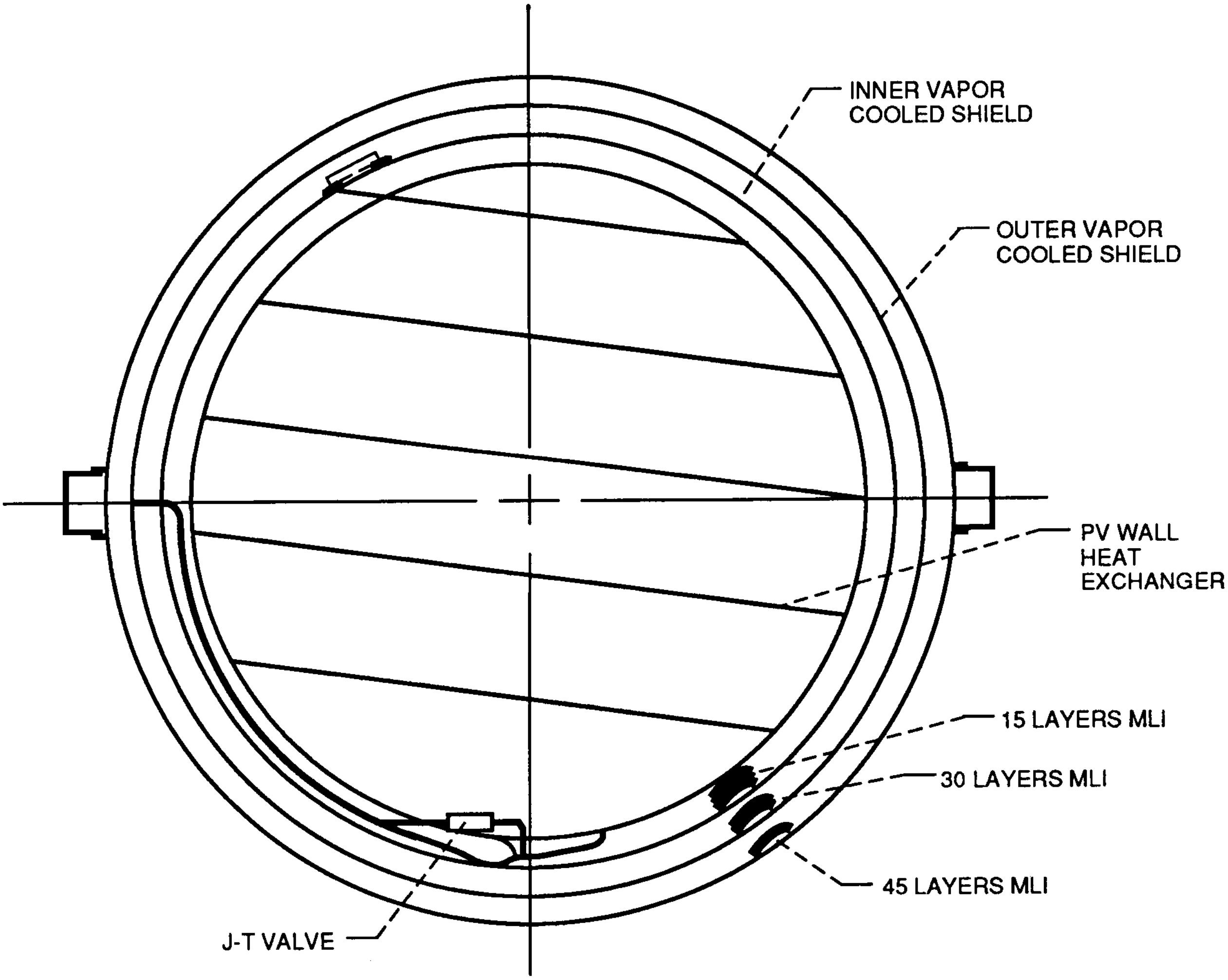

Figure 7. - Schematic of cryogenic storage tank (from Beechcraft).

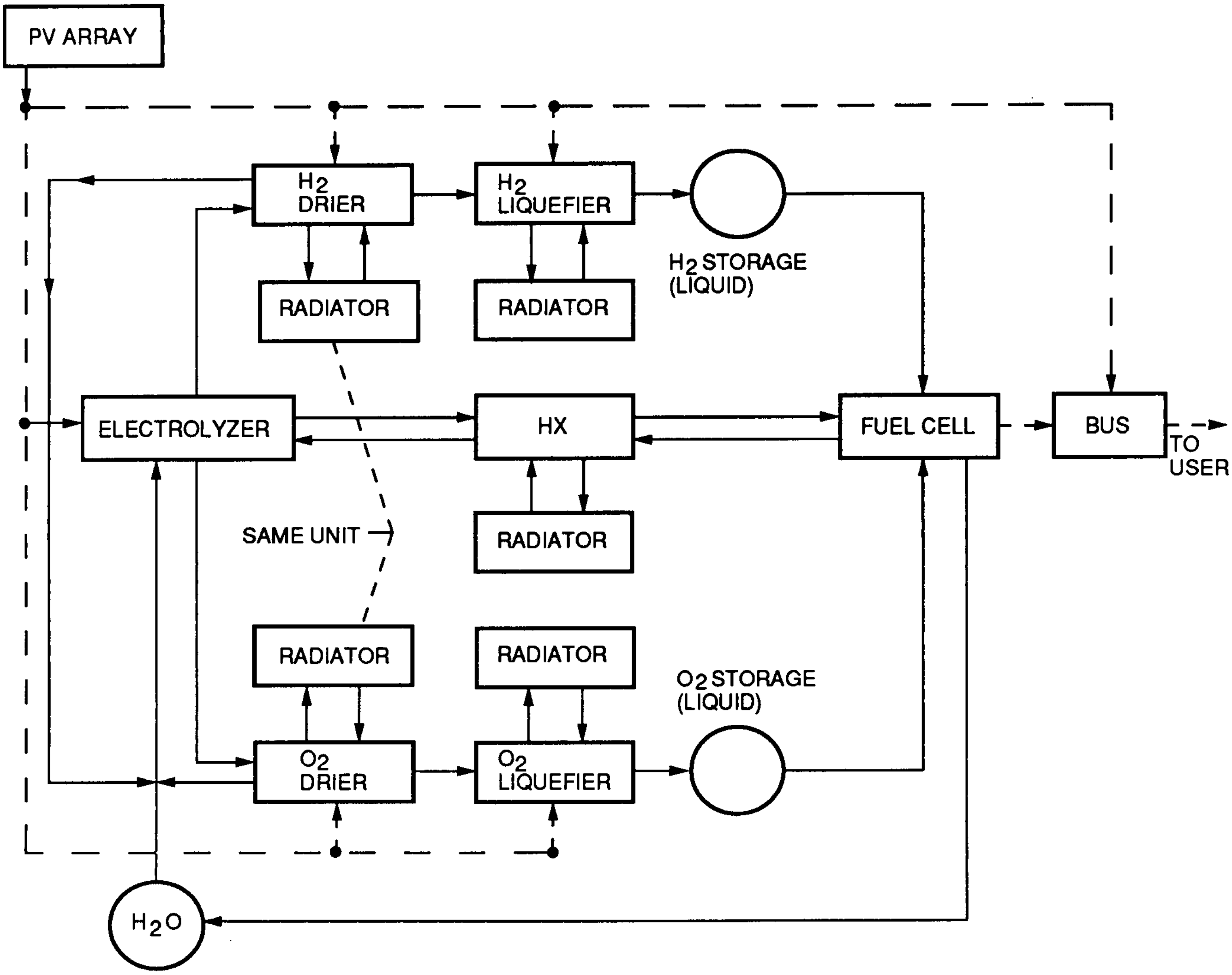

Figure 8. - Layout of RFC system with cryogenic storage.

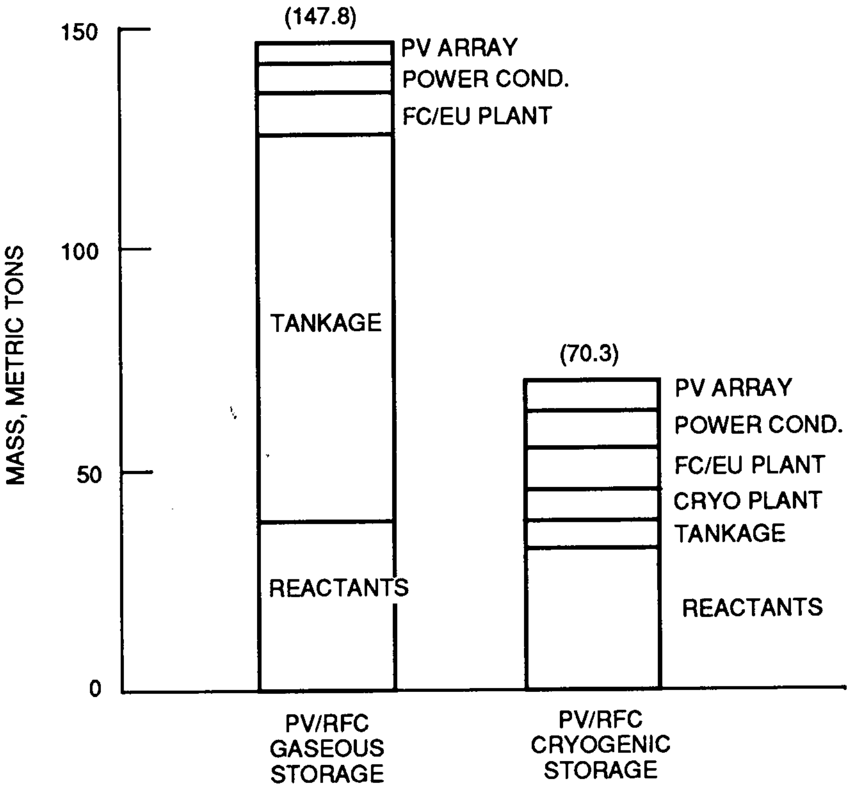

Figure 9. - 250 kW lunar surface power system comparison.

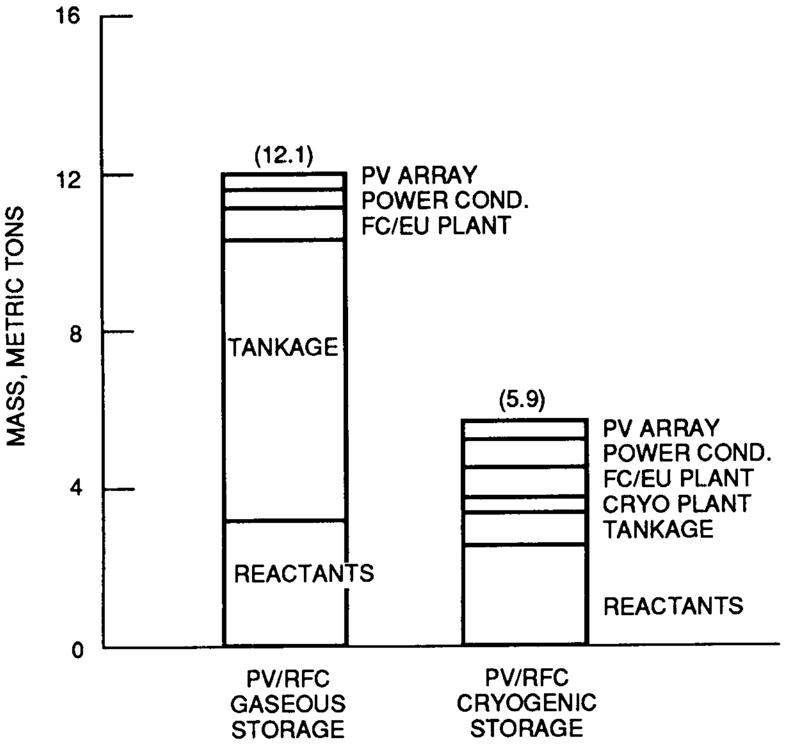

Figure 10. - 20 kW lunar surface power system comparison.

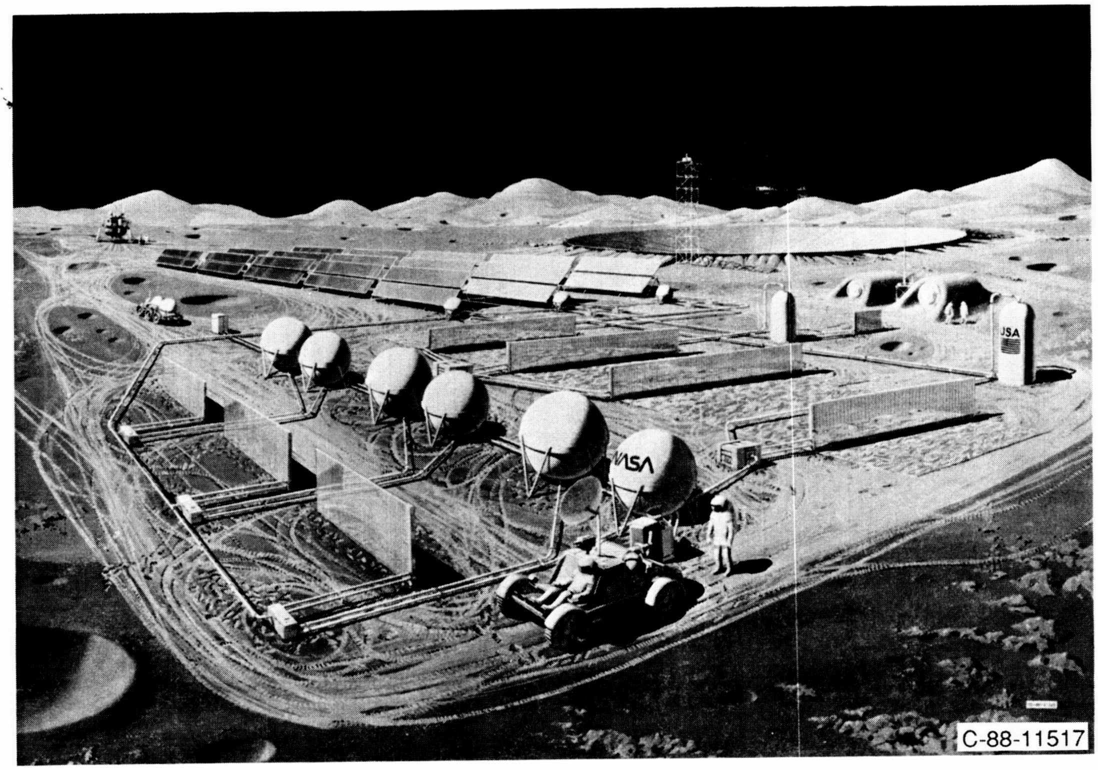

Figure 11. - 50 kWe solar photovoltaic-regenerative fuel cell power system with cryogenic storage for a lunar observatory.

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16. Abstract

There are major advantages to be gained by integrating a cryogenic reactant storage system with a hydrogen-oxygen regenerative fuel cell (RFC) to provide on-site electrical power during the lunar night. Although applicable to any power system using hydrogen-oxygen RFC s for energy storage, cryogenic reactant storage offers a significant benefit whenever the sun/shade cycle and energy storage period approach hundreds of hours. For solar power installations on the moon, cryogenic reactant storage reduces overall specific mass and meteoroid vulnerability of the system. In addition, it offers synergistic benefits to on-site users, such as availability of primary fuel cell reactants for surface rover vehicles and cryogenic propellants for OTV's. The integration involves processing and storing the RFC reactant streams as cryogenic liquids rather than pressurized gases, so that reactant containment (tankage per unit mass of reactants) can be greatly reduced. Hydrogen-oxygen alkaline RFC s, GaAs photovoltaic (PV) arrays, and space cryogenic processing/refrigeration technologies are assumed to be available for the conceptual system design. Advantages are demonstrated by comparing the characteristics of two power system concepts: (1) a conventional lunar surface PV/RFC power system using pressurized gas storage in SOA filament wound pressure vessels and, (2) that same system with gas liquefaction and storage replacing the pressurized storage. Comparisons are made at 20 and 250 kWe. Although cryogenic storage adds a processing plant (drying and liquefaction) to the system plus 30 percent more solar array to provide processing power, the approximate order of magnitude reduction in tankage mass, confirmed by this analysis, results in a reduction in overall total system mass of approximately 50 percent.

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