N91-19221

Indium Phosphide Solar Cells

I. Weinberg, Chairman
NASA Lewis Research Center
Cleveland OH

The indium phosphide working group considered the folowing questions.

1. What appears to be the most fruitful directions for InP solar cell research?
2. What can be done to decrease cell cost?
3. What can be done to increase cell efficiency?
4. What measurements are needed for a better understanding of cell performance?
5. n/p vs p/n? Is the question settled? If not what should be done?
6. What is known about SRV?
7. Which areas in radiation effects require additional effort?
8. What are the major problems in cell contacting?
9. Should the present level of InP solar cell research in the U.S.A. be maintained, increased or decreased?

With regard to research directions, the working group recommended continued or additional effort on increasing cell efficiency, reducing cost and the production of larger area cells. Considering the latter it was felt that scale up was not a problem and that high efficiency cells with areas comparable to the present GaAs cells appeared to be feasible.

Suggestions for reducing cell cost included heteroepitaxial growth on cheaper, sturdier substrates such as silicon or germanium, use of processes, such as CLEFT and peeled film technology, which enable one to reuse the presently used, expensive, InP substrate. It was suggested that new crystal growth techniques, to replace the presently used LEC method of crystal growth, could be helpful in reducing substrate cost. With respect to the latter an increase in the number of suppliers, by introducing more competitive pricing, would possibly tend to reduced substrate cost as would the more obvious procedure of procuring large quantities of substrates in a single order. Obviously this would depend on the capability and necessity of producing large quantities of solar cells or on initiation of a Mantech program.

To increase cell efficiency, there is a need for lattice matched window materials in order to reduce the SRV. Semiconductors suggested for this application included AlAsSb and AlInAs with components in the appropriate proportions. The development of multibandgap cells is an obvious direction to take in attaining higher efficiencies. While this would not necessarily lead to higher efficiencies for InP per se it could result in higher efficiency multicomponent cells, one component of which would be InP. Improved substrate material is a necessity in these efforts. Research directed at higher efficiency should also have as a goal the maintenance of high radiation resistance while at the same time yielding high BOL efficiencies.

Measurements needed for a better understanding of cell performance include absorption coefficients at wavelengths greater than 0.85 micrometers, minority carrier lifetimes, diffusion lengths, SRV and experimental determinations of heavy doping effects. Although there is presently some activity in several of these measurement areas, there is a need for determinations over a wide range of dopant concentrations. Also wherever feasible it would be desirable to perform measurements on the actual solar cell structures.

The question of which configuration is preferable, n/p or p/n, is still undecided. Although several modelling efforts have yielded slightly higher theoretical efficiencies for the p/n configuration, additional experimental results are needed in order to make an intelligent choice. One would have greater confidence in the modelling results if more accurate input parameters were available. It was pointed out that, because of the lower emitter sheet resistance, the n/p configuration was preferrable for shallow junction cells. Furthermore, the problem of contacting p–type material needs to be considered in making the final choice. In addition, the few experiments in which both configurations were compared show a slightly lower radiation resistance for the p/n configuration at the higher 1 MeV electron and 10 Mev proton fluences.

Considering surface recombination velocity, there is a need for making this difficult measurement on actual solar cell surfaces. Modelling calculations suggest values approaching 10^7cm/sec for the surface of heavily doped emitters. Although measurements on heavily doped InP, using photoluminescence, indicate values approaching this magnitude there is a need for direct measurements, if feasible, on actual solar cell emitter surfaces. It was pointed out that older measurements, which yielded SRV's in the 10^3–10^4 cm/sec range, were obtained on InP which was cleaved in vacuum. Hence, the need for real world measurements.

In the area of radiation effects, there is a need to obtain data over a wide range of energies for both protons and electrons. Additional annealing experiments are required, especially with regard to photon annealing. Flight experiments are a necessity and every effort should be made to seek out and utililize flight opportunities as they arise. Defect studies should be expanded to obtain a more definitive answer to the reasons for the superior radiation resistance of InP.

The working group concluded that InP solar cell research in the US should be at least maintained at its present level and preferrably increased. The group surfaced a requirement for increased university participation in the areas of crystal growth, cell fabrication and analysis. In addition to strengthening the present program, this would result in graduates trained in the special requirements presented by growth of InP crystals and cell processing. In addition the present program would benefit from increased activity in surface passivation and improvements in base substrate material quality.

Space Cell Theory and Modeling

James Hutchby
Research Triangle Institute
Research Triangle Park, NC

The workshop on PV Theory and Modeling was attended by about thirty people drawn from the industrial, government and academic communities

Discussed during the workshop were current concerns in cell modeling, both general and material-specific, a discussion of PC-1D, a commercial PV modeling computer code, and future issues. The major points discussed at the workshop are displayed in the following viewgraphs.

Current Issues in Cell Modeling--GaAs

Physics

- Anomalous Log I vs V behavior at P_{max}
- Reverse Bias Breakdown Mechanism(s)
- Dominant Defect Structures Governing Radiation Damage Effects

Parameters

- Minority Carrier Parameters

  (determine directly from minority carrier measurements)

Current Issues in Cell Modeling--InP

Physics

- Heavy Doping Effects
  - -Bandgap Narrowing
  - -Optical Absorption Coefficient
- Anomalously Low V_{oc} ?
- Surface Recombination

Parameters

- Many important parameters not well known
  - n_i, (N_D, N_A)
  - L_n, L_p, τ_n τ_p (N_D, N_A)
  - S_n, S_p $(N_D, N_A, \ldots)$

PC - 1D V.2

Description

- One-dimensional solar cell model
- Numerical
- Runs on IBM-PC; User-friendly
- Steady-state and transient analysis
- Si, GaAs, AlGaAs built-in models; also user-specified models

Validation

- Si predictive, GaAs near-predictive

Issues

- Absorption Coefficient vs. temperature needs more work

Future Issues

New problems for modeling

- **Light-trapping cells**
- **Thin films**

Theory and Modeling--Conclusions

GaAs

- Physics appears to be well understood
- Accurate modeling requires material/process specific parameter measurements
- Radiation induced defects not understood

InP

- Physics needs more work
  - heavy doping effects
  - low V_{oc}
  - surface recombination
- Many inportant parameters need better measurements

Thin films

- Physics--uncertain
- Parameters--not well known

Invited Paper

Cryogenic Reactant Storage for Lunar Base Regenerative Fuel Cells

Lisa Kohout
NASA Lewis Research Center
Cleveland OH

CRYOGENIC REACTANT STORAGE FOR LUNAR BASE REGENERATIVE FUEL CELLS

LISA L. KOHOUT

NASA LEWIS RESEARCH CENTER
CLEVELAND, OHIO

CRYOGENIC REACTANT STORAGE FOR LUNAR BASE REGENERATIVE FUEL CELLS

<u>OBJECTIVE</u>

TO DETERMINE THE IMPACT OF CRYOGENIC REACTANT STORAGE ON THE MASS OF AN ALKALINE REGENERATIVE FUEL CELL POWER SYSTEM FOR LUNAR APPLICATION

i.e. DOES STORING THE REACTANT CRYOGENICALLY, INCLUDING A REFRIGERATION PLANT AND EXTRA SOLAR ARRAY TO POWER IT, RESULT IN A LOWER OVERALL SYSTEM MASS THAN CONVENTIONAL PRESSURIZED GAS STORAGE?

<u>THE CARROT</u>: CRYOGENIC STORAGE TAKES MUCH LESS TANK WEIGHT PER POUND OF REACTANT THAN GASEOUS STORAGE

<u>THE STICK</u>: CRYOGENIC STORAGE REQUIRES A REFRIGERATION PLANT AND EXTRA POWER

CRYOGENIC REACTANT STORAGE FOR LUNAR BASE REGENERATIVE FUEL CELLS

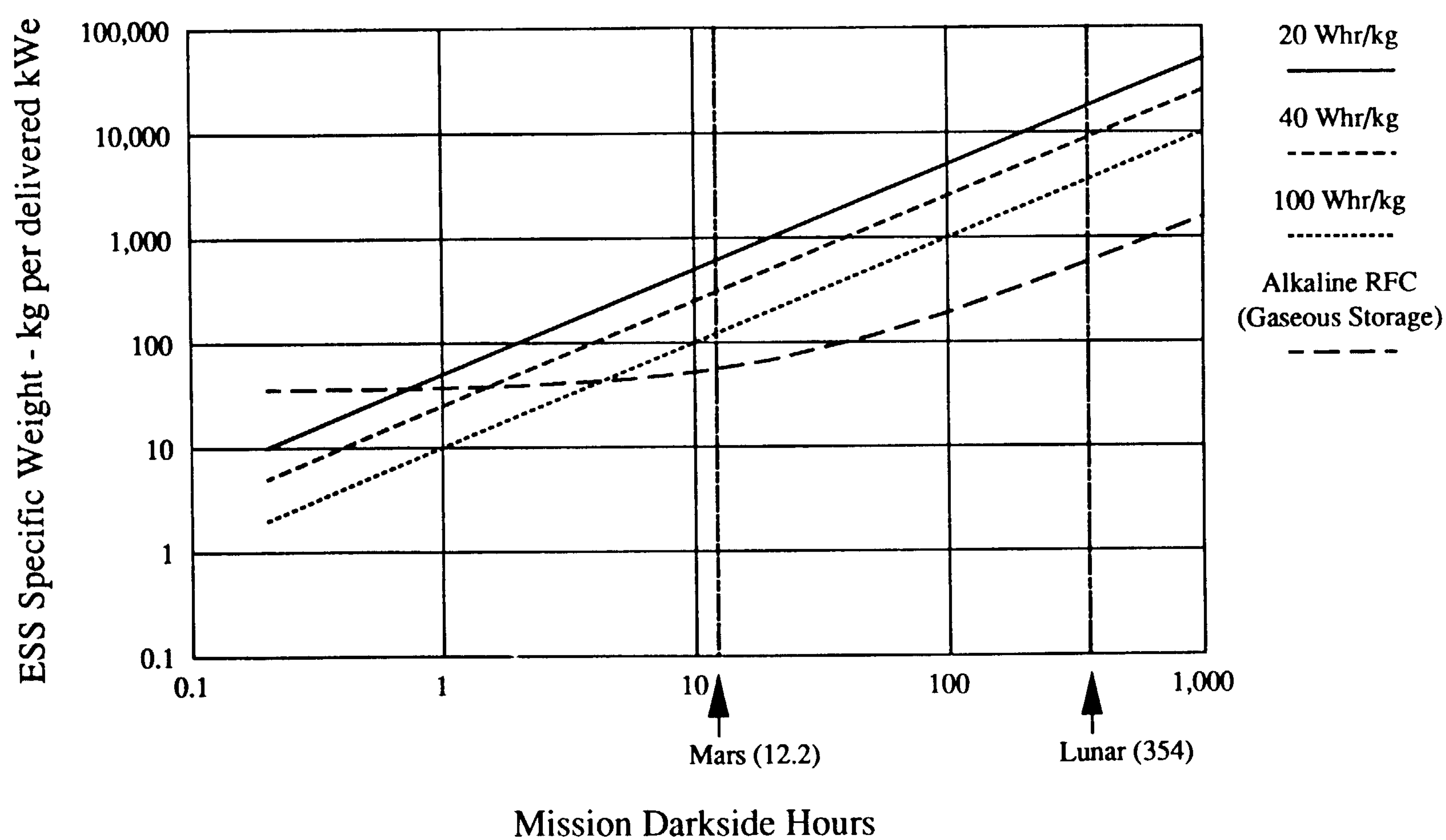
APPROACH

- MODEL A CONVENTIONAL RFC POWER SYSTEM FOR A MANNED LUNAR INSTALLATION

- REPLACE THE GASEOUS HYDROGEN AND OXYGEN STORAGE TANKS WITH LIQUEFACTION UNITS AND CRYOGENIC STORAGE TANKS

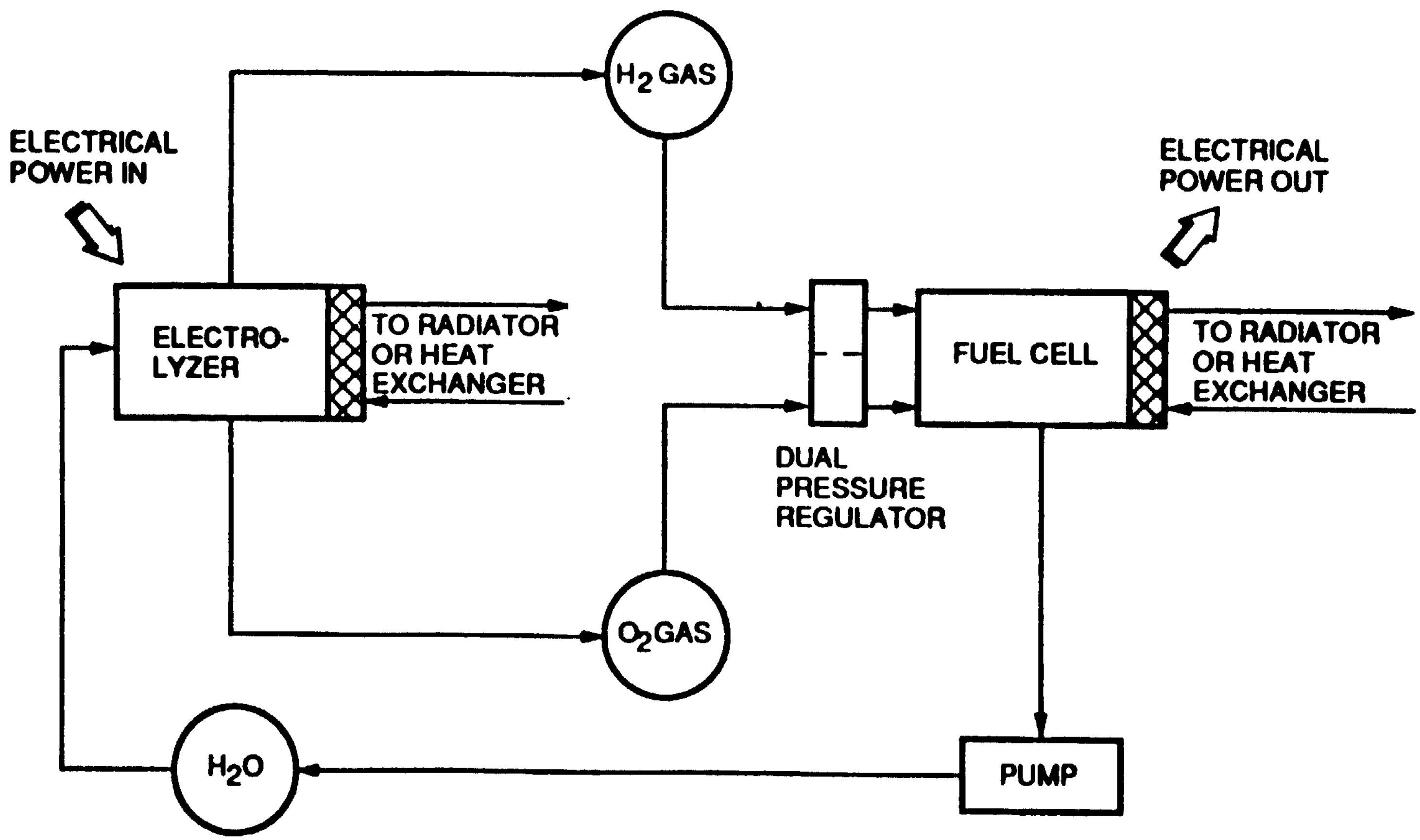
- CONSIDER 20 kW AND 250 kW SYSTEMS

RFC vs. Batteries for Varied Darkside Periods

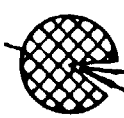


POWER TECHNOLOGY DIVISION

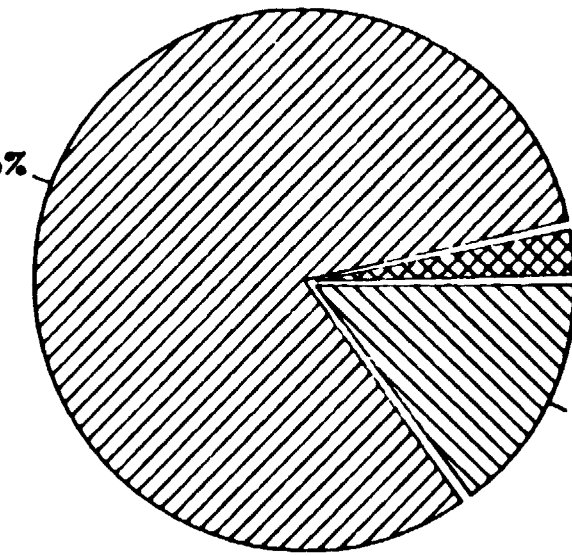
CONVENTIONAL REGENERATIVE FUEL CELL SYSTEM (REACTANTS STORED AS PRESSURIZED GASES)



COMPARISON OF MASS BREAKDOWNS FOR A 250 kW REGENERATIVE FUEL CELL SYSTEM



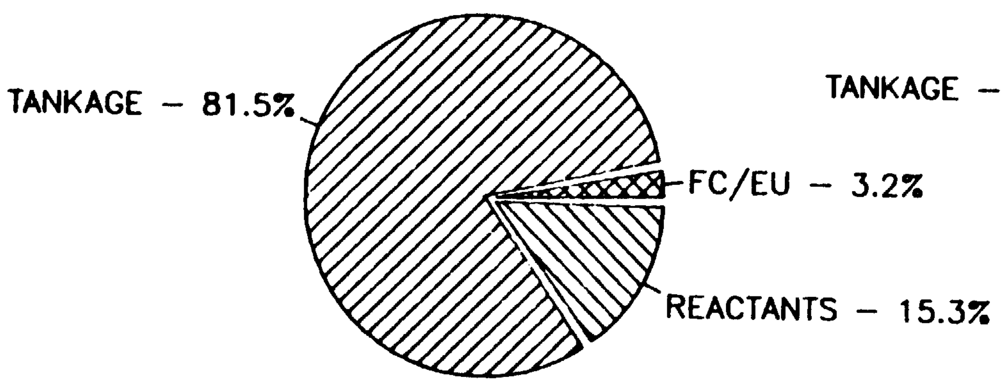
LEO RFC
(~0.5 HR. STORAGE)



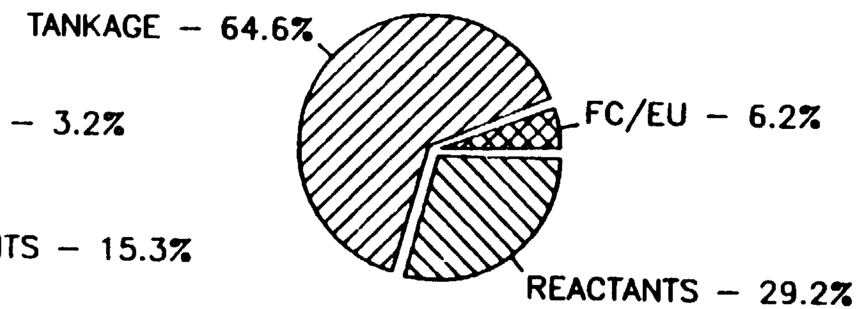
LUNAR RFC
(~330 HR. STORAGE)

(INCONEL TANK MATERIAL)

MASS BREAKDOWN FOR A 250 kW LUNAR REGENERATIVE FUEL CELL SYSTEM

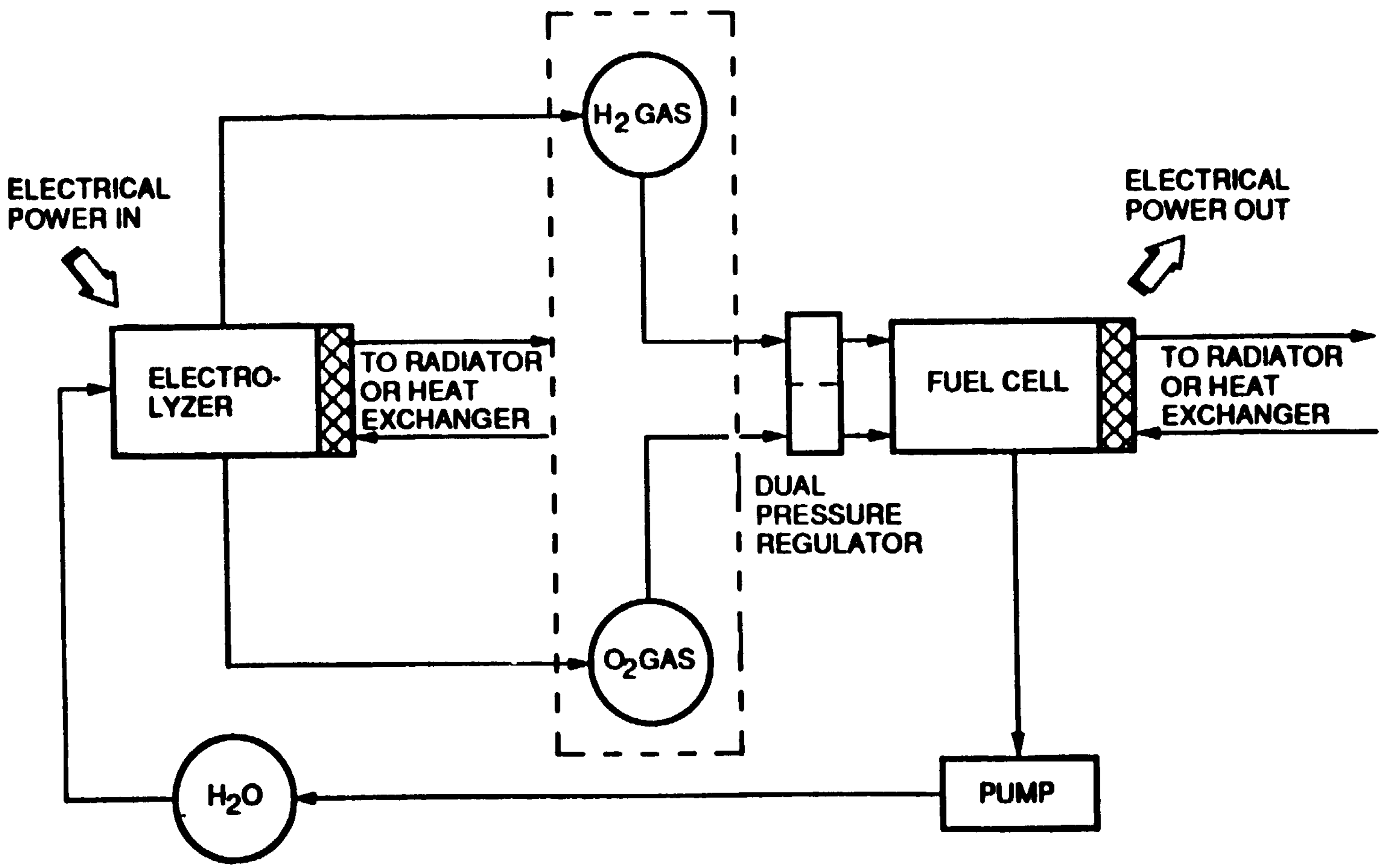


INCONEL TANKS

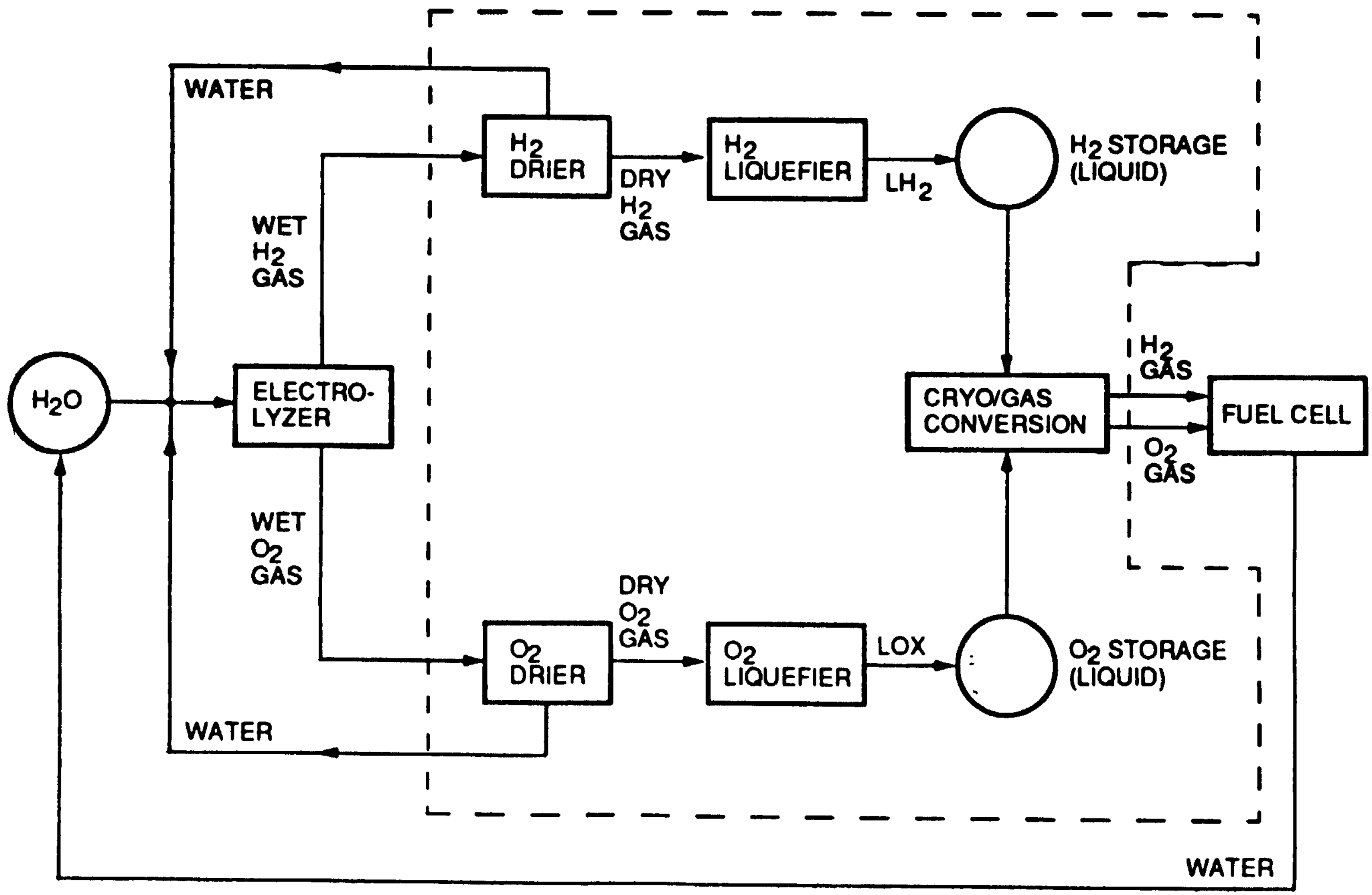


KEVLAR TANKS

CONVENTIONAL REGENERATIVE FUEL CELL SYSTEM (REACTANTS STORED AS PRESSURIZED GASES)



REGENERATIVE FUEL CELL SYSTEM
(REACTANTS STORED AS CRYOGENIC FLUIDS)



MODELING OF FUEL CELL / ELECTROLYZER SUBSYSTEM

- MODELED USING CODE DEVELOPED AT NASA LEWIS BY M. HOBERECHT AND L. RIEKER

- OPERATING CONDITIONS

FUEL CELL	
CELL ACTIVE AREA	930 SQ.CM.
OPERATING TEMPERATURE	355 K
OPERATING PRESSURE	0.4 MPa
CURRENT DENSITY	161 mA/SQ.CM.
ELECTROLYZER	
CELL ACTIVE AREA	930 SQ.CM.
OPERATING TEMPERATURE	355 K
OPERATING PRESSURE	2.2 MPa
CURRENT DENSITY	161 mA/SQ.CM.

MODELING OF DRYING AND LIQUEFACTION SUBSYSTEMS

PRIMARY REFERENCE FOR PRODUCTION OF CRYOGENS IN SPACE:

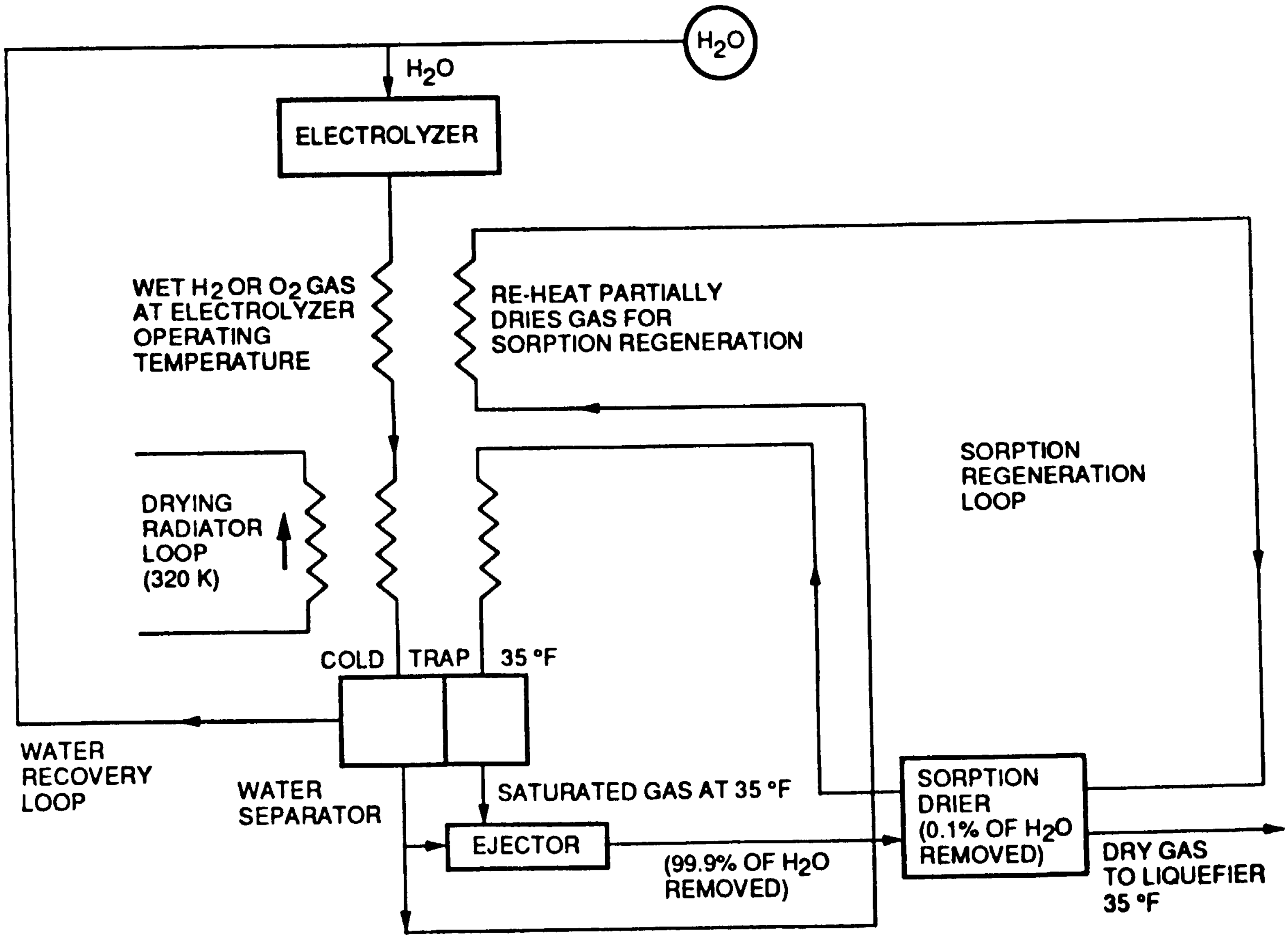
"IN-SPACE PROPELLANT PROCESSING USING WATER DELIVERED AS SHUTTLE CONTINGENCY PAYLOAD," E.H. BOCK AND J.G. FISHER, GENERAL DYNAMICS CONVAIR DIVISION, 1978.

SCENARIO

- O SHUTTLE DELIVERS WATER STORED AS CONTINGENCY PAYLOAD TO ON-ORBIT PROPELLANT PROCESSING FACILITY
- O AT PROCESSING FACILITY, WATER IS ELECTROLYZED AND PRODUCT GASES LIQUEFIED AND STORED AS CRYOGENS
- O CRYOGENS USED AS PROPELLANTS FOR SPACE-BASED OTV

REFERENCE DESCRIBES THE DEFINITION AND PRELIMINARY DESIGN OF THE PROPELLANT PROCESSOR SUBSYSTEMS INCLUDING DRYING, LIQUEFACTION, AND STORAGE

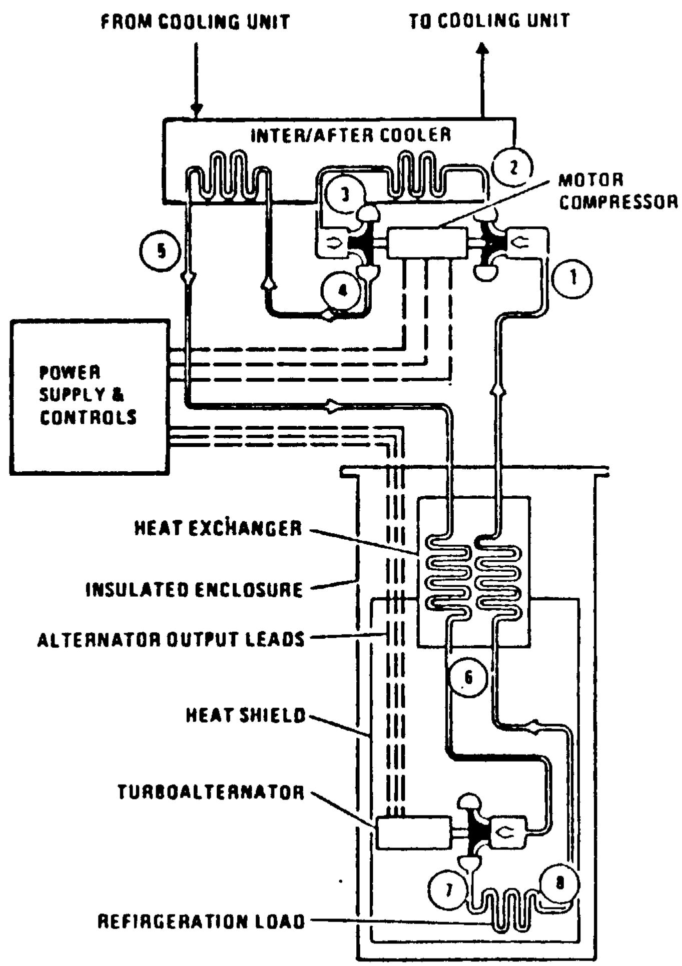
GASEOUS HYDROGEN/OXYGEN DRYING SYSTEM

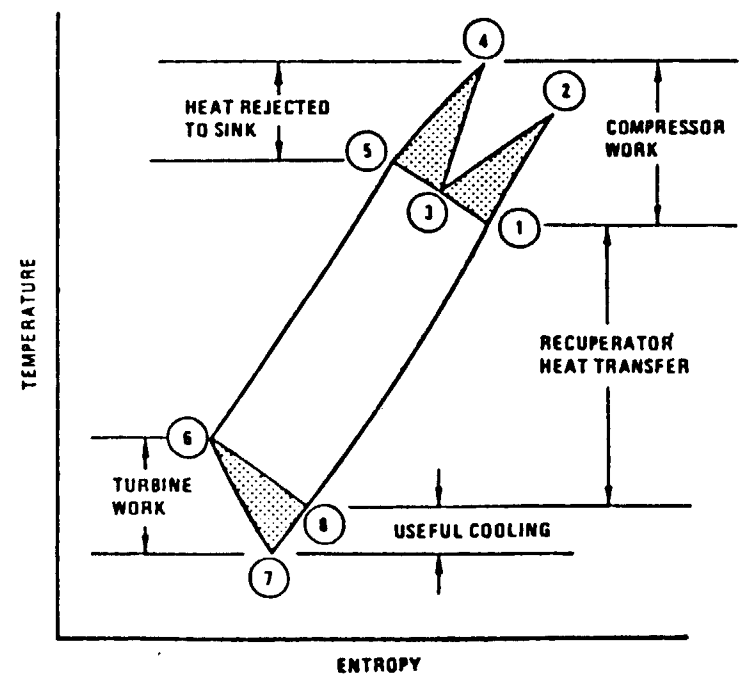


MODELING OF HYDROGEN/OXYGEN LIQUEFACTION SYSTEM

- UTILIZES REVERSED BRAYTON CYCLE FOR LIQUEFACTION
- LIQUEFIES H2/02 GAS AS WELL AS BOIL-OFF FROM STORAGE TANKS
- EQUIPMENT REQUIRED FOR HYDROGEN AND OXYGEN LIQUEFACTION IS SIMILAR EXCEPT THAT TWO REFRIGERATION STAGES ARE REQUIRED FOR HYDROGEN

REVERSED BRAYTON LIQUEFACTION CYCLE





REFRIGERATION CYCLE

MODELING OF CRYOGENIC REACTANT STORAGE TANKS

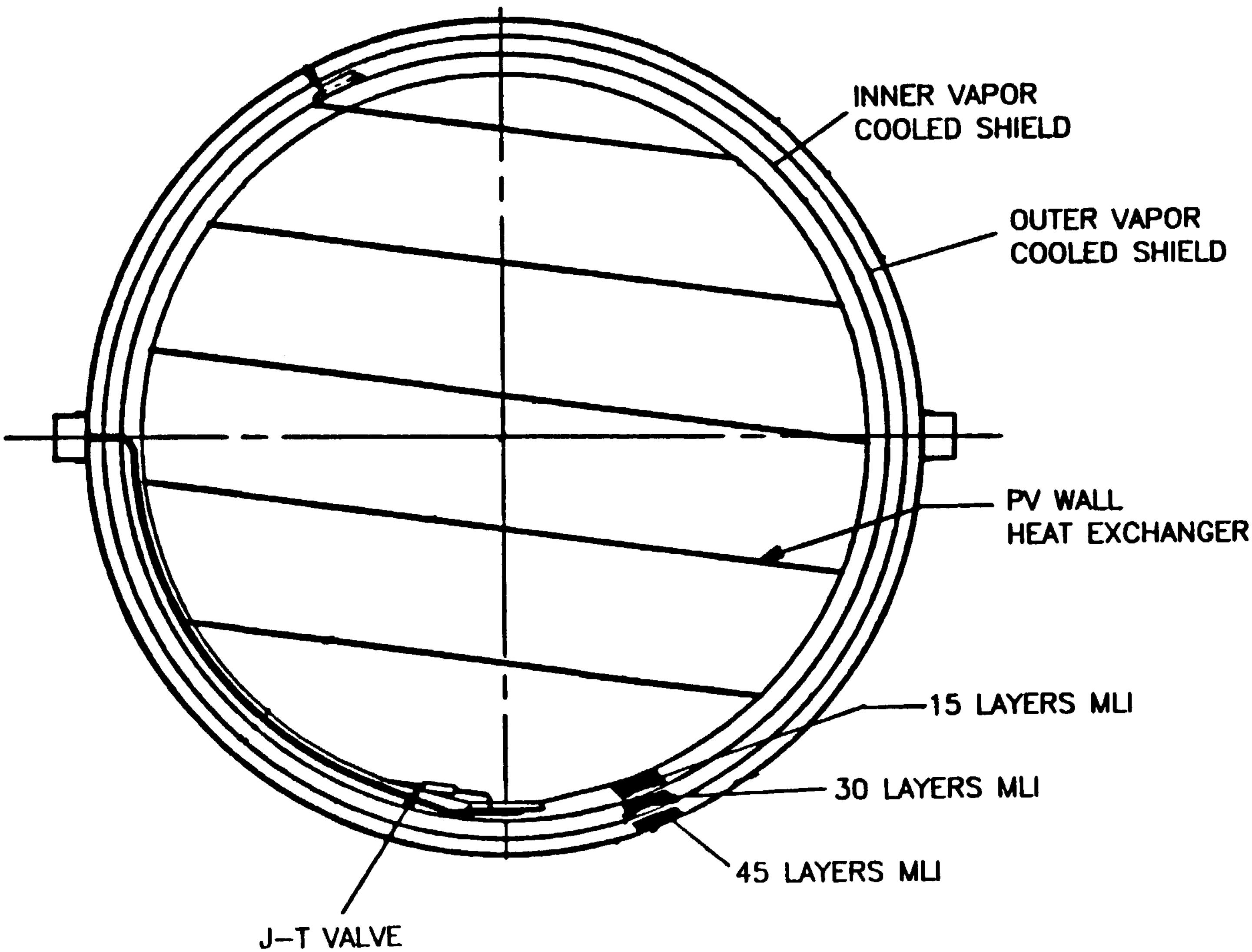
- O BASED ON BEECHCRAFT DESIGN

  SPACE STATION EXPERIMENT DEFINITION:
  LONG-TERM CRYOGENIC FLUID STORAGE

- O ALUMINUM INNER PRESSURE VESSEL AND OUTER SHELL
- O 90 LAYERS OF MULTILAYER INSULATION AND 2 VAPOR COOLED SHIELDS PLACED BETWEEN CONCENTRIC INNER AND OUTER SHELLS
- O 5% REACTANT RESIDUAL ALLOWED
- O ADDITIONAL 10% TANK VOLUME ALLOWED TO ACCOMMODATE MAXIMUM ACHIEVABLE FILL LEVEL

POWER TECHNOLOGY DIVISION

SCHEMATIC OF CRYOGENIC STORAGE TANK



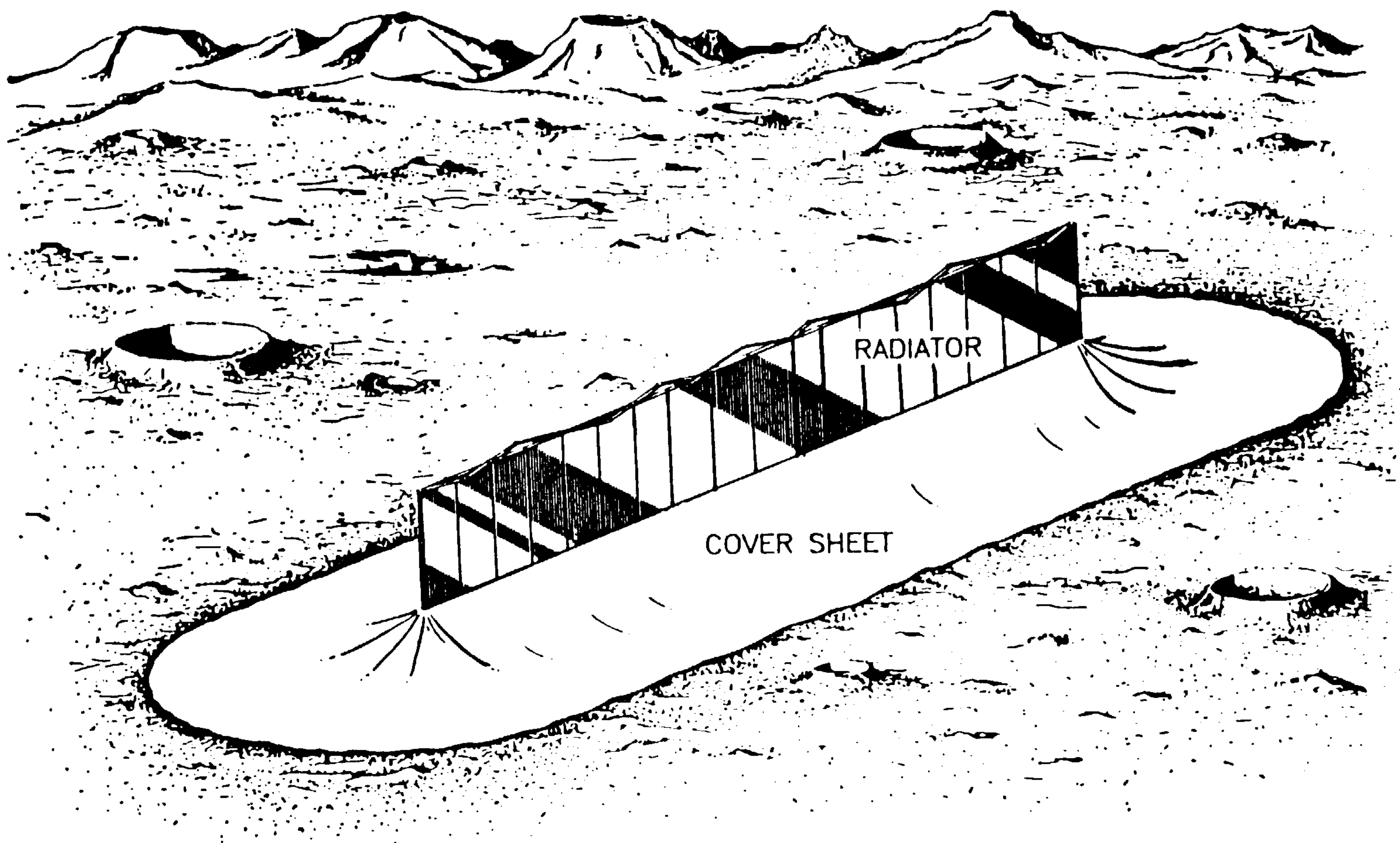
MODELING OF SUBSYSTEM RADIATORS

- RADIATORS ARE REQUIRED FOR THE FOLLOWING SUBSYSTEMS:
  - FUEL CELL
  - DRYING
  - OXYGEN LIQUEFACTION
  - HYDROGEN LIQUEFACTION
- ALL RADIATORS EXCEPT FUEL CELL RADIATOR WERE SIZED BASED ON REJECTION TEMPERATURES AND APPROXIMATED HEAT LOADS FROM BOCK AND FISHER REFERENCE
- FUEL CELL RADIATOR WAS SIZED BASED ON REJECTION TEMPERATURE AND HEAT LOAD FOUND FROM RFC CODE
- DAYTIME SINK TEMPERATURE OF 220 DEG K WAS USED (VERTICAL ORIENTATION OVER SURFACE SHEET)

POWER TECHNOLOGY DIVISION

NASA Lewis Research Center

SCHEMATIC OF RADIATOR WITH GROUND COVER SHEET



REFERENCE: "A METHOD FOR REDUCING THE EQUIVALENT SINK TEMPERATURE OF A VERTICALLY ORIENTED RADIATOR ON THE LUNAR SURFACE", D. BIEN AND D. GUENTERT, NASA LERC, 1968

MODELING OF SOLAR PHOTOVOLTAIC ARRAY

O GaAs SUN–TRACKING ARRAY ON LUNAR SURFACE

– INCLUDES ARRAY BLANKET, SUPPORT FRAME, PIVOTS, TRACKING MOUNT, AND WIRING HARNESS

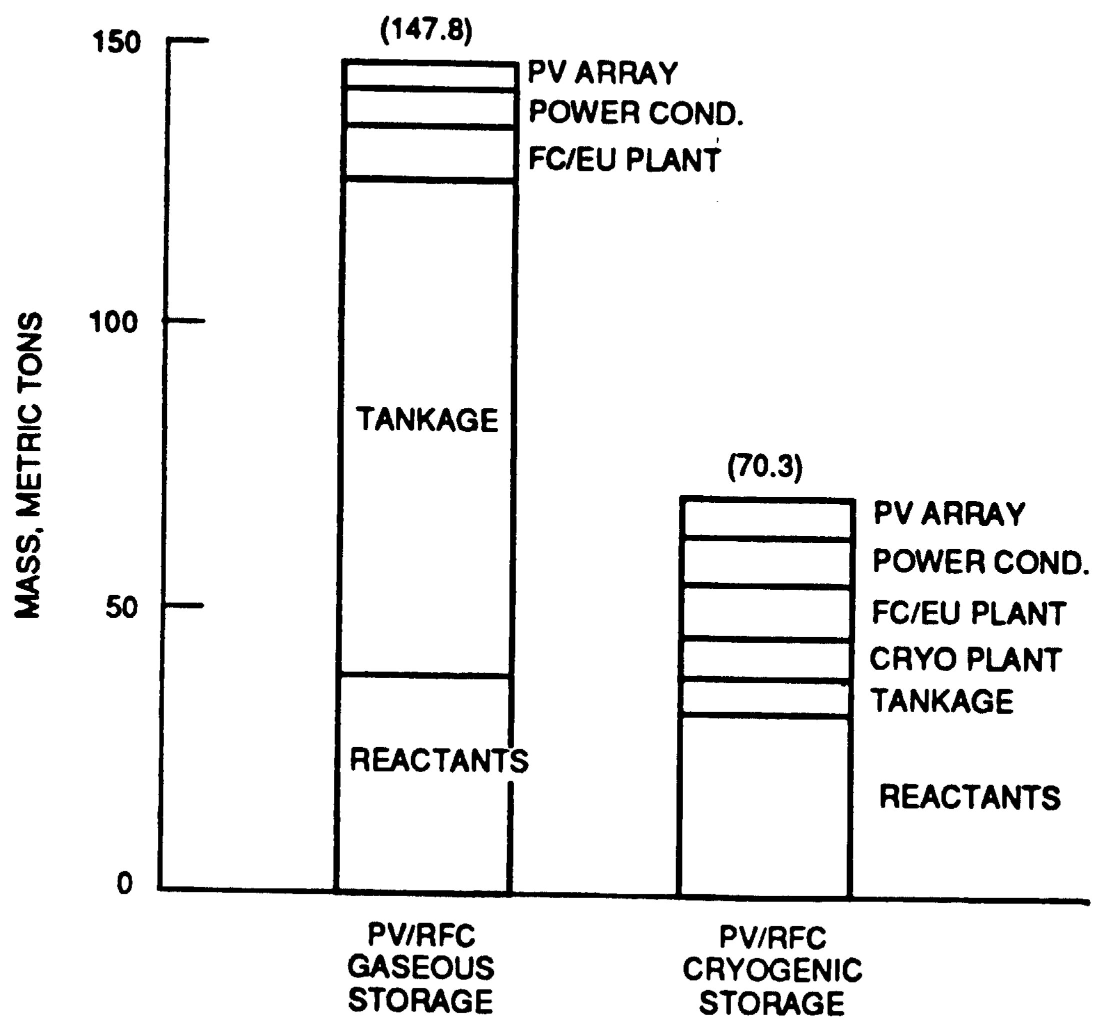
EFFICIENCY	22.512 %
SPECIFIC POWER*	123 W/KG
SPECIFIC MASS	2.48 KG/SQ.M.

* (@ 22.512% EFFICIENCY, 110 DEG.C.)

BREAKDOWN OF POWER REQUIREMENTS
250 kW SYSTEM

COMPONENT	POWER TO BE SUPPLIED BY PV ARRAY (kW)
ELECTROLYZER	400.0
H2/02 DRIERS	2.0
H2 LIQUEFACTION UNIT	123.5
02 LIQUEFACTION UNIT	71.3
BASELINE POWER TO USER	250.0
TOTAL POWER TO BE DELIVERED BY PV ARRAY:	846.8
REQUIRED ARRAY AREA:	2780 SQ.M. (2134 SQ.M. W/O CRYO STORAGE)

250 kW LUNAR SURFACE POWER SYSTEM COMPARISON

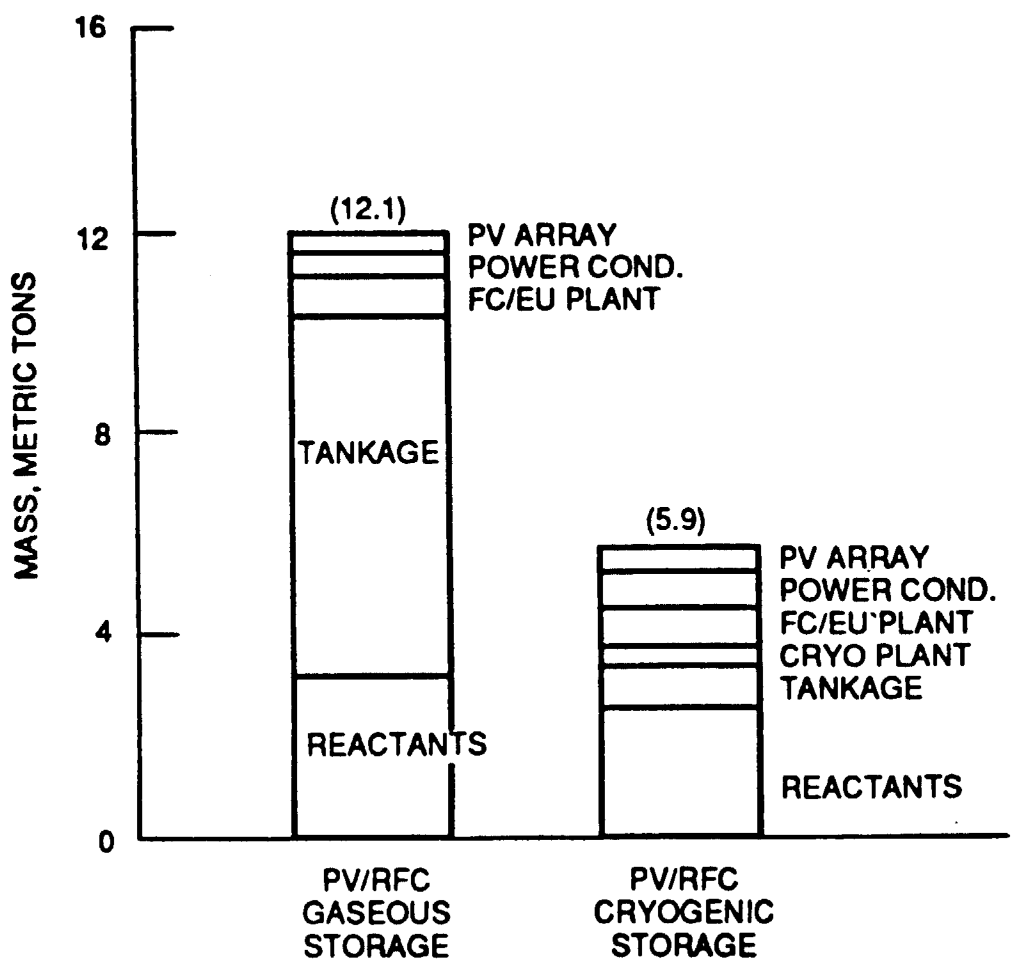


COMPARISON OF REACTANT STORAGE TANK SIZES
250 kW SYSTEM

	GASEOUS STORAGE (KEVLAR)	CRYOGENIC STORAGE
HYDROGEN TANK		
MASS OF H2 (M.T.)	4.40	3.59
RADIUS (M)	9.0	INNER SHELL: 2.4 OUTER SHELL: 2.6
VOLUME (CU.M.)	2969	56
OXYGEN TANK		
MASS OF O2 (M.T.)	34.9	28.5
RADIUS (M)	7.1	INNER SHELL: 1.9 OUTER SHELL: 2.0
VOLUME (CU.M.)	1485	27

(BASED ON SINGLE TANK PER REACTANT)

20 kW LUNAR SURFACE POWER SYSTEM COMPARISON



CONCLUSIONS

- O CRYOGENIC REACTANT STORAGE APPEARS TO HAVE A MAJOR BENEFIT FOR LUNAR SURFACE REGENERATIVE FUEL CELL ENERGY STORAGE SYSTEMS

- O REDUCTION IN TANK WEIGHT MORE THAN COMPENSATES FOR THE ADDITIONAL WEIGHT OF LIQUEFACTION PLANTS, RADIATORS, AND PV ARRAYS

- O FOR SOLAR PV/RFC POWER SYSTEMS UTILIZING CRYOGENIC STORAGE, THE RESULTING OVERALL MASS REDUCTION IS APPROXIMATELY 50 PERCENT (COMPARED WITH GAS STORAGE USING FILAMENT WOUND PRESSURE VESSELS)

- O SYNERGISTIC USER BENEFITS ALSO EXIST – THE CRYO RFC SYSTEM CAN PROVIDE LOX AND LH2 ON–SITE FOR OTHER USES (REFUELING, PROPELLANTS, ETC.)

AREAS FOR FURTHER STUDY

- SCALABILITY OF THE LIQUEFACTION PROCESS COMPONENTS
- OPTIMIZATION OF SUBSYSTEMS
- CRYOGEN–FUEL CELL INTERFACE
- INFRASTRUCTURE CONSIDERATIONS
- RELIABILITY/REDUNDANCY TRADE–OFFS