# A Closed Brayton Cycle Power System for Deep Submersible Vehicles

H. BALUKJIAN*
*Naval Ship Engineering Center, Hyattsville, Md.*
AND
R. RACKLEY†
*AiResearch Manufacturing Company, Phoenix, Ariz.*

**The closed Brayton power cycle system utilizing the combustion of hydrogen and oxygen as a heat source was evaluated for the U.S. Navy by AiResearch. A system with a nominal 50-kw electrical output is described and weights and volumes shown for a 1000-kw-hr 20,000-ft depth mission. Investigations were conducted to select the compressor specific speed and recuperator effectiveness that resulted in a minimum total system weight. Comparisons are shown for both cryogenically stored and high-pressure gaseous stored hydrogen/oxygen systems.**

## Nomenclature

$g$ = acceleration of gravity, 32.2 ft/sec$^2$
$E_R$ = recuperator expectiveness
$H$ = head, ft
$M$ = mass flow rate, lb/sec
$mw$ = molecular weight
$N$ = revolutions/sec
$N_{sc}$ = compressor specific speed
$P$ = pressure, psia
$Q$ = volumetric flow rate, ft$^3$/sec
$Q_{in}$ = heat in, kw
$r_c$ = compressor pressure ratio
$r_t$ = turbine pressure ratio
$T$ = temperature, °R
$\beta$ = $r_t/r_c$
$\eta_{cy}$ = cycle efficiency
$\eta_g$ = generator efficiency

## Introduction

PRESENT design trends for deep submergence vehicles reflect the need for energy subsystems having increased power density (kw/lb and kw/ft$^3$) and energy density (kwh/lb and kwh/ft$^3$).

The energy map (Fig. 1) compares on a weight basis, the regions for application of several categories of energy systems in relation to power level and endurance. The secondary battery offers a relatively inexpensive simple class of power supply which applies to the low power and low endurance domain. The nuclear fission category stands out in the high power and extended endurance region. Conversely, radioisotope systems apply to the lower power and extended endurance region.

Finally, between the power-endurance capabilities of secondary batteries and nuclear fission plants is a gap within which the fuel cell and thermal chemical dynamic systems apply. The power-endurance profiles of many deep submergence vehicles will fall within this gap. The thermal chemical dynamic and fuel cell regions overlap. Thermal chemical dynamic systems tend to be more attractive at higher powers and lower endurance, whereas fuel cells tend to be more attractive toward lower powers and higher endurance.

The Navy currently has contracted for studies of a 50 kw, 1000 kwh thermal chemical dynamic power source as part of the Deep Ocean Technology Program (DOT). These contracts are for a closed Brayton cycle plant and include both $H_2$-$O_2$ and boron slurry -$O_2$ as possible reactants (Refs. 2 and 3).

This paper is concerned with the closed Brayton cycle power plant (Fig. 2). Two depths were considered in this study: 8000 and 20,000 ft; and two endurances: 20 and 40 hr.

## Design Criteria

In selecting power supply concepts for various mission definitions, it is necessary to compare the candidate system relative to appropriately weighted criteria which would include, where applicable, the items shown in Table 1.

The basic characteristics which affect an undersea power plant are 1) design depth of the vehicle, 2) total power (both propulsion and auxiliary) required at any one time, and 3) endurance or length of time under water for any specific mission.

As the design depth increases, the technological problems and their solutions are directly proportional. Choice of hull material and construction, choice of propulsion and power plant, space and weight available for machinery, electric

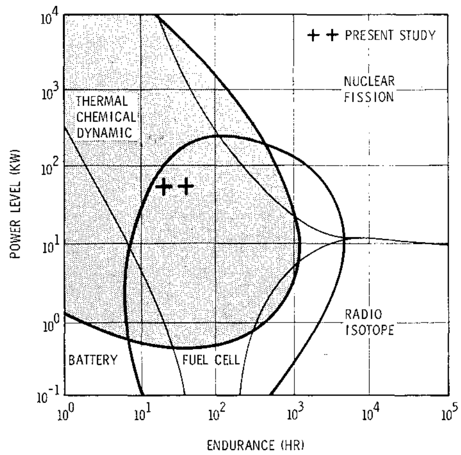


**Fig. 1 Energy map (weight basis, Ref. 1).**

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* Marine Engineer.
† Assistant Project Engineer.

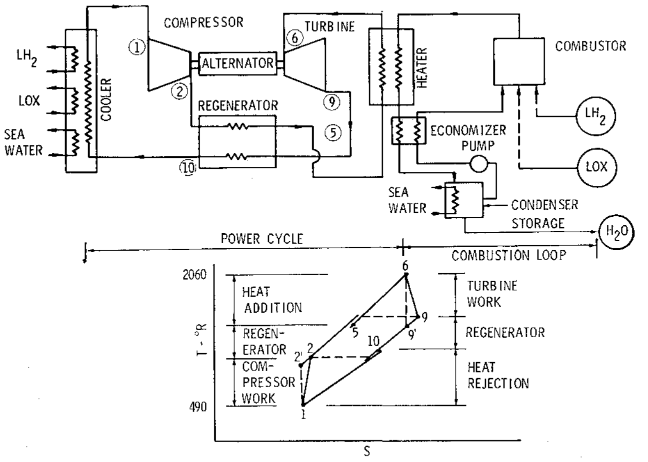


**Fig. 2 Closed Brayton cycle schematic.**

plant, communications and control, auxiliary systems, habitability and personnel are all associated with the selected design depth.

Figure 3 shows the percent of the ocean that exists at various depths. A depth of 1500 ft would allow coverage of the continental shelf and about 11% of the ocean bottom; 8000 ft would cover the significant areas of the Atlantic Ridge and about 19% of the ocean; 20,000 ft would cover the deep ocean plains and 98% of the ocean; 36,000 ft would cover the deepest trenches and 100% of the ocean. For the purpose of this study, the depths considered were 8,000 and 20,000 ft.

The power profile will vary according to the application. The power plant could be for a small submarine, a temporary ocean bottom habitat or work platform, a permanent ocean bottom habitat, or a commercial mining operation and others. Each application has its own particular requirements for minimum and maximum power level, endurance and depth capability. To simplify this study a 50-kw module was selected, and the endurance calculated for 20 and 40 hr. With a modular design, the power level can be varied by adding increments of 50-kw power units and the endurance varied by adding reactant vessels.

An important design consideration for a submersible vehicle is the disposal of the combustion waste products and their effect on buoyancy control and trim. The closed Brayton cycle can operate with a hydrogen-oxygen combustion system. The exhaust product from the reaction is water which can be stored in a volume that is a fraction of the original reactant volume. Although the net bouyancy remains constant, the trim may alter to a degree depending on the arrangement of the storage vessels.

Figure 4 (adapted from Ref. 5 with permission) is a graph showing energy and power requirements for undersea systems. As can be seen, there is a need for a number of power plants in the 50-kw and 200-kw power level with endurances ranging from 20 hr to 4 days.

**Table 1 Candidate system relative to weighted criteria**

| | |
|---|---|
| Safety | Noise level |
| Size | Power level control range |
| Weight | Recharging or refueling time |
| Development effort | Exhaust disposal |
| First cost | Operational life |
| System complexity | Time between overhauls |
| Logistics | Shelf or storage life |
| Maintenance | Depth insensitivity |
| Development cost | Training requirements |

According to Ref. 5, power requirements for deep submergence vehicles are contingent on the mission. It is anticipated that five types of missions will be important to the Navy in the coming years; 1) rescue: the rescue of personnel from disabled submarines; 2) search: the search of the ocean bottom for lost objects; 3) retrieval: the retrieval of objects from the ocean bottom; and 4) military oceanography: the study of the ocean three dimensionally; and 5) acoustical: the use of deep submergence vehicles as mobile acoustical platforms.

For each of the previous applications, the peak power requirements are expected to be much higher (e.g., 2 fold) than the average power requirement. The length of time during which the higher power is required will usually be small compared to the total operating time.

The power and energy requirements indicated for deep submergence vehicles in Fig. 4 have been influenced to some extent by the capabilities of currently available or anticipated energy sources and conversion systems. Further improvements in power sources (particularly with respect to energy density and specific power) are likely to lead to increases in these power and energy requirements. The advantages to be gained are self evident: greater range, higher search speed, or smaller vehicles and/or more space for crew and equipment.

## Study Results

The candidate Brayton cycle systems were evaluated by systematically varying each of the significant closed cycle parameters through a range of discrete steps. At each step, a complete system was defined and all component weights were calculated using computerized design techniques. Total system weights were calculated at each step, including all components, reactants and pressure vessels. In this way, the proper tradeoff between system efficiency and component and reactant weight and volume was achieved to assure a true minimum weight system. To complete this analysis over 50 different Brayton cycle system variations were investigated.

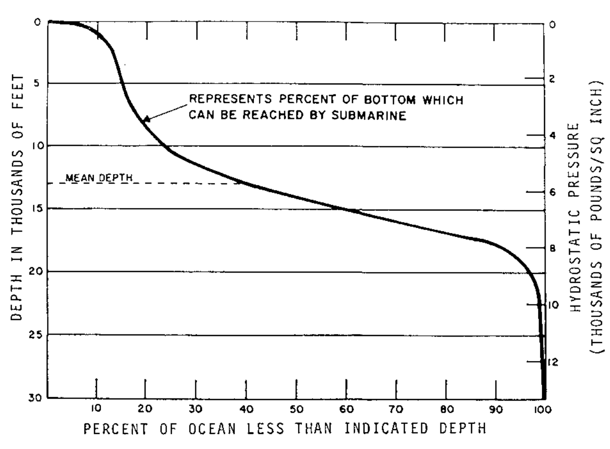


**Fig. 3 Ocean bottom distribution (Ref. 4).**

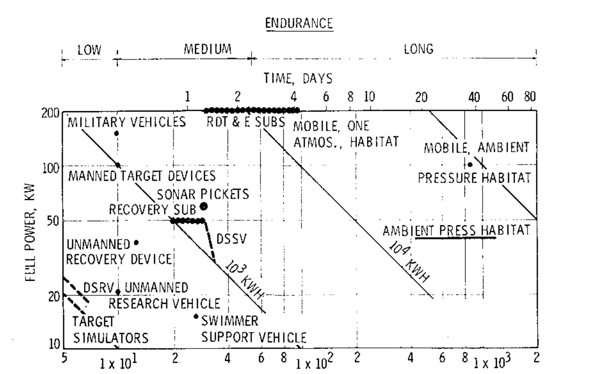


**Fig. 4 Energy and power requirements for undersea systems (Ref. 5).**

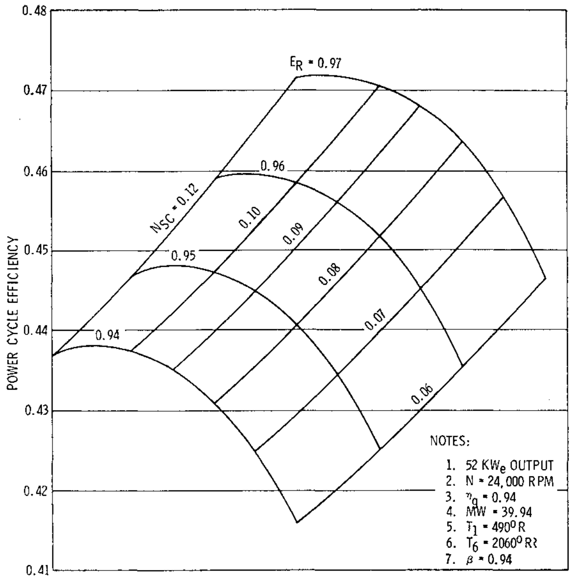


**Fig. 5 Cryogenic stored $H_2$ and $O_2$ system efficiency.**

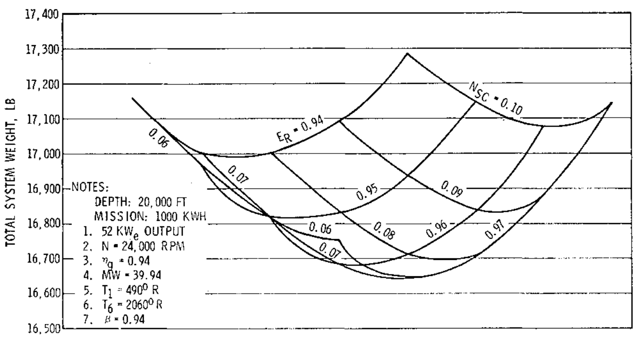


**Fig. 6 Total system weight cryogenic ($H_2$ + $O_2$) storage.**

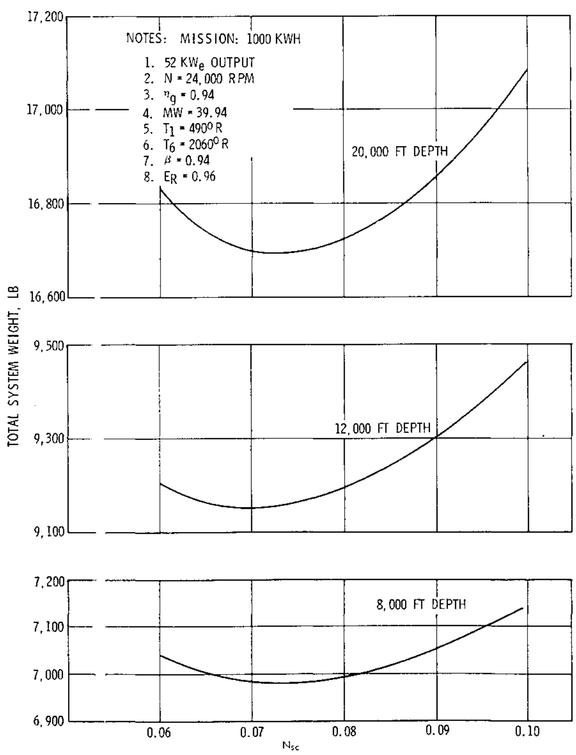


**Fig. 7 D.O.T. system weight estimate cryogenic ($H_2$ and $O_2$) storage.**

**Table 2 Base system parameters**

| | Base system |
|---|---|
| Working fluid (Xe-He) molecular weight | 39.94 |
| Recuperator effectiveness | 0.96 |
| $\beta = r_t/r_c$ | 0.94 |
| Compressor specific speed | 0.09 |
| Gross output power, $kw_e$ | 52 |
| Compressor inlet temp, °R | 490 |
| Turbine inlet temp, °R | 2,060 |
| Shaft speed, rpm | 24,000 |
| Total system weight, lb | 17,410 |

**Table 3 Comparison of parameters for base system and selected system**

| | Base system | Selected system |
|---|---|---|
| Working fluid (Xe-He) molecular wt | 39.94 | 39.94 |
| Recuperator effectiveness | 0.96 | 0.96 |
| $\beta = r_t/r_c$ | 0.94 | 0.94 |
| Compressor specific speed | 0.09 | 0.07 |
| Gross output power, $kw_e$ | 52 | 52 |
| Compressor inlet temp, °R | 490 | 490 |
| Turbine inlet temp., °R | 2,060 | 2,060 |
| Shaft speed, rpm | 24,000 | 24,000 |
| Total parametric system weight, lb | 17,410 | 16,697 |

Approximately 500 heat exchanger designs were evaluated by computer design programs.

Results are shown in the following sections for a cryogenically stored $H_2$-$O_2$ system and a high-pressure gas stored $H_2$-$O_2$ system. Both of these systems are sized at a design point of 50-kw net output power.

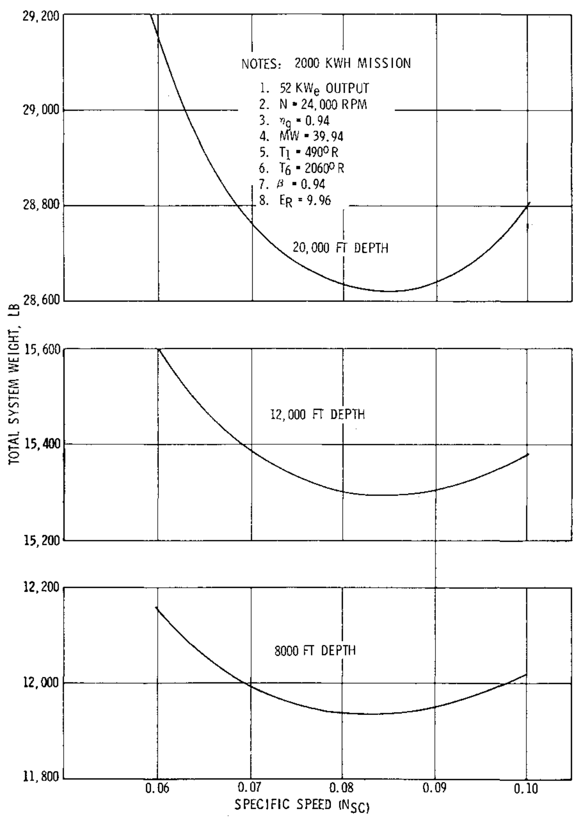


**Fig. 8 D.O.T. system weight estimate cryogenic ($H_2$ and $O_2$) storage.**

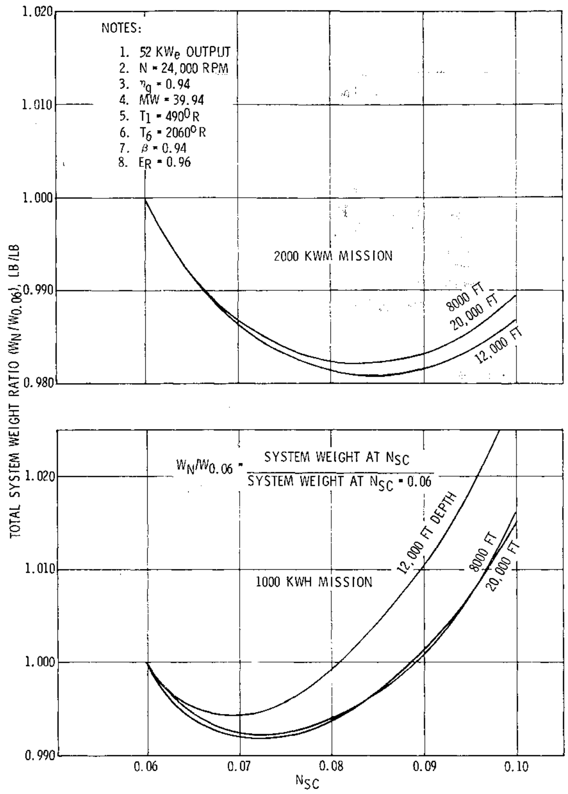


**Fig. 9 System weight ratios cryogenic ($H_2$ and $O_2$) storage.**

## Cryogenic Stored Hydrogen/Oxygen System

Parametric evaluation of the cryogenic system resulted in the selection of several gas cycle parameters that have a resulting decrease in the system total weight. These parameters are shown in Table 2 for a 1000-kwh mission and a 20,000-ft operating depth.

The selection of recuperator effectiveness and compressor specific speed listed previously were made to illustrate the minimum total system weight obtainable.

Additional investigations were conducted to select the compressor specific speed ($N_{SC}$) and recuperator effectiveness ($E_R$)

**Table 4 Reference cycle performance for cryogenic storage**

| | Design point |
|---|---|
| Net generator output, kw | 50 |
| Gross generator output, kw (400 Hz) | 52 |
| Working fluid, Xe-He, mw | 39.94 |
| Shaft speed, rpm | 24,000 |
| Recuperator effectiveness | 0.96 |
| $\beta = r_t/r_c$ | 0.94 |
| Compressor | |
| Mass flow rate, lb/sec | 2.13 |
| Bleed flow | 1.0 |
| Inlet temperature, °R | 490 |
| Inlet pressure, psia | 29.24 |
| Diam, in. | 8.117 |
| Pressure ratio, $r_c$ | 1.927 |
| Efficiency | 0.845 |
| Specific speed | 0.07 |
| Turbine | |
| Inlet temperature, °R | 2060 |
| Inlet pressure, psia | 54.76 |
| Diam, in. | 11.12 |
| Pressure ratio, $r_t$ | 1.811 |
| Efficiency | 0.874 |
| Rice generator | |
| Diam, in. | 6.0 |
| Efficiency, $\eta_g$ | 0.94 |
| Windage loss, kw | 1.273 |
| Bearing friction loss, kw | 0.275 |
| Electrical losses | |
| Fan, kw | 1.0 |
| Controls, kw | 0.2 |
| VRE and signal conditioner | 0.2 |
| Pump, kw | 0.6 |
| Cycle efficiency, $\eta_{cy}$ | |
| $\eta_{cy}$ = (net output)/($Qin$) = 52/116 | 0.447 |
| Specific speed = $NQ^{1/2}/(gH)^{3/4}$ (dimensionless) | |
| $N$ = rev/sec, $g$ = ft/sec$^2$, $Q$ = ft$^3$/sec, $H$ = ft | |

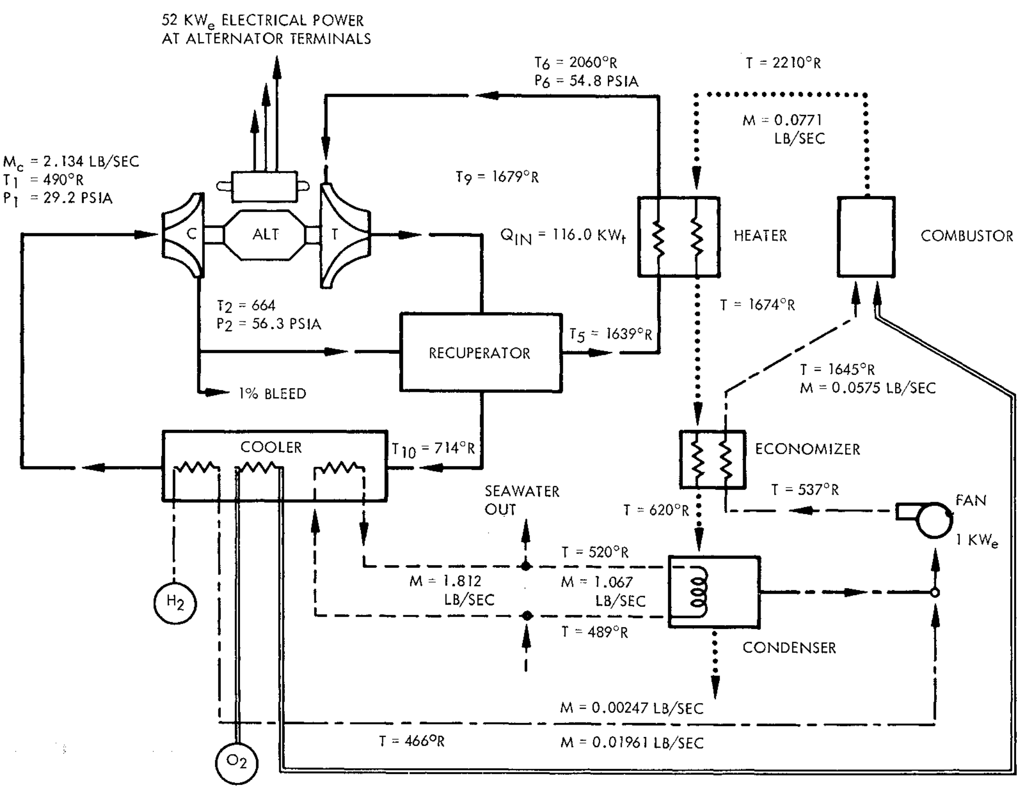


**Fig. 10 Closed Brayton cycle schematic cryogenic fuel storage.**

on the basis of total system weight. The definition of specific speed is in Table 4. Figure 5 shows the effects of varying $N_{SC}$ and $E_R$ on the over-all gas cycle efficiency. A $N_{SC}$ value of 0.11 appears optimum on the basis of cycle efficiency. However, as the compressor specific speed is reduced the gas loop pressure increases, which reduces the gas loop heat exchanger weight and volume. Figure 6 shows the total system weight as a function of $N_{SC}$ and $E_R$. This figure reflects the weight and volume variations of the gas loop heat exchangers designed at the gas cycle conditions. Since the hydrogen loop components are not sensitive to cycle loop pressure, their weights were varied as a function of cycle efficiency only.

A definite minimum system weight is evident for a $N_{SC}$ value of 0.07. The value of $E_R$ for minimum weight would appear to be 0.97 or possibly greater. However, the design of recuperators with effectiveness greater than 0.96 is at best difficult to achieve and, thus, a value of 0.96 is selected as the highest practical $E_R$ value obtainable. These results are for an output energy of 1000 kwh and 20,000-ft operating depth. Since operating conditions of 8000-ft depth and energy requirements of up to 2000 kwh are also required, the previous analysis was repeated to determine if the $N_{SC}$ value of 0.07 was the best for the various operating conditions.

Figures 7 and 8 show the results of varying specific speed, operating depth, and total output energy with the recuperator effectiveness held constant at 0.96. $N_{SC}$ value of 0.07 appears optimum for systems with total output energy of 1000 kwh. When the output energy is increased to 2000 kwh, the added reactant inventory and pressure vessel weight forces the minimum weight design to higher cycle efficiencies, i.e., higher specific speeds. For 2000 kwh, the minimum weight designs occur at $N_{SC}$ in the range of 0.08–0.09. Figure 9 shows the system weight ratios for both energy conditions. The minimum weight designs are more sensitive to $N_{SC}$ at an energy condition of 1000 kwh.

An additional consideration for the selection of the design $N_{SC}$ value is the compressor inlet pressure. The rotating unit is supported on gas journal and thrust bearings. The gas bearing load capacity is a function of the bearing compartment pressure. Since the system incorporates a relatively heavy rotor, the higher compressor inlet pressure (29.2 psia) of the 0.07 $N_{SC}$ case (vs 22.3 psia for the 0.08 $N_{SC}$ case) is attractive.

Thus, the final compressor specific speed selected is 0.07. The complete gas cycle and resulting parametric system weight for 20,000 ft and 1000 kwh is shown in Table 3.

After the $N_{SC}$ value of 0.07 was selected, the remainder of the hydrogen combustion loop components were designed to arrive at a detailed system weight and volume definition. Figure 10 and Table 4 show the finalized cycle schematic and

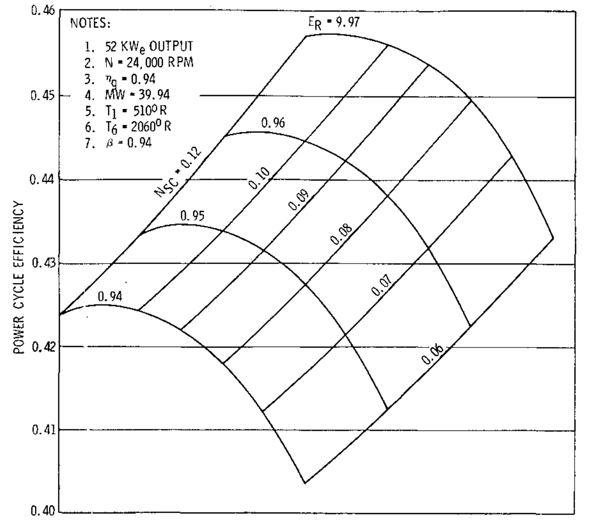


**Fig. 11 Deep ocean technology high-pressure gaseous storage hydrogen/oxygen system efficiency.**

**Table 5 Cryogenic system weight summary**

| Subsystems | Components wt, lb | Components Vol, ft³ | 8000-ft operating depth: 1000 khw wt, lb | Vol, ft³ | 2000 kwh wt, lb | Vol, ft³ | 20,000-ft operating depth: 1000 kwh Wt, lb | Vol, ft³ | 2000 kwh Wt, lb | Vol, ft³ |
|---|---|---|---|---|---|---|---|---|---|---|
| BRU | 260.0 | 8.80 | | | | | | | | |
| Recuperator | 306.5 | 3.86 | | | | | | | | |
| Cooler (all circuits) | 101.4 | 1.02 | | | | | | | | |
| Heater | 119.2 | 0.73 | | | | | | | | |
| Combustor | 50.0 | 0.90 | | | | | | | | |
| Economizer | 86.8 | 0.72 | | | | | | | | |
| Condenser | 8.1 | 0.04 | | | | | | | | |
| Ducting, Fan, Misc | 150.0 | 3.50 | | | | | | | | |
| TOTAL | 1082.0 | 19.57 | | | | | | | | |
| Total PCS components | | | 1082.0 | 19.57 | 1,082.0 | 19.57 | 1,082.0 | 19.57 | 1,082.0 | 19.57 |
| Condensate tank | | | 0 | 25.47 | 0 | 50.95 | 0 | 25.47 | 0 | 50.95 |
| Total power conversion module (dry) | | | 1082.0 | 45.04 | 1,082.0 | 70.52 | 1,082.0 | 45.04 | 1,082.0 | 70.52 |
| Hydrogen tank (dry) | | | 269.9 | 46.88 | 512.5 | 92.19 | 269.9 | 46.88 | 512.5 | 92.19 |
| Oxygen tank (dry) | | | 177.8 | 23.62 | 334.1 | 46.23 | 177.8 | 23.62 | 334.1 | 46.23 |
| Total dry system (without pressure vessel or consumables) | | | 1529.7 | 115.54 | 1,928.6 | 208.94 | 1,529.7 | 115.54 | 1,928.6 | 208.94 |
| Hydrogen inventory | | | 181.4 | | 362.8 | | 181.4 | | 362.8 | |
| Oxygen inventory | | | 1440.2 | | 2,880.3 | | 1,440.2 | | 2,880.3 | |
| PCM pressure vessel | | | 1463.8 | 47.74 | 2,284.3 | 74.69 | 3,570.8 | 51.34 | 5,572.5 | 80.50 |
| Hydrogen pressure vessel | | | 1528.6 | 53.38 | 3,095.1 | 107.5 | 3,729.9 | 57.55 | 7,548.6 | 116.07 |
| Oxygen pressure vessel | | | 1108.8 | 27.47 | 1,507.7 | 52.65 | 1,909.1 | 29.56 | 3,678.9 | 56.77 |
| Totals in air | | | 7252.5 | 128.59 | 12,058.8 | 234.84 | 12,361.1 | 138.45 | 21,971.7 | 253.34 |
| Displaced water | | | 8229.8 | | 15,029.7 | | 8,860.8 | | 16,213.8 | |
| Net buoyancy (+ denotes up) | | | +977.3 | | +2,917.0 | | −3,500.3 | | −5,757.9 | |
| Required foam at 34 lb/ft³ | | | | | | | 3,967.0 | | 6,525.7 | |
| Total weight positive or neutral buoyancy | | | 7252.5 | | 12,058.8 | | 16,328.1 | | 28,497.4 | |

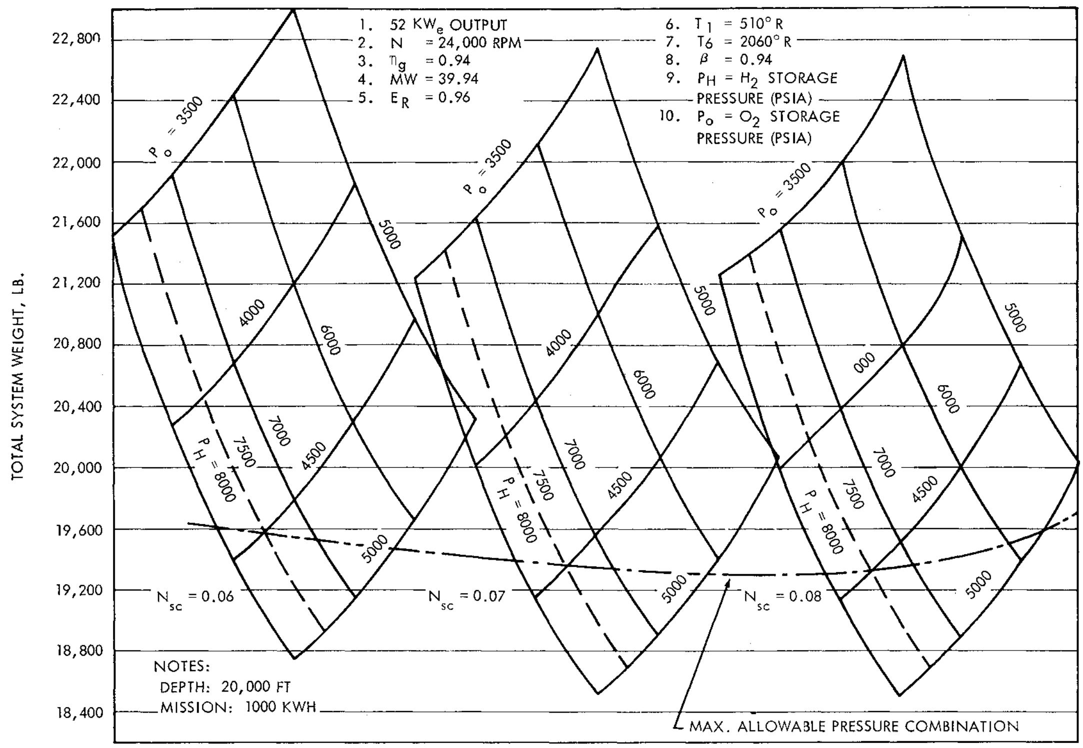


**Fig. 12 System total weight high-pressure ($H_2$ and $O_2$) storage.**

component parameters, and Table 5 presents the system weight and volume summary for the two operating depths and total output energies.

## High-Pressure Gaseous Stored Hydrogen/Oxygen System

An alternative to the cryogenic stored hydrogen/oxygen system is high-pressure gaseous storage. The principal advantages of this approach are 1) reduced logistic support and support equipment; 2) simple reactant tankage construction and control system; 3) fewer penetrations chargeable to the reactant storage method are required. A total of 2 penetrations into the power conversion module is required vs 8 for the cryogenic system. The penetrations are at sea water temperature vs the more difficult cryogenic temperature penetrations.

Several disadvantages are also present: 1) the system is heavier, 2) lower cycle efficiency since the compressor inlet temperature cannot be lowered as when using cryogenic liquids, and 3) there is a potential hazard associated with handling and storing very high-pressure oxygen.

Figure 11 shows the results on cycle efficiency of varying the compressor specific speed ($N_{SC}$) and recuperator effectiveness ($E_R$). This figure differs from Fig. 5 only in that the compressure inlet temperature ($T_1$) is 510°R instead of 490°R. The evaluation of high-pressure gaseous storage was restricted to a system operating depth of 20,000 ft and an output energy of 1000 kwh.

A system weight summary of the high-pressure stored system is shown in Fig. 12 for a constant $E_R$ of 0.96, selected as a result of the storage pressures and is quite insensitive to $N_{SC}$. Thus, the gas cycle design parameters selected for the cryogenic system are applicable to the high-pressure storage system. In fact, if at a later date, the system was changed from a cryogenic to high-pressure storage, the only gas cycle component to be changed would be the cooler. The remaining heat exchangers in both the gas loop and the hydrogen combustion loop could remain without a perceivable performance penalty.

## Conclusions

The closed Brayton cycle plant is an energy subsystem with a high-power density (kw/lb and kw/ft$^3$) and energy density (kwh/lb and kwh/ft$^3$). This type of power plant is at a high state of development as the result of many years of effort in surface and aerospace applications. For a specific application to a deep submersible vehicle improvements can be made by optimizing compressor specific speed and recuperator effectiveness to result in a minimum total system weight. Cryogenically stored reactants offer a lighter system weight. However, pressure storage of hydrogen/oxygen has advantages in logistic support, handling, and construction.

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