FEASIBILITY STUDY

DIVER HEATING SYSTEM FOR USE ABOARD JOHNSON-SEA-LINK

BY

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A B S T R A C T

The control and maintenance of a comfortable working environment for divers working under pressure and exposure to cold water is not only a comfort control measure, but an absolute necessity for the safety of the diver. The purpose of this report is to define the problem and criteria for a heating system, the feasibility of various types of heat sources and to present conclusions and recommendations, based upon the findings.

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INTRODUCTION

Integral to any environmental control system is the reduction of heat losses, from the dive compartment, to an acceptable level and provision of a safe, reliable, low-maintenance system to provide any supplemental heat required.

In addition to the heating of the diver lock-out compartment, any system must also supply heat to a free-swimming diver for the duration of operations outside the submersible.

This report will try to provide ideas into all three areas of interest.

BASIC REQUIREMENTS

Diver Compartment Requirements

The temperature in the dive compartment must be maintained at a level which will provide the occupants with an acceptable skin temperature while working in a cold, damp environment and wearing a minimum of protective clothing.

Finds of Ralph Nevins and Associates in 1965 (1) stated that a suitable comfort level may be maintained for a wide range of conditions when a skin temperature of 91-93^{o} F. is maintained. Thus, this will be the target temperature for the JOHNSON-SEA-LINK.

Our first problem to investigate is the heat transfer from the JOHNSON-SEA-LINK and to minimize this loss. As a base study, I used the Thermal Response of the JOHNSON-SEA-LINK Lock-Out Chamber by Robert Randall. In his report, he gives a detailed theoretical practical work-up of the heat transfer from the JOHNSON-SEA-LINK. There are three basic methods of heat transfer from a high to low temperature region, and these are conduction, convection, and radiation. In the underwater environment, radiation heat transfer is only important when considering the heat radiated by individuals to the walls of their pressure vessel. The most important methods of heat transfer underwater are conduction and convection.

The law regarding one-dimensional heat conduction for a sphere is:

$$q = 4\pi r_o r_i k (T_o - T_i)/(r_o - r_i)$$

k = thermal conductivity

r_o = outside radius

r_i = inside radius

T_o = outside temperature

T_i = inside temperature

For Mr. Randall's report an equivalent sphere was used to predict the steady state heat transfer from the JOHNSON-SEA-LINK lock-out chamber. The results are shown in Figures 1 & 2.

Table 1, Charts 1 and 2 are reproduced here from Mr. Randall's report as guidelines for study of heat loss from the diver compartment.

Temperature Difference F	Heat Transfer from Actual Chamber (2) * BTU/hr
10	1711
20	3422
30	5133
40	6844
50	8555
60	10266

*Chamber has an air atmosphere at 1 atm, and the convection coefficients inside and outside are 2 and 10 BTU/hr ft^2 respectively.

For the requirements of heating the lock-out compartment, I shall use a case of a 1000 ft. dive with ambient water of 28^o F. (worse case to be normally experienced) as any heating system must supply adequate heat plus reserve for any condition which might be encountered during an operation.

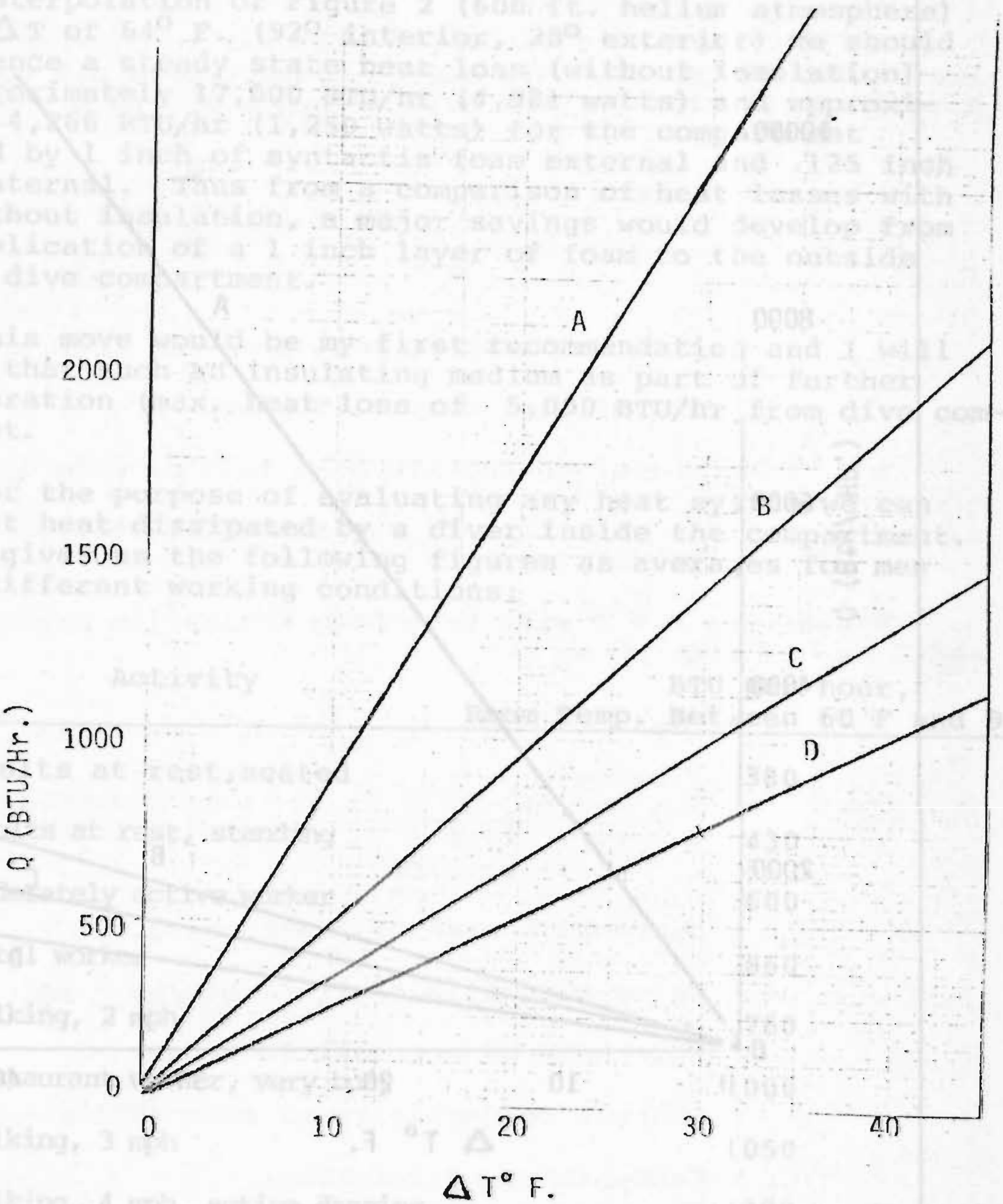

Figure 1. Chamber Steady State Heat Transfer
Air Atmosphere 150 feet.

Inches of Insulation Outside & Inside

A- none, B- 1 &.125, C- 2 & .125, D - 3 & .125

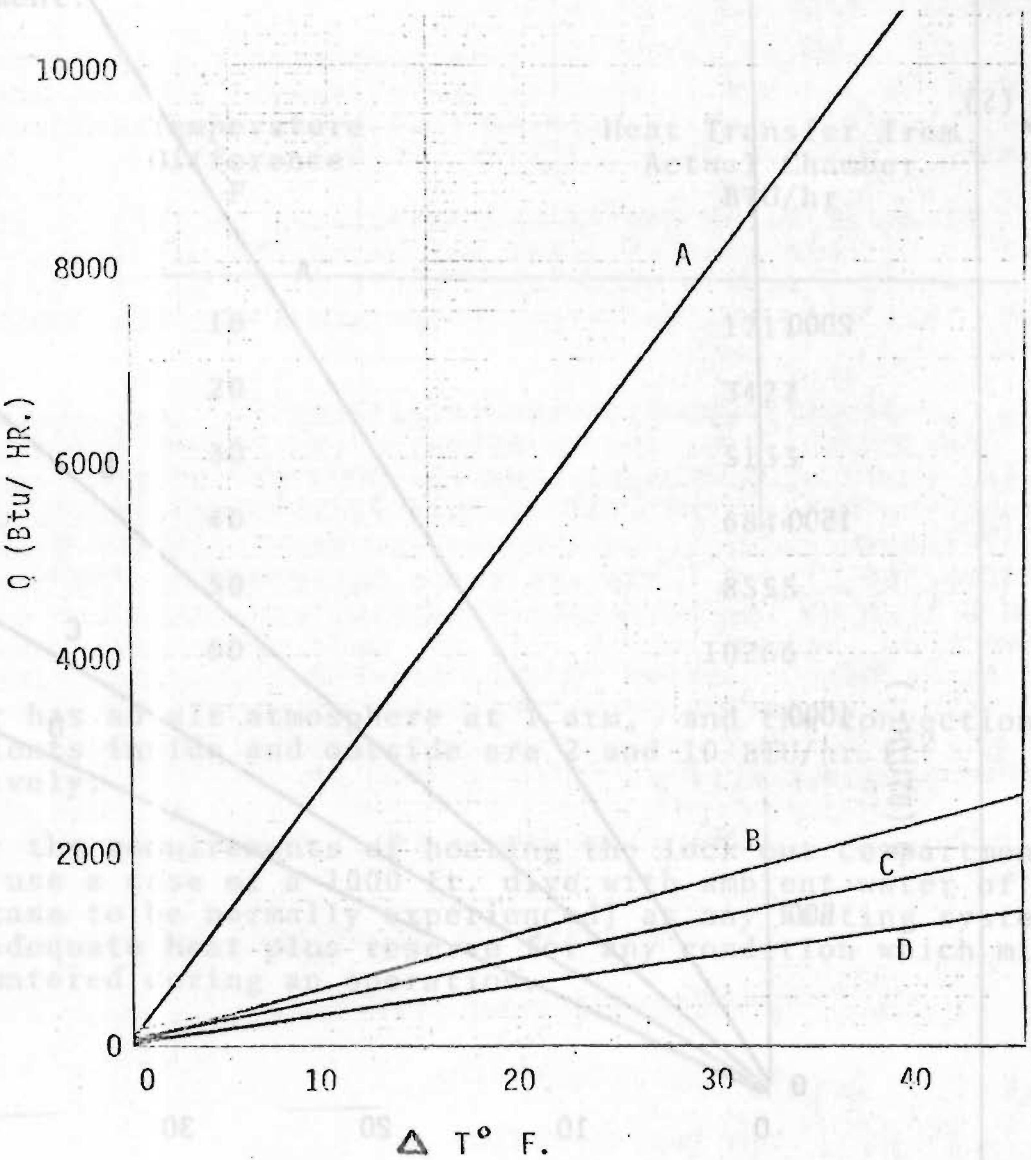

Figure 2. Chamber Steady State Heat Transfer
Helium Atmosphere 600 feet.

Inches of Insulation Outside & Inside

A- none, B- 1 & .125, C- 2 &.125, D- 3 & .125

Interpolation of Figure 2 (600 ft. helium atmosphere) for a ΔT of 64^{o} F. (92^{o} interior, 28^{o} exterior) we should experience a steady state heat loss (without insulation) of approximately 17,000 BTU/hr (4,981 watts) and approximately 4,266 BTU/hr (1,250 watts) for the compartment covered by 1 inch of syntactis foam external and .125 inch foam internal. Thus from a comparison of heat losses with and without insulation, a major savings would develop from the application of a 1 inch layer of foam to the outside of the dive compartment.

This move would be my first recommendation and I will assume that such an insulating medium as part of further consideration (max. heat loss of 5,000 BTU/hr from dive compartment.

For the purpose of evaluating any heat system we can subtract heat dissipated by a diver inside the compartment. Nevins gives us the following figures as averages for men under different working conditions:

(5)

Activity	BTU per hour, Room Temp. Between 60 F and 90 F
Adults at rest, seated	380
Adults at rest, standing	430
Moderately active worker	600
Metal worker	860
Walking, 2 mph	760
Restaurant worker, very busy	1000
Walking, 3 mph	1050
Walking, 4 mph, active dancing	1390
Slow run	2290
Maxium exertion	3000 to 4800

Thus for a seated adult, the heat produced will be 380 BTU/hr (760 BTU/hr for 2 divers) and this will not need to be generated by the heating system.

Diver Requirements

A diver working outside the submersible experiences heat losses associated with his closer contact with his surroundings. A general equation for the heat exchange may be given by

$$H + M - W = C \qquad (6)$$

where

M = rate of metabolic heat produced (BTU/hr)

W = rate of work output (BTU/hr)

C = rate of convective heat loss or gain (BTU/hr)

H = heat supplied by environmental control system (BTU/hr)

Values for M-W I will take form Nevins (in previous chart) and C can be written as

$$C = V A_c (Ts - Tw) \qquad (7)$$

with V being

$$V = \frac{1}{\frac{1}{h_o} + \frac{x}{k} + \frac{1}{C_l}}$$

Ac = Convective area of diver - (sq. ft.)

ho = Water-side film coeff - (BTU/hr - sq. ft. ^oF)

x = Thickness of wet suit in inches

k = Thermal conductivity of suit (BTU/hr - sq.ft. ^oF)

C_l = Conductance of interface

T_s = Skin temperature - ^oF

T_w = Water temperature - ^oF

Thus

$$H \left\{ \left[\frac{1}{\frac{1}{C_s} + \frac{x}{k}} \left(T_s - T_w \right) \right] A_c \right\} + M - W$$

given: M − W for moderately active worker = 600 BTU/hr, A_c = 19.5 sq. ft., C_s = 1.82 BTU/hr − sq. ft. ^oF, Tb = 98.6^o, Tw = 28^o F, x = .25 in, K= 0.087.

$$H = \left(19.5 \left(\left(\frac{1}{\frac{1}{1.82} + \frac{.25}{.087}} \right) 70.8 \right) \right) - 600$$

$$H = \frac{19.5\ (70.8)}{.288} - 600 \cong 4200 \text{ BTU/hr}$$

Diver Gas Requirements

The third heating requirement for this system is to supply warm breathing gas to a diver working outside the lock-out compartment.

A theoretical basis for this requirement was not found and thus I will use the general findings of Perry Ocean Engineering and the Naval Civil Engineering Laboratory for needed heating figures.

Perry System

Perry diver-lock-out-compartment Prod-659 specifications for breathing gas heating is given as -

870 BTU/hr @ 1000 ft. 28^{o} F.

Naval Civil Engineering Laboratory

(9)

Requirements of up to 500 watts (1706 BTU/hr) are needed to counteract respiratory heat losses.

For the use by this report, I will use the Perry figures as average heating requirements.

For heat exchange systems available at this time, check Kinergtics file on Diver gas H-E.

Total System Requirements

Dive Compartment	-	5000 BTU/hr
Diver Suit Heater	-	4000 BTU/hr
Breathing Gas Heater	-	870 BTU/hr
		9870 BTU/hr
+ 25% Reserve	~	12300 BTU/hr
+ 50% Reserve	~	14805 BTU/hr

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Requirements of up to 500 watts (1706 BTU/hr) are needed to counteract respiratory heat losses, depending on type of breathing gas, inspired gas volume, temperature, depth and exertion.

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HEATING SYSTEM DESIGN

General System Design

Although the possible heat sources may vary greatly in their method of heat generation, all systems would have a similar overall approach to the system downstream of the heat source.

The absolute criteria for design of any heating system is the safety of the submersible occupants. Thus a heat source located outside the interior of the dive compartment is indicated. This type of system could use a liquid closed-cycle loop utilizing high efficiency heat-exchangers already available from commerical sources.

Components - Heating System

The main components of such a system would be:

(1) Heat source, heat exchanger module -

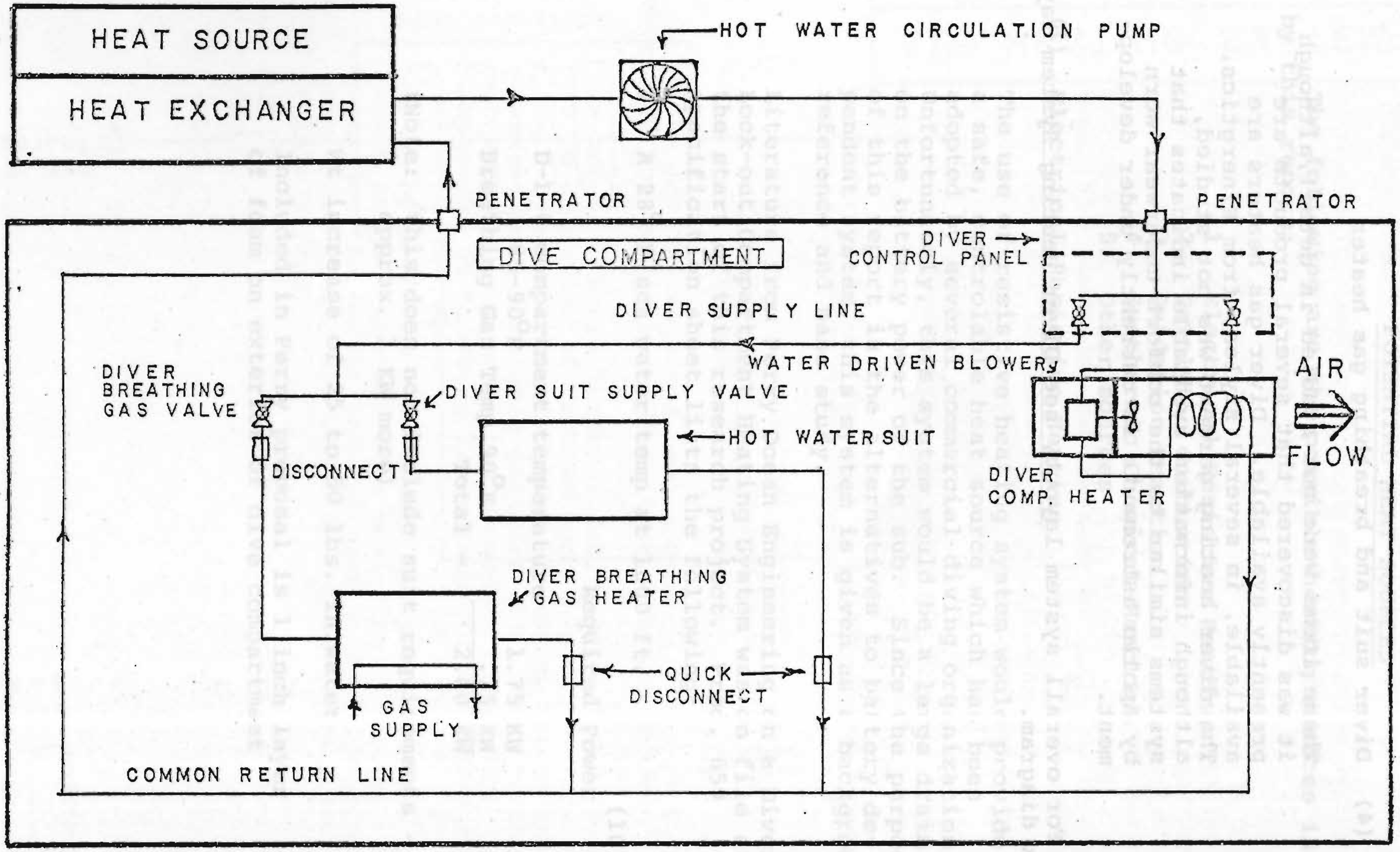
This package should be a compact, self-contained heat generator and exchanger which could be mounted at any convenient location on the exterior of the JOHNSON-SEA-LINK. The component should allow for easy maintenance of the generator. A master cut-off should be available for any emergency shutdown, as well as pressure and temperature relief controls.

(2) Closed-cycle liquid circulation system

A simple pumping arrangement should be designed for delivery and return of the hot water to the dive compartment. System should have flow rate controls either by varying pump rate or a constant rate system with a by-pass around the dive compartment.

(3) Compartment heater

This system is comprised of a heat exchanger and air circulation fan (powered either by water flow or electric motor). Several commercial systems are available and could be fitted into the system



SUB. HEATING SYSTEM

JOHNSON SEA-LINK

HEATING SYS. LAYOUT

(4) Diver suit and breathing gas heater

These items were not studied in detail, although it was discovered that several products are presently available. Diver gas heaters are available, in several styles, from Kinergtics. The diver heating garment was not studied, although information available indicates that systems similar to the comfort underwear worn by Apollo astronauts is currently under development.

For overall system layout, see Diver Heating System layout, block diagram.

POTENTIAL HEAT SOURCES

The following are the possible heating sources investigated by this report:

1. Electrical Resistive Heating
2. Catalytic Combustion
3. Oxidation Reaction
4. Exethermic Chemical Reaction
5. Other sources

(1) Electrical Resistive Heating

The use of resistive heating system would provide a safe, controlable heat source which has been adopted by several commercial diving organization. Unfortunately, this system would be a large drain on the battery power of the sub. Since the purpose of this report is the alternatives to battery dependent system, this system is given as a background reference and base study.

Literature from Perry Ocean Engineering on a Diver Lock-out Compartment Heating System was on file at the start of this research project. Prod. 659 specification sheet lists the following:

1. A 28^{o} F sea water temp at 1000 ft.

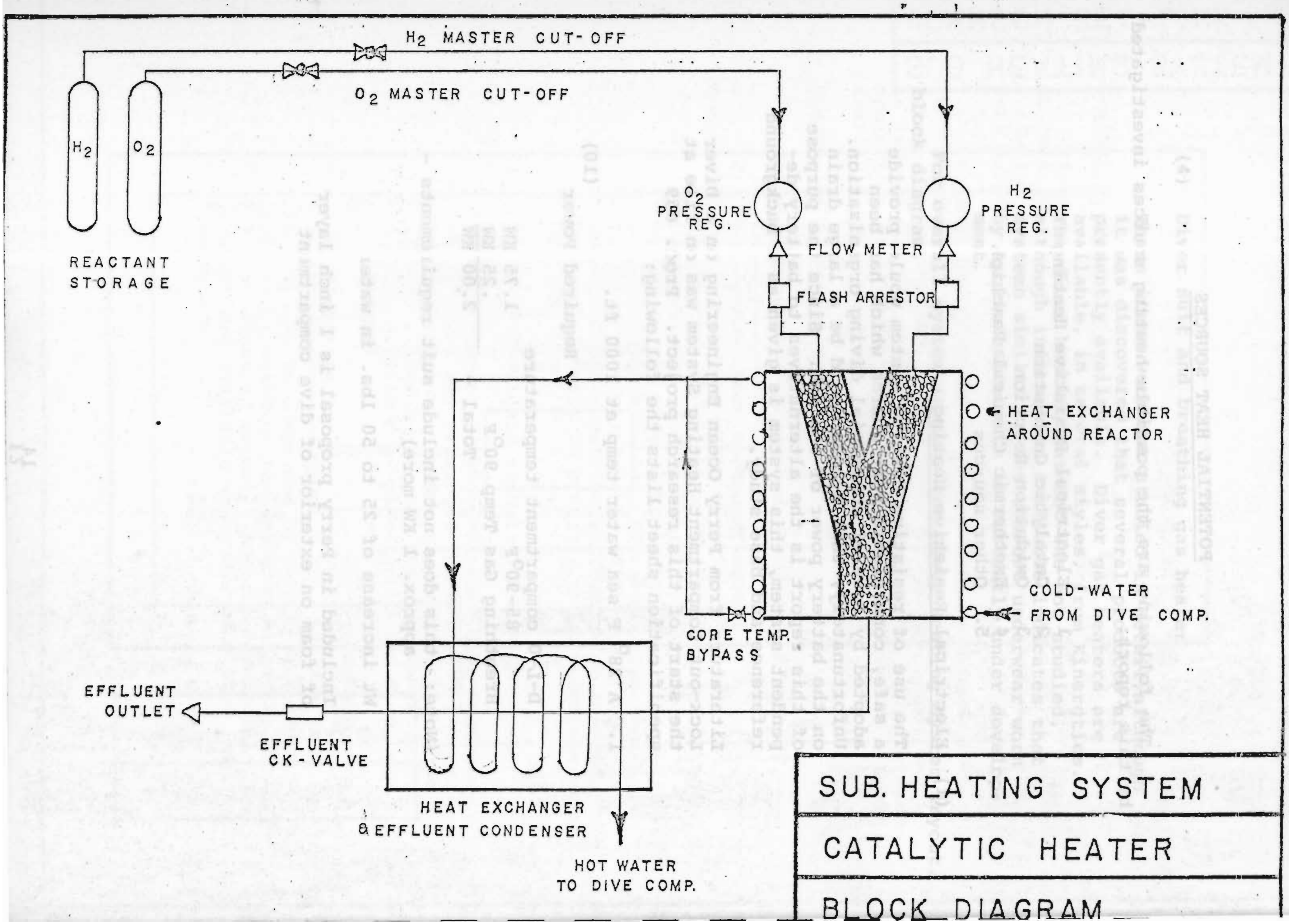
(10)

	Required Power
D-L-0 compartment temperature 85-90^{o}F	1.75 KW
Breathing Gas Temp 90^{o}F	.25 KW
Total -	2.00 KW

(Note: this does not include suit requirements - approx. 1 KW more)

Wt increase of 25 to 50 lbs. in water

Included in Perry proposal is 1 inch layer of foam on exterior of dive compartment


H2 MASTER CUT-OFF
O2 MASTER CUT-OFF
H2
O2
REACTANT STORAGE
O2 PRESSURE REG.
H2 PRESSURE REG.
FLOW METER
FLASH ARRESTOR
HEAT EXCHANGER AROUND REACTOR
COLD-WATER FROM DIVE COMP.
CORE TEMP. BYPASS
EFFLUENT OUTLET
EFFLUENT CK-VALVE
HEAT EXCHANGER & EFFLUENT CONDENSER
HOT WATER TO DIVE COMP.
SUB. HEATING SYSTEM
CATALYTIC HEATER
BLOCK DIAGRAM

(2) Catalytic Combustion

A catalytic combustion heat source for the JOHNSON-SEA-LINK would consist of a reaction chamber of yet undetermined configuration filled with a bed of catalyst appropriate type for reaction used. The combustion components of hydrogen (or possibly a hydrocarbon fuel such as propane) and oxygen would be injected into the reaction chamber and would react spontaneously to produce the required heat. A heat exchanger surrounding the reaction chamber would remove a portion of the produced heat and maintain the proper temp in the catalytic bed. The remainder of the heat of reaction would be removed from the products after the gas flow had been passed from the reaction chamber to a downstream heat exchanger. Reaction products would finally be expelled from the system as liquid water (and CO2).

For conceptual design, see Catalytic Heating Conceptual Design.

The heat available for such a reaction would be in the order of:

H_2 –	61,031 BTU/lb.
Propane	21,670 BTU/lb.
Butane	21,316 BTU/lb

Thus for the required heat approx. 1/3 lb. of H_2 gas per hour would be needed (1 lb. for propane and butane).

An area of future interest for further design research is to determine if such an open system previously outlined could be used and still keep all gases out of the explosive range. Most catalytic gas-line scrubbers for the removal of hydrogen recommend the pressence of no more than 3% oxygen or 6% hydrogen in a stream of the opposite gas.

If an open system were deemed too great a risk, then I would suggest the use of a semi-closed system. In such a system the oxygen and hydrogen would be kept below explosive limits and would be supported on a recirculated helium stream.

(3) Oxidation Reaction

There are several reactions of metal with water which will provide heat as a result of the reduction of the metal to it, oxide or hydroxide state. The most widely investigated reaction is:

$$Mg + 2H_2O \longrightarrow H_2\ (gas) + Mg(OH)_2 + \Delta h$$

The theoretical energy output from such a system is 1.85 Kw - h/1b. (6211 BTU/1b.)

The Naval Civil Engineering Laboratory, Port Hueneme, California, designed & tested an experimental system utilizing this metallic reduction. To increase the reaction rate to a useable level, magnesium plates were shorted by a washer to an iron cathode.

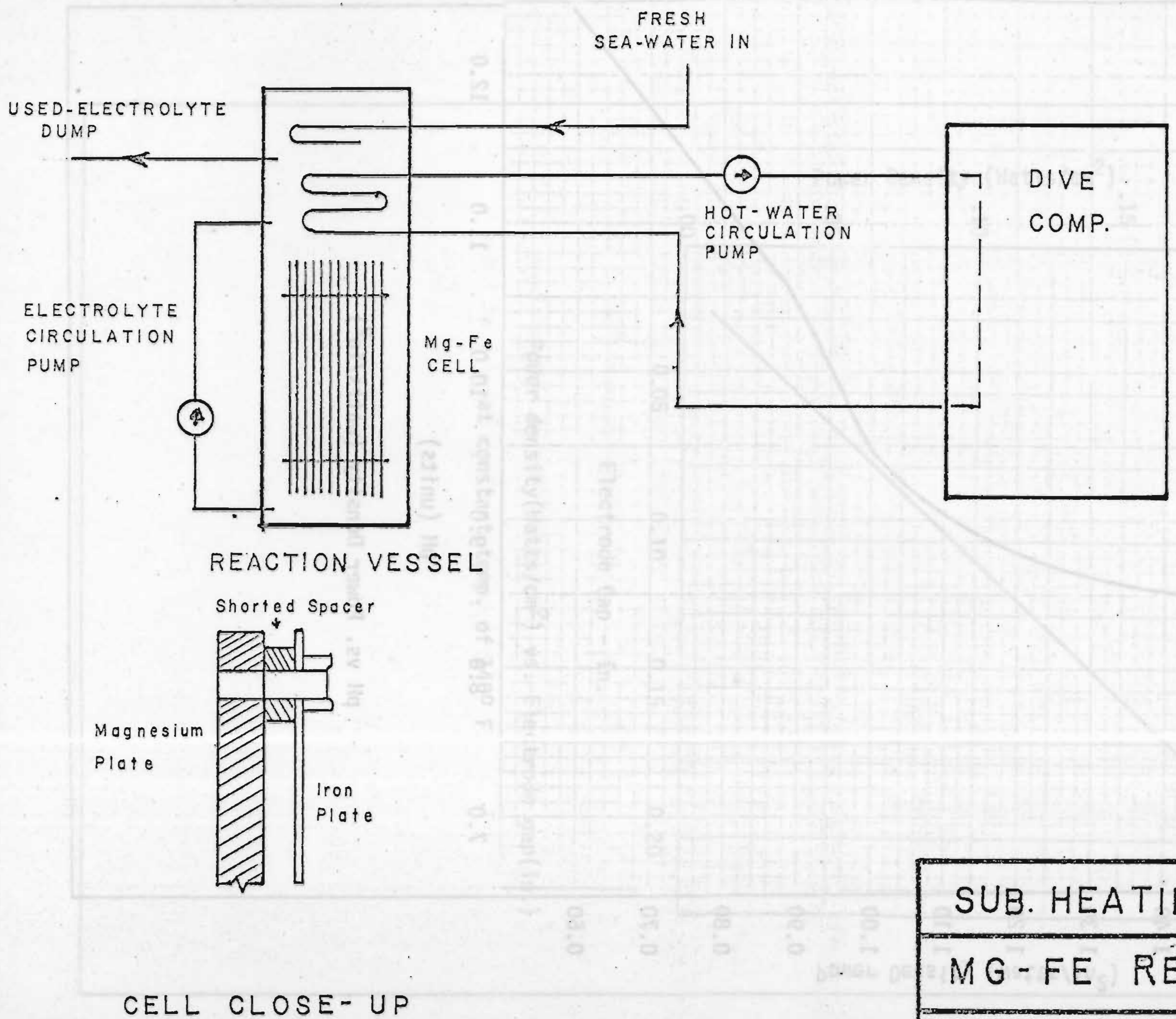
The average energy density of the Mg-Fe system is approximately .620 watts/in^2 (for a running period of 8 hr.) for a plate spacing of .100 in. For a 5-Kw heater, the required area of the plate system would be approximately 7100 in^2 of magnesium (and of an equivalent area of Iron).

See Magnesium-Iron Cell Schematic for detail.

The available output of this type of system is dependent upon the following parameters:

1. Electrode gap
2. Electrolyte condition
3. Electrolyte gap

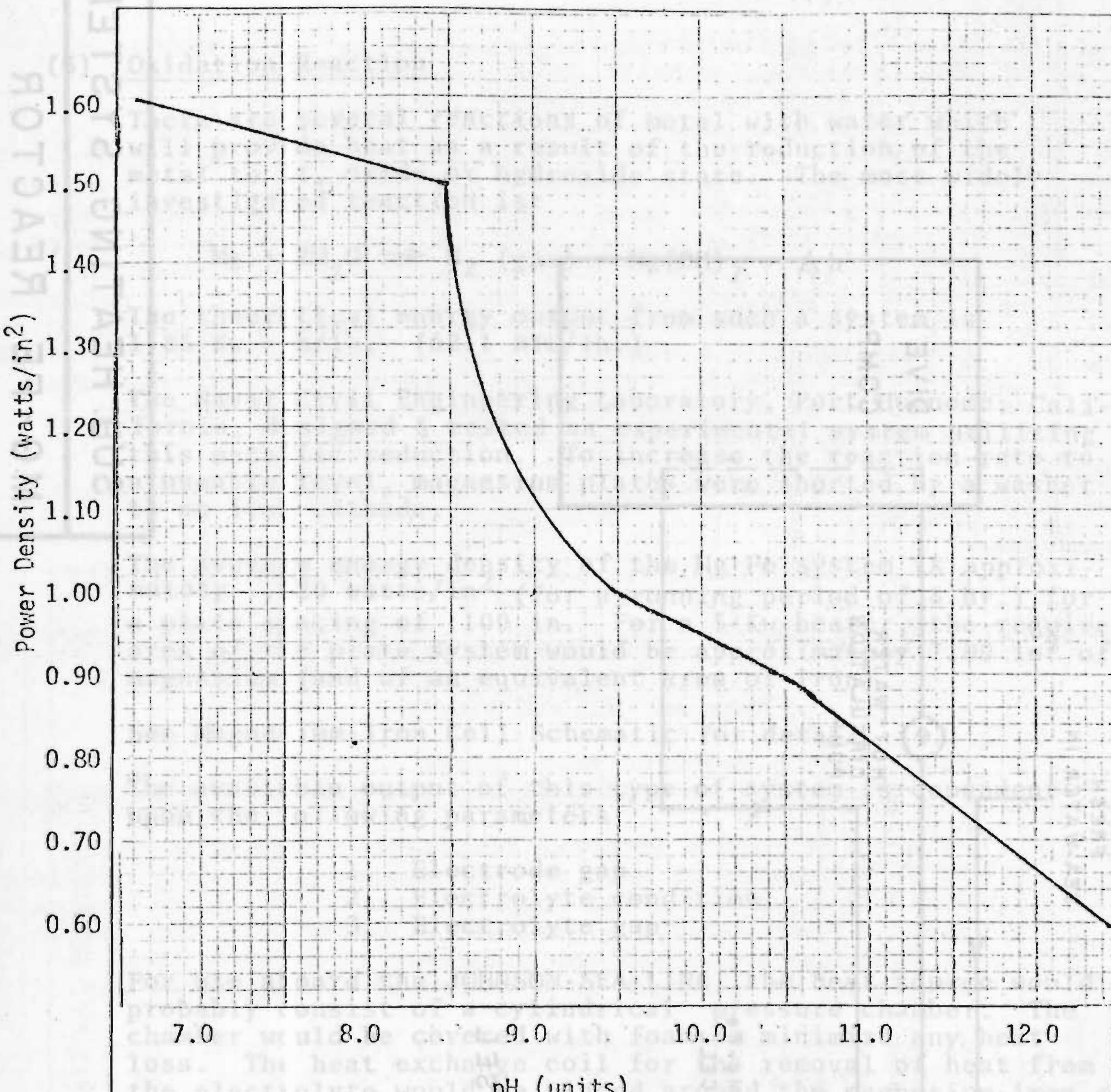
For use aboard the JOHNSON-SEA-LINK, the heat source would probably consist of a cylindrical pressure chamber. The chamber would be covered with foam to minimize any heat loss. The heat exchange coil for the removal of heat from the electrolyte would be placed around the magnesium-iron cell on the inside circumference of the chamber. All pumps, controls and electronics would also be housed in a separate section of the cylinder. Thus the heater would be a complete, bolt-on addition to the sub.



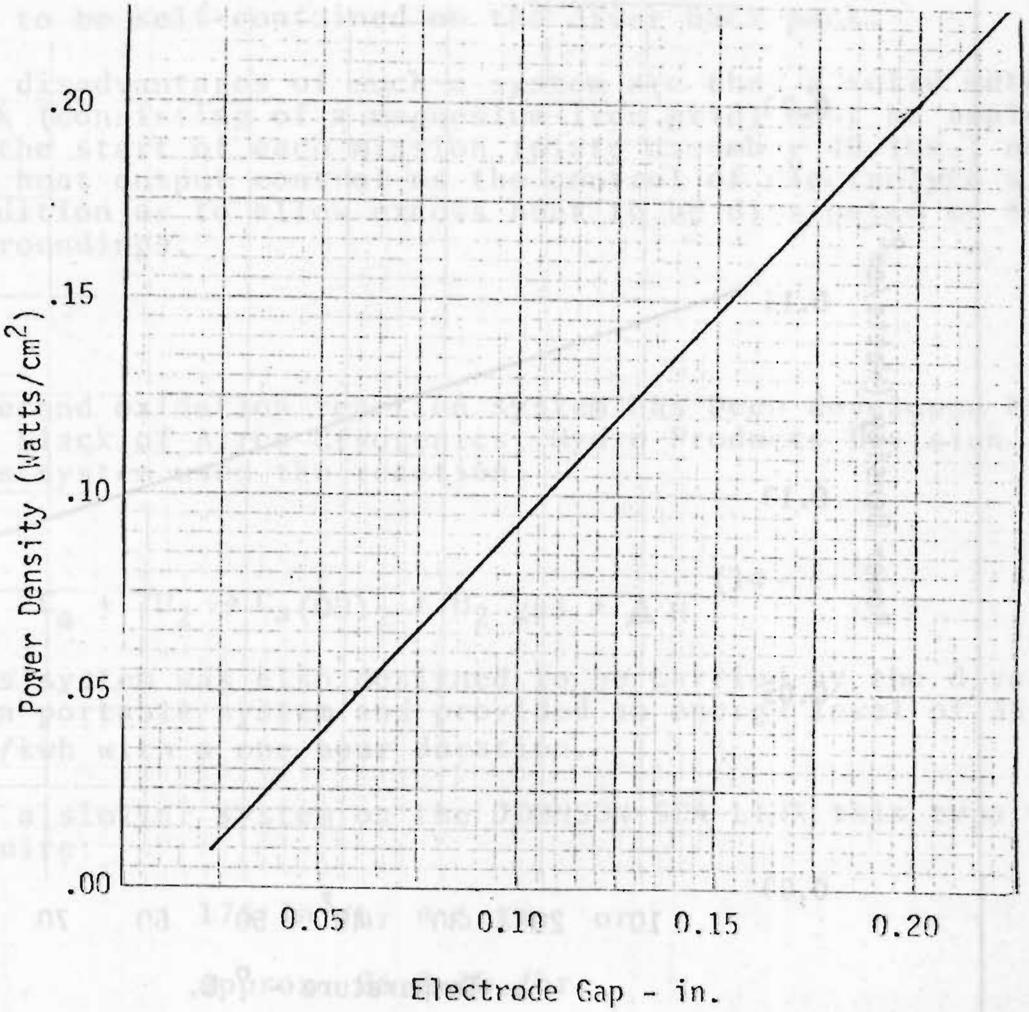
SUB. HEATING SYSTEM

MG-FE REACTOR

BLOCK DIAGRAM

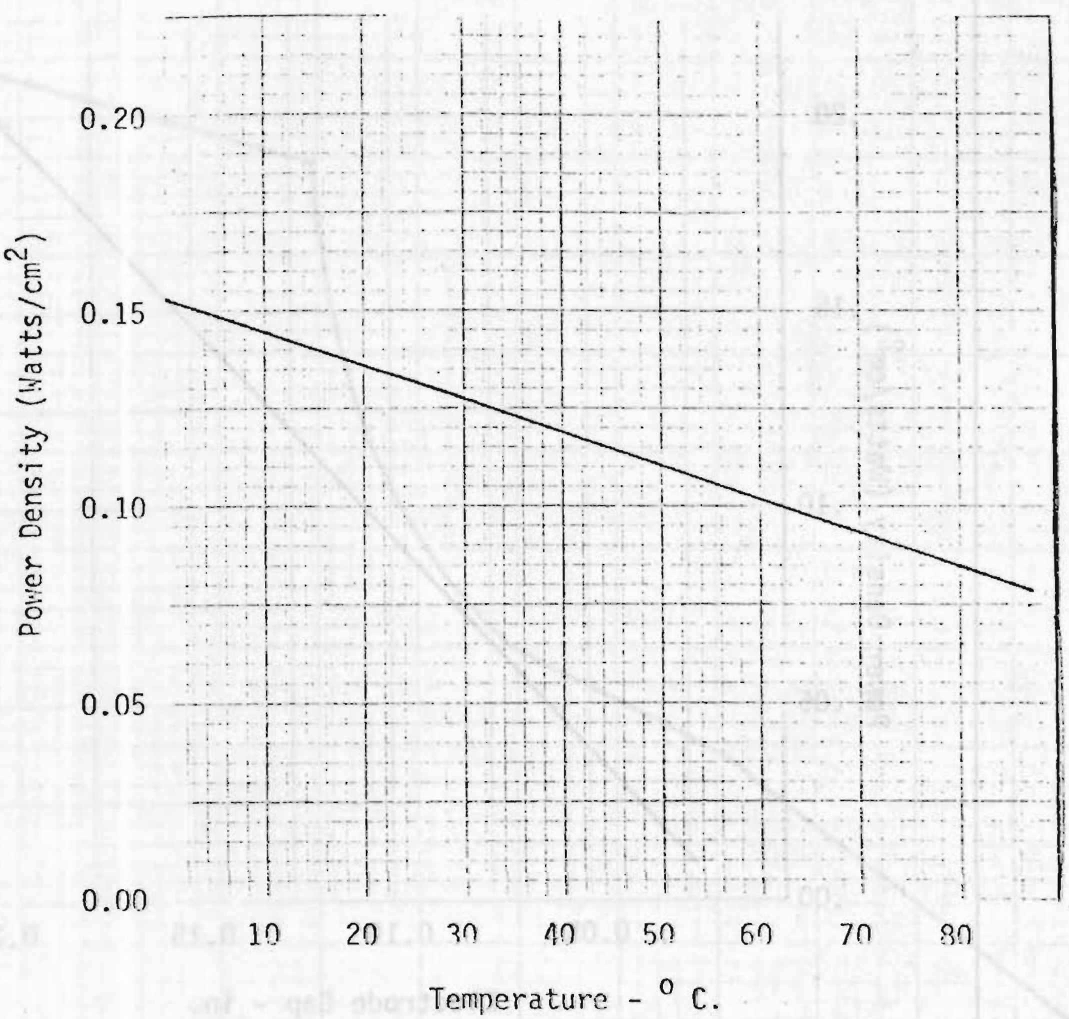


pH vs. Power Density (watts/in^2)



Power density(Watts/cm^2) vs. Electrode gap(in.)

at constant temp. of 140^o F.



Power Density vs. Temperature

at a constant electrode gap of 1.5mm

Kinergtics, Inc. has submitted a proposal to the NCEL for a production model of this heater (2 KW model), which was to be self-contained on the diver back-pack.

The disadvantages of such a system are that a solid metal pack (consisting of a magnesium-iron grid) must be replaced at the start of each mission (plate assembly 40 lbs.) and that the heat output control as the control of electrolyte slurry condition or to allow excess heat to be dissipated to the surroundings.

A second oxidation reaction system has been developed by Don Slack of Airco Cryogenics, Hydro Products Division. This system used the reaction:

$$C_a + 2H_2 \rightarrow C_a(OH)_2 + H_2 \text{ gas} + \Delta H \qquad (14)$$

This system was also designed to be carried by the diver as a portable system and provided an energy level of 35 in^3/kwh with a one hour duration.

For a similar system on the JOHNSON-SEA-LINK this type would require:

175 in^3/hr @ 5 KW or

approx. 26.2 lb./hr.

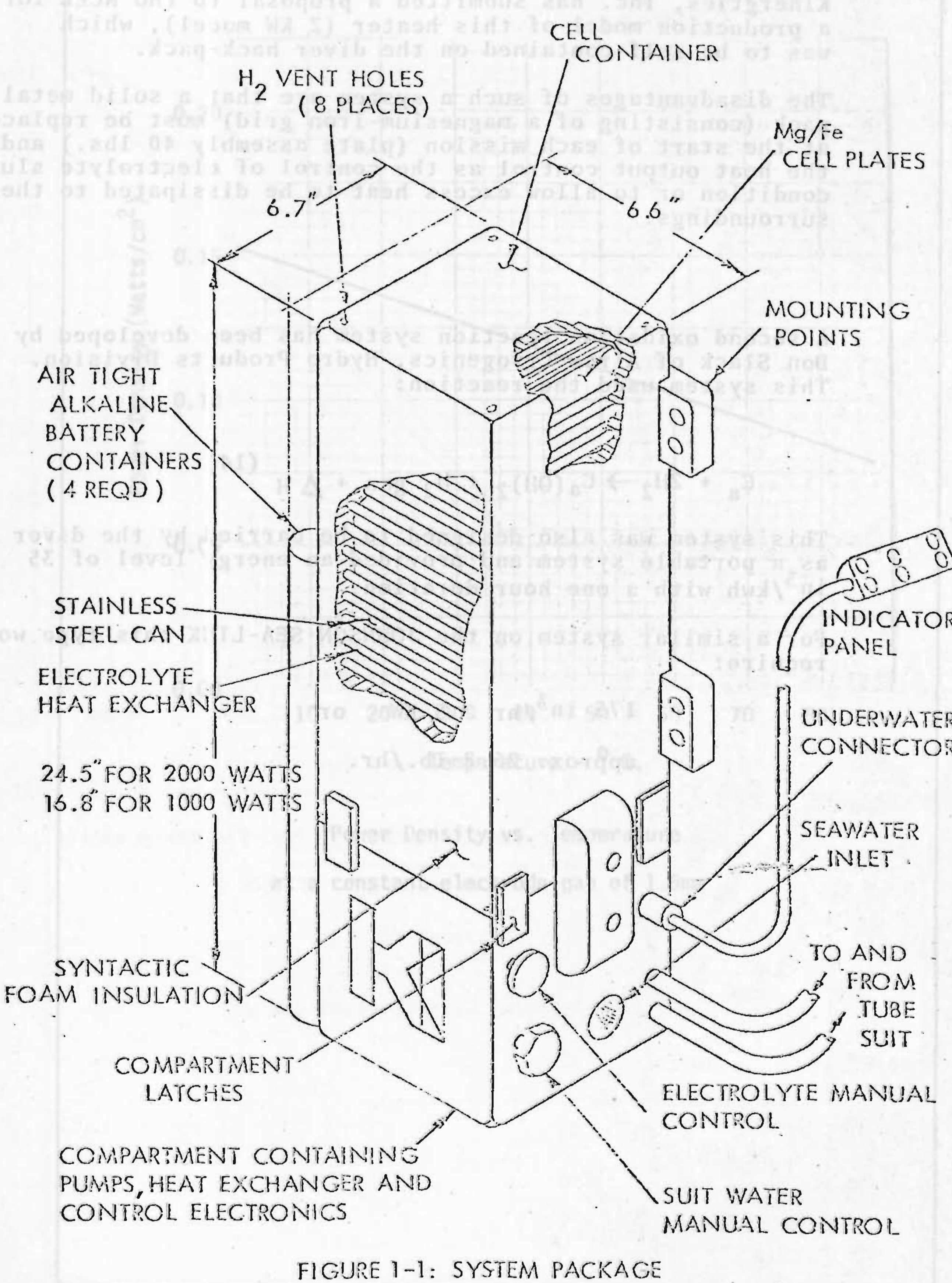


FIGURE 1-1: SYSTEM PACKAGE

(4) Chemical Reactions

Another system for heating a diver has been designed a patented heating system using a liquid exothermic reaction. This system uses the following reaction:

$$PCl_3 + 3H_2O \rightarrow 3HCl + P(OH)_3 + \Delta h \qquad (15)$$

After initial study, this system was not seriously considered for the following reasons:

1. Production of Hydrogen Chloride would produce a corrosive reaction.

2. Low heat of reaction would require that the reactant itself be circulated through the system (a dangerous situation in case of a suit leak).

3. Large amount of reactants must be expended

16.67 lb/hr. (energy density 1500 BTU/lb.)

(5) Other Sources

(A) Radioisotopes

A system utilizing the radioactive isotope plutonium - 238 as a heat source. This system was studied for use on the Sea-lab project but was abandoned because of low heat output and lack of adequate shielding protection for the diver.

(B) Internal Combustion

The Naval Coastal Systems Laboratory is currently working on a closed system using the Wankel cycle internal combustion engine with a propane fuel.

This study has so far been a test of the basic system and was run at STP and for a relatively short duration (30 min. max.). Further study of the results of this program might yield some useful data both as to a useful power source but particularly the techniques for maintaining a closed cycle system.

V. Conclusions

As a result of this summer research project, I would make the following conclusions and recommendations:

(1) If the JOHNSON-SEA-LINK is to be used for deep-water saturation dives, a hot-water heating system is imperative. This is due to the fact that the divers, by themselves, can neither generate the required heat nor be properly insulated from their environment.

(2) Any heat source which is to be installed aboard the JOHNSON-SEA-LINK should include at least 1 inch of a syntactic foam insulation around the exterior of the dive compartment.

(3) Further development of the actual heat source should be undertaken at some future time when it is deemed feasible.

This heat source research, I believe, should be a safety, maintenance, size and cost analysis of the catalytic heating unit vs. the Magnesium-oxidation reduction heater.

(4) A prototype unit of the desired system should be constructed.

(1) Nevins, Ralph: Heat Loss Analysis for Deep-Diving Oceanauts. ASME Pub. 65 WA/HT-25.

(2) Randall, Robert: Thermal Response of J-S-L. p. 13

(3) " " " " " " p. 11

(4) " " " " " " p. 12

(5) Nevins, Ralph: p. 3

(6) " " p. 2

(7) " " p. 7

(8) Perry Ocean Engineering Product Specification Prod.659

(9) Black, S. A.: Development of Self-Contained Heater for Military Divers, IEEE Ocean '75, p. 1

(10) Perry Ocean Engineering, Prod. 659

(11) Black, S. A.: p. 259

(12) Black, S. A.: p. 259

(13) Black, S. A.: p. 261

(14) Slack, Don: A Diver Chemical Powered Wet Suit Heater. MTS Journal V7, n4, p. 35

(15) Curtis, Daniel L.: Deep Submergence Heating System. U. S. Patent 3,599,625