16 POTENTIAL TECHNIQUES AND DEVELOPMENT ACTIVITIES IN DIVER SUIT HEATING

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INTRODUCTION

Thermal insulating materials, suitable for application in diving suits, so far are unable to provide sufficient protection against excessive heat loss. Low water temperatures, the high thermal conductivity of water (relative to air), and heat loss resulting from breathing of cold gas result in body heat losses far exceeding metabolic heat production.

Insulating materials are normally made of low thermal conductivity solids arranged such that heat paths in the solid are long and devious. The bulk of the insulating material consists of small gas-filled pores. External pressures of deep submergence tend to collapse these pores; hence, insulating capability degrades with increased submergence pressure.

Attempts have been made to provide pores structurally capable of withstanding the external pressures. Microspheres were embedded in elastomeric materials in the expectation that the small diameter and spherical shape would provide sufficient resistance against collapse under deep submergence pressures. The resulting materials, while providing an improvement relative to the elastomeric foam materials used in standard wet suits, still do not provide, at acceptable thickness, sufficient thermal protection. The special-purpose vacuum insulating techniques, used for cryogenic and space applications, are obviously not applicable where flexibility is required and external pressures are high. Thermal insulation, as applied in standard wet suits, provides only limited protection, suitable for shallow dives, so long as water temperatures are mild.

Satisfactory thermal protection of a diver can be defined as the capability to maintain a sufficient temperature gradient between skin surface and surrounding ambient water. For the extreme case of a water temperature of 28° F (freezing point of seawater), a skin temperature of 90° F, and an assumed metabolic rate of 400 Btu/hr (essentially a resting diver), maintenance of the 62° F temperature gradient would require a thermal conductance as low as 0.02 Btu/hr-ft-° F for a 0.75 in. thick thermal insulating material. Only a drastic breakthrough in thermal insulating techniques could achieve a thermal conductance as low as this under deep submergence pressures in a suitably flexible material; thus, a heat supply is necessary to keep the diver's body temperature at an acceptable level.

Supplying heat from a heat source to the proximity of the diver's body surface does not mean that heat is actually added to the diver's body. Rather, metabolic heat generated by his body and lost through thermal insulation is supplemented by additional heat from an auxiliary source to maintain a sufficient temperature gradient. Using Ohm's law as an analogy, "current flow" is increased to maintain a sufficient "potential difference," because "resistance" cannot be increased beyond a certain value.

Heat transfer analysis based on available thermal insulating materials and reports from experimental investigations indicate that approximately 1500 thermal watts are required to keep a

diver sufficiently warm for efficient performance and reasonable comfort. A large fraction of this amount of heat must be supplied to the proximity of the diver's body surfaces. Some of it will be applied to preheating the breathing gas and to other parts of the diver support system.

DIVER SUIT HEATER SYSTEM

The complete diver suit heater system has three elements:

1. A source of thermal energy.
2. A means of transmitting energy to the proximity of the diver's body surfaces.
3. A means of controlling heat supply and temperature in accordance with requirements, and adapting system operation to the variations of pressure from sea level to the maximum submergence level anticipated.

Sources of thermal energy considered include electrical energy from batteries, nuclear energy from an isotope heat source, heat stored by a suitable method (such as a liquid/solid phase change), and exothermic chemical reactions.

Techniques for transmission of energy to the proximity of the diver's body require only a wiring system for electric heating. Forced circulation of a heat transfer fluid in a fashion similar to that of the Apollo suit undergarment will apply to systems generating heat in a portable pack carried by the diver.

Techniques for control of heat supply vary. Electric energy can easily be controlled by switching arrangements, turning heat supply on or off, or reducing or increasing the number of heating circuits. For an electric blanket-type garment no adaption to pressure variation is required. Heat from isotope heat sources, with their fixed-energy output, would be controlled by valves in the forced flow circulating loop, providing control of heat supplied and rejection of excess heat to the surrounding water. Similar techniques will apply to the application of stored heat, except that excess heat rejection is neither required nor desirable.

Exothermic chemical reactions have the advantage that reaction rates can be made variable over a relatively wide range and reactant (fuel) consumption can be adjusted to heat requirements.

Pressure equalization with the submergence ambient is normally accomplished for submerged hydraulic systems by use of a flexible diaphragm or bellows that transmits submergence pressure to the closed hydraulic system's loop. Similar techniques will satisfy the requirements of a diving suit fluid loop.

The availability of enough thermal energy for the full duration of a mission appears to be the key for a practical and satisfactory diving suit heater system.

THE HEAT SOURCE

As transmission of thermal energy to the body surfaces and control of fluid flow or electric current do not represent fundamental problems, this paper is concerned mainly with the source of thermal energy.

Assuming missions in the order of 2- to 6-hr duration, requiring 1500 W or over 5000 Btu/hr, requires a high energy-density source of heat. Electric resistance heating in an arrangement similar to an electric blanket was tested during the Sea Lab II mission. Results were not too satisfactory. Difficulties included distribution of heat over the body surfaces, and resistance wires getting too hot. While better design could overcome these difficulties, the total amount of available energy was limited by battery size to 3 hr at only 350 W (ref. 1).

After Sea Lab II, heating with circulating warm water by a water tube-type undergarment, similar to the one used on the Apollo extravehicular space suit, was suggested. A radioisotope was suggested as a convenient, compact source of heat. References 2 and 3 discuss a system, applying a Plutonium 238 heat source of 420 thermal W. Reference 2 describes the difficulties of shielding of even this inadequate heat source in an experimental diving suit heater system, built under a joint effort by the Navy and the AEC. The same reference mentions that during the development time span of this system the initial requirement of 300 W was upgraded, first to 800 W, then to 1100-1500 W. Only 270 thermal W (about 64 percent) were eventually useful to the diver from the 420 W isotope heat source used. It became apparent that isotopes would not provide a practical solution when energy levels in the range of 1500 W are required.

Interest was then directed to exothermic chemical reactions. Since diver suit heater systems application differs significantly from space suit applications in regard to probable number of units required, first cost and fuel costs would have to be moderate. The objective was a suit heater system that would serve both military applications and commercial divers. Desirable objectives were formulated as a set of design criteria (table 16.1), which provided a basis for the evaluation of several selected exothermic processes (table 16.2). Engineering problems connected with the design, development, and fabrication of a suitable reactor were considered, along with operational aspects such as refueling, storage, cost, and availability of the reactants.

Table 16.1 *Diving suit heater criteria.*
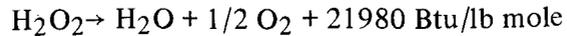
The self-contained heater system will permit free-swimming for 4 hr or longer

The free-swimming diver will have minimum encumbrance

Complete system including heat generator for heating of circulating water, circulating pump, and controls for temperature and submergence level will require only a minimum of battery-supplied electric energy

Construction materials will be conventional (such as stainless steel, copper alloys, and plastics) so no exotic alloys, refractories, or other expensive materials can be used

Fuel and oxidizer will be readily available, of low cost, and permit simple refueling

Fuel will be of high energy-density, and exothermic chemical reactions should be essentially stoichiometric to avoid the need for excess fuel or oxidizer

Fuel and oxidizer will be used in their undiluted form to avoid excess storage bulk

Reaction products discharged into the ocean should not cause "telltale" of diver operation

Table 16.2 *Exothermic processes evaluated.*

Catalytic decomposition of hydrogen peroxide

Rocket fuels

Oxidation of shredded or powdered metals with oxygen

Hydration of alkali metals

Combustion of hydrocarbon fuels with oxygen

Hydrogen Peroxide

Hydrogen peroxide decomposes exothermally in contact with a catalyst, forming gaseous oxygen, steam, and heat by the reaction

$$H_2O_2 \rightarrow H_2O + 1/2\ O_2 + 21980\ Btu/lb\ mole$$

Hydrogen peroxide is attractive because it is a single fluid that will generate heat when brought in contact with a catalyst. The water vapor (steam) formed could be used to heat the diver if condensed and circulated through the suit or routed through a heat exchanger. One pound of peroxide (approximately 25 cu in. at 70 percent concentration) will provide approximately 1150 Btu after the steam is condensed. There are two obstacles to application:

1. Hydrogen peroxide in concentrations sufficiently high to undergo exothermic decomposition is dangerous to handle. Almost any metal and a number of other substances will act as catalysts and induce the above reaction. The reaction could occur in storage tanks during shipment, in transfer hoses or any container used, unless extreme cleanliness precautions are applied. The reaction generates heat and tends to become spontaneous above 350° F. The oxygen generated is in a highly reactive state and presence of organic contaminations would aggravate the danger of explosions.
2. Decomposition products of the peroxide dissociation must be expelled into the ambient ocean environment. This requires the reactor to operate above the submergence ambient pressure. The hydrogen peroxide decomposition process is accompanied by an increase in volume; hence, increased pressure may adversely affect decomposition.

Rocket Fuels

As in the case of hydrogen peroxide, rocket fuels, such as hydrazine or hydrazine hydrate, require special precautions in storage and handling. Extreme cleanliness, protection against toxic effects of vapors or contact with the human skin, and the difficulties in shipping, storing, and handling of fluids with inherently dangerous characteristics preclude the application of these fuels, for logistic reasons, to diving suit heaters.

Metal Combustion with Oxygen

Several metals in a form providing a large surface area and small bulk density, as when powdered or shredded like steel wool, can be burned with oxygen, yielding significant amounts of heat. Flammability of magnesium, even in air, is well known. Aluminum and steel will sustain combustion processes at sufficiently high temperatures and in the presence of sufficient oxygen concentrations. Combustion of aluminum is used in flashbulbs and in the aluminothermic (thermit) welding process. Combustion of iron takes place in oxygen torch-cutting of iron or steel, which when heated to approximately 1500° F is cut by a stream of oxygen. Potentially, a number of other metals could be used for this purpose. Iron, copper, and aluminum are readily available in shredded form, and they are perfectly safe to handle.

Combustion of a metal with oxygen for generation of heat becomes attractive when the combustion product is a solid, which because of its high density can be retained in the combustor for the duration of a mission. This eliminates the need of expelling of combustion products against submergence pressure.

For iron/oxygen, for example, each of the following possible reactions will result in a solid reaction product:

1. $2Fe + O_2 \rightarrow 2FeO + 1608$ Btu/lb reactants
2. $4Fe + 3O_2 \rightarrow 2Fe_2O_3 + 2243$ Btu/lb reactants
3. $3Fe + 2O_2 \rightarrow Fe_3O_4 + 2071$ Btu/lb reactants

Apparent difficulties in application of these reactions include the requirement that the metals be maintained at their combustion temperature, which in the case of iron is $\sim 1500°$ F.
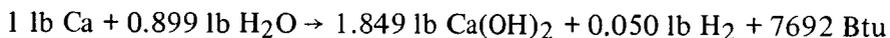
The technique normally applied to obtain useful heat output from combustion processes is to first complete the combustion process at the temperature required to sustain the reaction, and then route the gaseous products of combustion through a heat exchanger. This technique is obviously not applicable when the combustion product is a solid. It will probably be necessary to maintain a sufficiently high temperature gradient between the burning metal and the water to be heated such that the temperature of the burning metal is not reduced below the temperature at which efficient combustion can be sustained. If water is to be heated to $110°$ F and a combustion temperature of $1500°$ F is required, a temperature gradient between combustion zone and circulating water in the order of $1390°$ F must be maintained.

A metal fuel such as iron in the form of steel wool must have a relatively low bulk density to sustain combustion. With the assumption that the steel wool could be compressed to one-half its normal commercially available bulk volume, it was found that for a mission at 1500 W heat requirement, 0.22 cu ft of steel wool would be required for each hour of operation.

It is difficult to visualize that a volume of steel wool sufficient for 4- or 6-hr mission (0.88 or 1.3 cu ft) could be directly incorporated into the combustor. Steel wool cannot be fed from a storage tank through tubes like a gaseous or liquid fuel to the combustion zone, but it could be applied in the form of a cartridge—like package. Recharging would be accomplished by removal of the old cartridge containing iron oxide and insertion of a new cartridge. To start combustion after recharging—that is, initiate the reaction with oxygen—the temperature must be raised by some means to about $1500°$ to $1800°$ F. Such a temperature increase will require the use of an auxiliary fuel or a relatively large amount of electric power. In spite of these problems, it is understood that a diving suit heater of this type has been developed.

Hydration Reactions of Alkali Metals

Alkali metals react violently when brought into contact with water, forming hydroxides of the metals, gaseous hydrogen, and heat. These reactions appear attractive because the diver is surrounded by one of the two reactants—that is, water. Both metallic calcium (Ca) and metallic sodium (Na) have been considered. The reaction of metallic sodium with water is possibly more difficult to control than that of calcium, but the former, used extensively as a heat transfer medium in nuclear reactors, is more readily available and lower priced. The thermal energy yield is high, as shown here for calcium:

$$1 \text{ lb Ca} + 0.899 \text{ lb } H_2O \rightarrow 1.849 \text{ lb Ca(OH)}_2 + 0.050 \text{ lb } H_2 + 7692 \text{ Btu}$$

However, the volumetric yield (heat per cu ft fuel) depends on the form in which the fuel is applied. For application of this approach to be practical, the metal must be packaged in such a way that the reaction can be slowed and controlled.

One approach would be to diffuse the metal in powder form into a water-soluble inert material. As the inert material is slowly dissolved, water will contact the small metal particles, which will react one at a time. The otherwise explosion—like reaction between metal and water may be controllable by this method, but fuel volume will be increased by the inert material. Whether, in practice, seawater can be used as one of the reactants is uncertain. Its composition is not always predictable, and certain areas show high turbidity (solid content) while in other areas where a diver must operate oil or other contaminations could be present.

The metal/water reaction results in the production of gaseous hydrogen, which must be expelled. Hydrogen is only slightly soluble in water and would possibly indicate the presence of a diver. Hydrogen would further present a danger if permitted to enter habitats or collect in the cavity of a shipwreck or sunken airplane, which may be the objective of a diver's activity.

Although the use of alkali metal/water reactions is an interesting possibility, the safety aspects, control of the reaction, and logistics, including manufacturing methods for inerted fuel cartridges, would entail extensive and probably quite costly development work.

Hydrocarbon Fuels and Oxygen

Combustion of hydrocarbon fuel with oxygen is attractive from the viewpoint of logistics as well as thermal yield. Oxygen, usually in the form of compressed gas, is used for breathing atmosphere replenishment in many diving operations. Its handling, shipment, and storage, therefore, is well known to diver support personnel. Hydrocarbon fuels such as kerosine, gasoline, propane, and butane are readily available, inexpensive, and can be applied in the commercially available form without special packaging in fuel cartridges or dispersions. A further advantage is that these reactants are liquids or gases, which can be easily transmitted through tubing, controlled by valves, pumped, and stored in containers. Safety precautions in handling are those normally observed in refueling automobile gas tanks or recharging cigarette lighters. Heat values are high, in the order of 20,000 Btu/lb of fuel at a liquid fuel density between 30 and 50 lb/ft^3.

From the criteria shown in table 16.1, the advantages of logistics and practicability were believed to warrant selection of this system for further development. As with any other system, certain engineering problems remained, but essentially all of these have now been resolved.

The objective was the development of a compact reactor, suitable for combustion of a selected hydrocarbon fuel with oxygen under shallow as well as deep submergence diving conditions. This development work was undertaken by the TRW Systems Group in Redondo Beach, Calif., as an in-house funded effort. For this reason, the information presented here is limited to results of these development activities.

Table 16.3 summarizes the engineering problems to be solved before the selected reaction could be used in heating water circulated through a water tube-type diving suit.

Table 16.3 *Engineering problems of water tube-type diver heating systems.*

Reaction must be confined in a fully enclosed reaction chamber

Reactor and heat exchange provisions for heating fo circulating water must be included in a compact, portable package

Stoichiometric reaction without significant fuel, oxidizer excess, or any dilutent is required to minimize storage tank size for fuel and oxidizer

Means are required to obtain efficient combustion without the need for temperatures of 3000° to 4000° F, as normally required, to avoid costly materials and construction

Table 16.3 *Engineering problems of water tube-type diver heating systems. (Concluded)*

Reaction chamber must operate at a pressure in excess of submergence ambient to permit expelling of combustion product against submergence ambient pressure

Combustion products expelled from the combustor must not result in "telltale" bubbles rising to the surface

The fuel selected was propane, which is readily available and, even in the commercially available form, is predominantly a single compound rather than a mixture (like gasoline). The use of a single compound simplified calculations of theoretical performance for comparison with measured heat output (thus establishing overall efficiency). Propane is sold in pressurized containers as a saturated liquid, and container pressure depends on temperature. For experimental work, tank pressure could be controlled by controlling tank temperature.

A basic closed-reactor design was developed and then upgraded as development work progressed. The third prototype is being tested. Each prototype included a reactor chamber, heat exchange surfaces, and channels for flow of the water to be heated.

The first prototype was a rather clumsy device made partially of leftover parts from another experiment, but sufficient for demonstration of basic feasibility of the concept. The second-generation prototype is shown in figure 16.1.
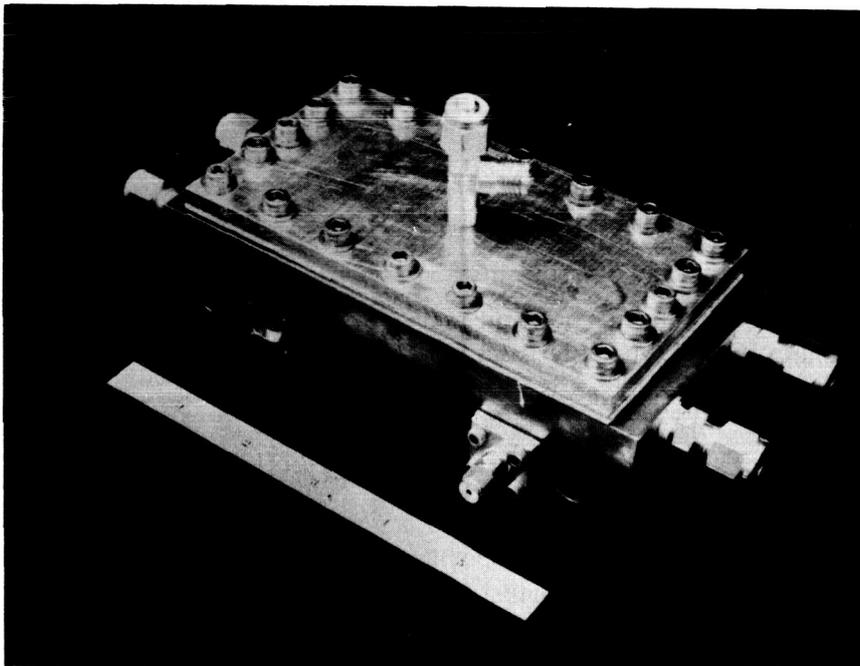

Figure 16.1 *Second generation prototype reactor.*

The efficient combustion of hydrocarbon fuel-oxygen mixtures usually requires temperatures of 3000° to 4000° F. In the presence of a catalyst, however, high combustion efficiency can be achieved at less than 1000° F, and high temperature resistant and costly materials are not needed.

In fact, the second prototype was machined from a solid block of copper with a flanged-on lid (fig. 16.1). After more than 200 hr of operation for data taking, there was no indication of melting or excessive oxidation of the copper. Dimensions of the prototype were 6 by 4 by 2 in.

Figure 16.2 shows a third-generation prototype, which is smaller than the second (6 by 3.75 by 1 in.) and is made of stainless steel.
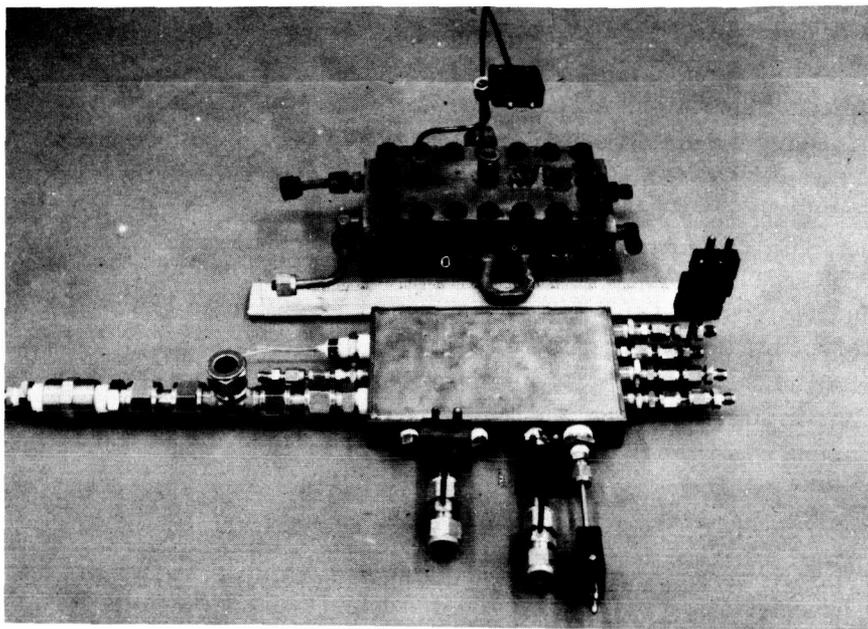

Figure 16.2 *Third generation prototype reactor.*

The prototypes were tested for performance, combustion efficiency, start-up characteristics, and flexibility of heat output. Figure 16.3 is a view of the test setup now in use. Water is circulated in a closed loop through the reactor and a water chiller, which serves as heat sink. The flow of fuel, oxidizer, and circulating water are measured. Temperatures are measured at several points including water "in" and "out," exhaust gas, casing, and combustion chamber.

Figure 16.4 shows an example of data on heat output performance obtained on one test run; for comparison the calculated heat output for a stoichiometric fuel-oxidizer mixture is shown. The

Figure 16.3 *Test setup.*

performance data points are based on measured water flow and temperature rise of the water. The difference between the calculated and actual measured performance includes, therefore, the effects of combustion and heat exchange efficiency. Efficiency at various heat output rates varies, but is, in general, better than 80 percent.
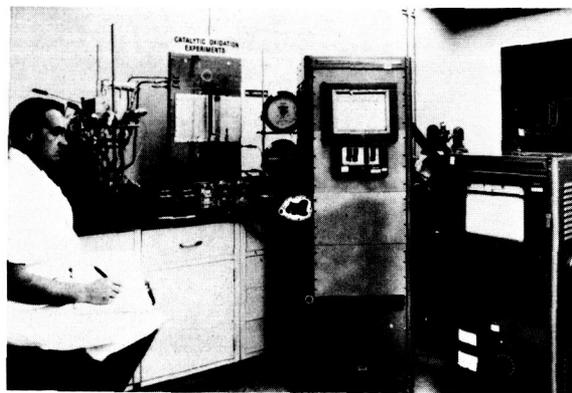
Other results of these test runs include:

1. Good overall efficiency.
2. Good combustion efficiency verified by gas chromatography.
3. Low casing temperature, generally well below 200° F. This is important because of the difficulties of providing thermal insulation under deep submergence pressure; little insulation is needed for personnel protection or reduction of heat loss to ambient.
4. Combustion process flexibility, which allows control of heat output by throttling of fuel and oxidizer flow over a wide range.
5. Measured heat output of these small and compact "water heaters" better than 2000 W, providing the potential for an abundant supply of heat to the diving system.

Figure 16.4 *Test results of catalytic heat source operated at stoichiometric mixture ratio.*

With this type of system, combustion products are expelled into the ambient. Therefore, combustion chamber pressure greater than that of the submergence ambient must be maintained. Supply pressure will therefore be regulated just as it is done on the surface, in relation to ambient pressure. This is the type of downstream pressure control normally used on standard compressed gas bottles.

In theory, the combustion process will be enhanced by increased pressure. Preliminary tests up to 30 psig have shown that operation of the reactor is unaffected. Test runs at higher pressures are in preparation.

In accordance with the criteria of table 16.2, there will be no indication of diver presence as a result of diving suit heater operation. The combustion products expelled into the ocean are carbon dioxide and water vapor. When expelled into the ocean ambient, the water vapor will, of course, immediately condense and disappear. Carbon dioxide is highly soluble in water, and preliminary experiments verify that it will disappear by going into solution. When carbon dioxide was injected, by nozzle, into the bottom of an approximately 8 ft tall glass tube filled with seawater, bubbles about 0.25-in. in size were released from the nozzle at the bottom. When they had risen approximately 4 ft, their size was noticeably reduced, and by the time they reached the top of the glass tube, some of them completely disappeared while others had shrunk in size to roughly the
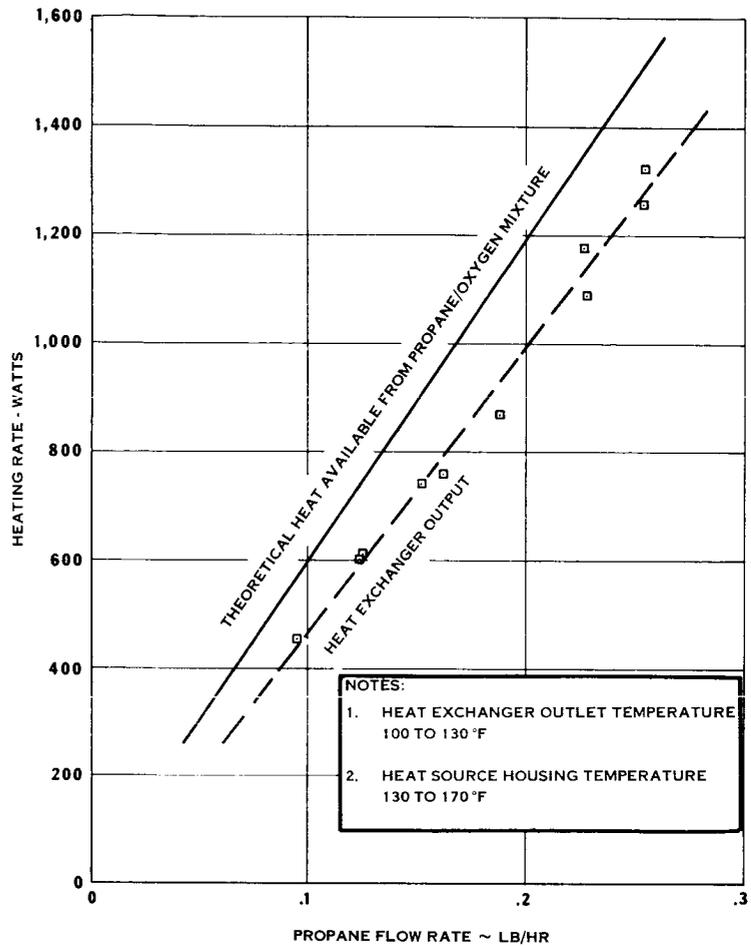
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dimensions of the bubbles in soda pop. The exhaust port can be designed such that the emitted carbon dioxide gas will disappear by solution in water within a few feet from the diver.

The successful testing of a heat source capable of providing an abundant amount of heat from a small portable package opens the way to development of a complete system for the free-swimming diver. Work has begun on a heat-operated pump for the circulation of water through the diver's suit and conceptual design has been completed of the system controls that will provide automatic adaption to variations of submergence level and control of temperatures and heat produced.

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