A Next-Generation AUV Energy System Based on Aluminum-Seawater Combustion

Timothy F. Miller, Jeremy L. Walter, Daniel H. Kiely
Applied Research Laboratory
The Pennsylvania State University
P.O. Box 30
State College, PA, 16804

Abstract-**This paper describes a hypothetical seawater-breathing AUV energy system based on the reaction of powdered aluminum. The reaction of aluminum with seawater offers improvement in energy density that will revolutionize long duration underwater operation. Although the system is hypothetical, the critical components are currently undergoing active engineering research and development. Consequently, this paper also describes in more detail the critical components of the system. The technical maturity level of this component development suggests that the development of a next-generation aluminum-seawater combustion system for AUV applications is feasible.**

I. INTRODUCTION

Metal-fueled heat engines represent the most energy dense power plants currently employed in autonomous undersea vehicles. Table I illustrates this by comparing the specific energy and energy density for various fuel/oxidizer combinations. Molten lithium and aluminum-based systems have been under investigation at the Applied Research Laboratory for over 20 years [1,2]. Previously these fuels were reacted with sulfur hexaflouride or water oxidant and the chemical energy released used to power a Rankine or Stirling cycle heat engine.

Although previous metal-fueled systems have been successfully operated (and deployed by the U.S. Navy), the development of a system based on solid aluminum fuel and seawater oxidizer has the potential for profound improvements in both chemical energy density and ease of operation. The use of powdered aluminum offers significant benefits in terms of fuel storage, utilization, and safety relative to molten aluminum (or lithium). The ability to use seawater as an oxidizer offers advantages in energy density as the volume otherwise required for oxidizer may now be occupied by fuel.

TABLE I
COMPARISON OF SPECIFIC ENERGY AND ENERGY DENSITY FOR SEVERAL OXIDIZER/FUEL COMBINATIONS

Fuel	Oxidizer	Energy Source	Specific Energy MJ/kg (HP-hr/lb)		Energy Density MJ/m^3 (HP-hr/ft^3)	
Al	H_2O	Open	15.2	(2.56)	41143	(434)
Al	$LiClO_4$	Closed	12.5	(2.12)	31758	(335)
Mg	F_2	Closed	18.1	(3.06)	28724	(303)
Li	F_2	Closed	23.7	(4.00)	23984	(253)
Mg	ClF_3	Closed	13.1	(2.22)	23510	(248)
Al/Li	$LiClO_4$	Closed	15.9	(2.68)	21804	(230)
Mg	O_2	Closed	14.9	(2.52)	21520	(227)
Li	ClF_3	Closed	17.4	(2.94)	20382	(215)
Li	$LiClO_4$	Closed	16.9	(2.86)	18486	(195)
Al	O_2	Closed	16.5	(2.78)	18107	(191)
Li	$FClO_3$	Closed	17.7	(2.99)	15737	(166)
Mg	SF_6	Closed	10.3	(1.74)	15452	(163)
B	O_2	Closed	17.4	(2.94)	14694	(155)
Li	SF_6	Closed	14.7	(2.48)	14030	(148)
Li	O_2	Closed	22.9	(3.87)	13651	(144)
JP-5	$LiClO_4$	Semi-Closed	6.8	(1.15)	13082	(138)
Li	CF_4	Closed	12.7	(2.15)	11850	(125)
Li	Cl_2	Closed	9.6	(1.63)	11471	(121)
B_2H_6	O_2	Semi-Closed	18.0	(3.05)	10144	(107)
Otto II		Open	2.5	(0.43)	3223	(34)

O_2 = 680 atm GOX

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There are several challenges to the successful implementation of an aluminum-seawater energy producing system. First, the solid aluminum must be stored and transported in a convenient manner. Second, solid aluminum does not react energetically with liquid water. Third, once combustion conditions are achieved, the oxide product acts to slow the rate of reaction and to create relatively large particles that can possibly accumulate as slag or erode system components.

In this paper we propose a power system based on the combustion of solid aluminum fuel and liquid seawater oxidizer. Although the system is hypothetical, we will show that promising engineering development work is currently underway on specific components of such a system. We will further show that these components can be configured to circumvent or mitigate the challenges just described.

II. ALUMINUM-WATER REACTION

The basic chemical reaction of interest here is as follows:

$$2\,\mathrm{Al} + (3 + 8)\,\mathrm{H_2O} \rightarrow \mathrm{Al_2O_3} + 3\,\mathrm{H_2} + 8\,\mathrm{H_2O}$$

On a mass basis, the above reaction has each kg of aluminum reacting with 1 kg of water to produce 1.89 kg of alumina and 0.11 kg of hydrogen. Enough diluent water is added to cool the exhaust to a practical 1100-1200 K turbine inlet temperature. (Obviously, the amount of diluent water may be varied to suit system requirements.) Research into aluminum combustion was initiated in the 1960's, prompted by the use of aluminum additives to solid propellant grains to reduce pressure oscillations and increase thrust. Initially research focused on aluminum/oxygen combustion, until the role of steam as the principal oxidizer in solid-propellant combustion was recognized.

In most systems of practical interest, aluminum particulate combustion is a heterogeneous process where the aluminum evaporates from a molten droplet and reacts with oxidizer diffusing into the flame zone from the surrounding atmosphere [3]. The initiation temperature is often associated with the melting point of the oxide and the maximum combustion temperature fixed by the vaporization (or dissociation) temperature of the oxide. A fraction of the oxide (20-30%) has been observed to recondense on the droplet surface and can act to slow or passivate the reaction. (The precise amount of recondensing oxide is dictated by temperature, pressure, and composition of the oxidizing environment.) The final oxide particle produced by combustion is typically 40% the size of the initial aluminum. The remainder of the oxide (70-80%) is dispersed in the form of submicron-sized smoke.

III. BASIC SYSTEM DESCRIPTION

Fig. 1 is a sketch depicting the conceptual aluminum-fueled, seawater-breathing power system. The heat engine is based on the classic Rankine cycle with feed-water heating. A detailed discussion of the key component technologies (designated by upper case letters) will follow, but an initial description of the system begins with a powder metal fuel feeder (A). The fuel is conveyed to and injected into the combustor (B) at two locations: one location associated with what we will call the "ignition" stream, and the second associated with the primary "reaction" stream. Similarly, two oxidizer-water and one diluent-water streams are injected into the combustor as well. The first oxidizer stream consists

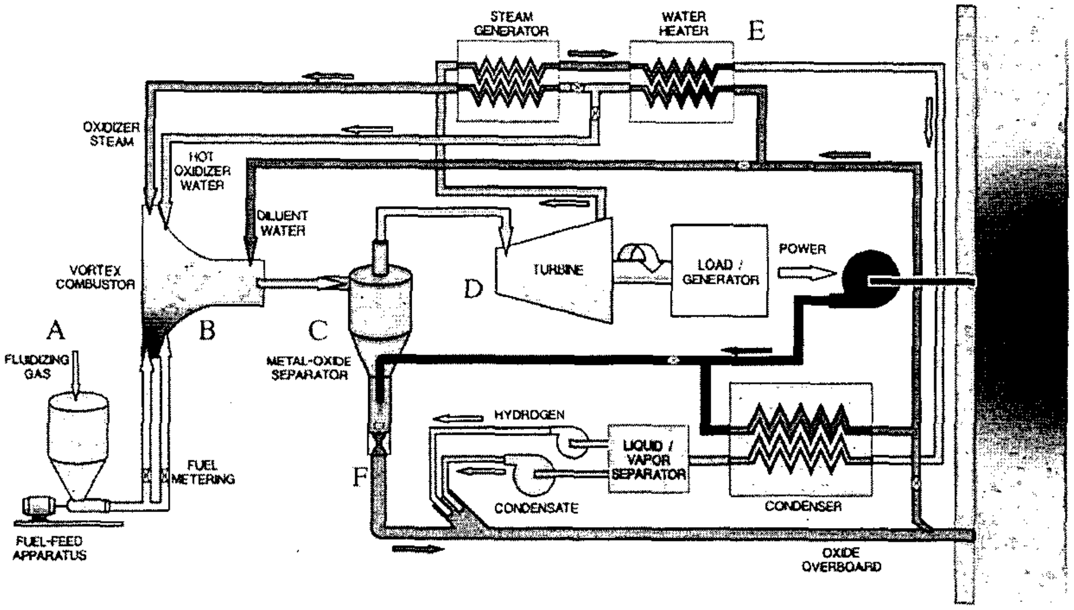

Fig. 1. Sketch of Proposed Al-seawater AUV Energy System.

of superheated steam that will be used to react with the "ignition" aluminum stream, and the second oxidizer stream consists of a saturated vapor that will react with the primary "reaction" fuel. The diluent water stream adds sufficient liquid to produce a nominal 1150 K exhaust, a temperature at which the oxide particles are solid. A nominal operating pressure is 25 atm.

As mentioned previously, metal combustion systems produce relatively large amounts of condensed-phase oxides–some of which are in the form of relatively large particles that can have a detrimental effect on turbine blades and other system components downstream of the combustor. A high-pressure cyclone separator (C) has been developed to remove the particulate phase. The novelty of the separator results from its ability to remove the particulate phase while maintaining elevated pressure, and in a way that permits the separated material to be conveyed away as a slurry for eventual disposal overboard. The clean high-pressure and high-temperature steam and hydrogen mixture is expanded through a turbine (D) that drives an alternator, direct mechanical load or other energy conversion device.

The exhaust from a typical compact turbine contains sufficient excess enthalpy to generate superheated steam for ignition and saturated steam for primary combustion in the two heat exchangers (E) depicted in Fig. 1. The exhaust stream is condensed in a feed water heater, and passes into a liquid/vapor separator to remove the hydrogen. The separated hydrogen is compressed and the condensate pumped to a pressure equal to the oxide separator pressure, and combined with the oxide/water slurry (F). The resultant mixture is conveyed overboard directly (or via a boost pump if necessary).

On a mass basis, the diluent water flow is 3 to 4 times the stoichiometric water requirements. Seawater is brought aboard (G) and if necessary pumped to system pressure. A portion is diverted to provide for the oxide separator slurry. The remainder is portioned into the diluent and oxidizer streams which flow through the feed water heater. The oxidizer stream passes through one or two heat exchangers (the number dependent on whether superheated ignition or saturated reaction steam is produced) and is heated by the turbine exhaust stream. These water streams are at greater pressure than the exhaust stream, hence excess water may be diverted to the exhaust (H). Although it may be possible to arrange the inlet and exhaust locations such that only a single hull piercing is required, it may be desirable to maintain separate inlet and exhaust locations to prevent contamination of the inlet stream.

The proof-of-concept system will likely be run with fresh water. However, the ultimate goal of this system is the use of seawater as an oxidizer. Seawater contains many different types of dissolved salts that when vaporized by high temperature can produce corrosive vapor. Consequently, some comment is required to address this issue. Note that both the ignition and the main combustion water come from a heater/evaporator and a superheater. Salts remain in solution and not in the oxidizer vapor. These salts either precipitate onto the heat exchanger surfaces (necessitating regular maintenance) or may remain in a brine that can be pumped overboard. The remaining diluent water exits the combustor at 1150 K – a temperature at which the salts are liquid. Although additional work is required to verify this, we feel that the liquid salts will, for the most part, attach to the oxide particulates to be removed from the exhaust stream by the separator. In any case, we contend that the mitigation of any possible adverse effects due to dissolved salts can be achieved readily during subsequent engineering efforts.

This system is amenable to a basic first-law thermodynamic analysis. Fig. 2 shows the results of such an analysis applied to the proposed system. The thermodynamic cycle efficiency ranges between 21 and 25%. Losses are associated with the inlet pump, exit pump, and exit compressor power requirements. These power requirements are functions of the operating depth, though the pumping of water and the compression of relatively small amounts of hydrogen gas are modest with regards to these requirements at all usual operational depths for AUVs. The separated oxide stream carries with it a large amount of stored thermal energy. Although not shown in Fig. 1, it is conceivable that efforts may be used to recuperate some of this energy before the waste stream is dumped overboard.

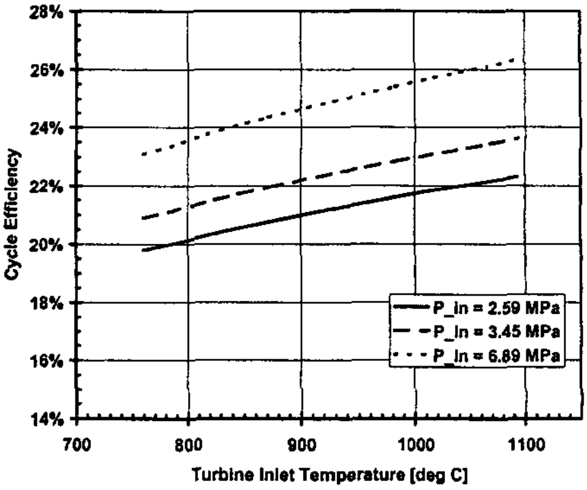

Fig. 2. Predicted cycle efficiencies for the proposed Al-seawater AUV energy system at different turbine inlet temperatures and pressures.

IV. SYSTEM COMPONENTS

A. *Fuel Feed*

Fig. 3 shows a sketch of the metal particle fuel feed device as well as a photograph of the assembled device. The fuel particles are stored in a cylindrical pressure vessel. The interstitial space between particles is occupied by a high-pressure carrier gas. The carrier gas may be an inert species, or may contribute to ignition or sustained combustion. The interstitial volume fraction is about 0.37 if the particles are of the same size (in a body-centered cubic packing structure) and much less if a bi- or multi-modal size distribution is employed. When the fuel feed valve is opened, the interstitial gas exits the cylinder carrying powder with it. Pressure may be maintained in the cylinder by use of a ram piston (which may alternatively be driven by motor, compressed gas, or by vehicle ram pressure in high speed applications).

This powder feed concept was first described by Fricke et al. [4] and Loftus et al. [5]. It was used in some of the linear aluminum steam combustor experiments of Foote et al. [6] conducted at atmospheric pressure. More recently, the concept has been refined at the Applied Research Laboratory for ease of use and high-pressure combustor application. Fig. 4 shows calibration flow measurements made of the device with a typically sized aluminum powder. As can be seen, a very stable powder flow rate can be maintained. The powder flow rate is dependent on the powder diameter, the molecular weight of the interstitial gas, and the operational pressure ratio. Powder flow rate control was superior with a carrier gas of higher molecular weight.

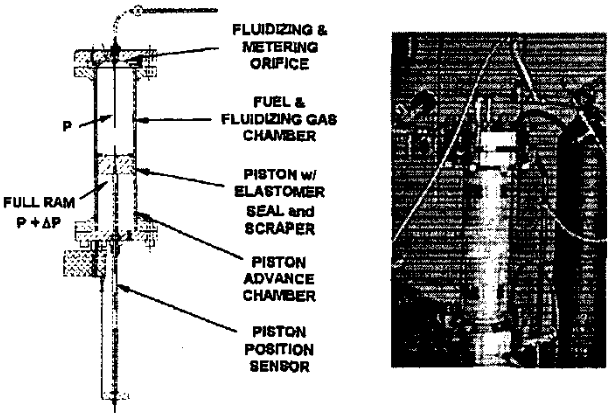

Fig. 3. Sketch and photograph of the powdered fuel feed system.

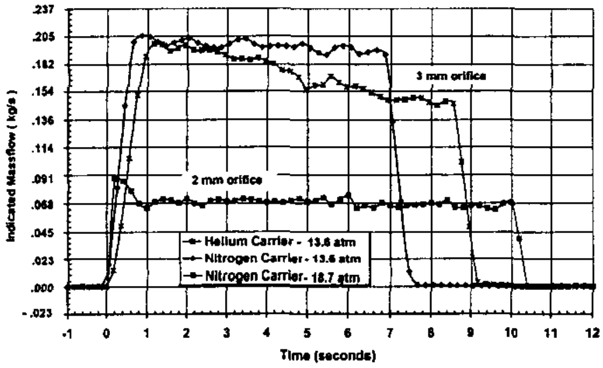

Fig. 4. Aluminum fuel feed rates showing effect of carrier gas and fluidization orifice size.

B. Vortex Combustor

Although the aluminum-water reaction possesses a large heat of reaction, several challenging aspects of the physics of the reaction have thwarted its use in the past. A relatively high ignition temperature is required, thus necessitating effective energy feedback from the primary combustion location to the ignition location. Superheated or saturated steam is required for the reaction. Relatively long residence times within the combustor are required to react all of the aluminum. A portion of the oxide product condenses on the reacting aluminum, eventually producing relatively large (approximately 40% of the initial aluminum diameter) oxide droplets that can accumulate on the combustor walls if not handled properly.

The Applied Research Laboratory has been working for the last seven years on aluminum combustion technology that addresses these challenges. The vortex combustor technology employs the unique hydrodynamic features of swirling flows to both facilitate combustion of aluminum and control the exhaust of aluminum oxide. Fig. 5 is a conceptual sketch of a vortex combustor. The oxidizer enters at the perimeter with a swirl component of velocity. A stoichiometric amount of aluminum enters as well. The relative swirl must be controlled well to ensure that the radially inwards drag force exerted on the particles equals (or just exceeds) the centrifugal outwards force experienced by the swirling particles. The particles move inwards though a heat-up and melt zone, and then through a preliminary ignition zone where the reaction of aluminum with steam takes place on the particle surface and is governed by an Arrhenius relationship. When the temperature reaches a point at which the mass flux of aluminum evaporating from the particle surface can push the reaction off of the surface, then a heterogeneous vapor-phase reaction takes place, and a reacting band of aluminum is suspended in the combustor. The relatively long reaction distance is transformed from an axial length to a spiral trajectory (with a much more modest length requirement for the combustor). The confined volume

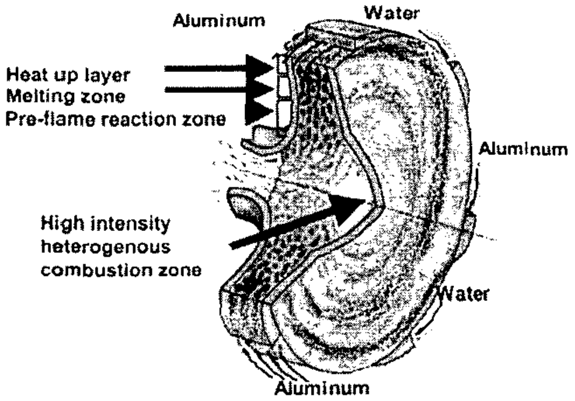

Fig. 5. Conceptual sketch of the vortex combustor flowfield.

acts to concentrate the reaction zone and facilitates the preheating and ignition of the incoming reactant stream.

Fig. 6 is a photograph of a vortex combustor operating in a high-power, direct thrust capacity. Test runs have been ongoing for over six years, and have identified operating conditions and combustor geometric configurations that facilitate clean, sustained combustion (as well as other conditions and configurations that facilitate oxide accumulation).

Fig. 7 illustrates a CAD image of a conceptual design of a low-power/long endurance version that takes advantage of "lessons learned" during the development of the high-power/short duration combustor. A portion of the energy released by this reaction feeds back to the inlet via radiation heat transfer to ignite the incoming stream, and a portion is convected/radiated radially inwards to ignite the main reaction portion of fuel and oxidizer.

Concurrent with testing and hardware development has been the development of numerical analysis and design tools [7]. A sample calculation from one of these tools is shown in Fig. 8. Here a two-fluid Eulerian/Eulerian model is employed to examine the disposition of the aluminum fuel. The ideal disposition locates a near stoichiometric mass fraction of fuel away from the walls of the combustor and about 50-75% of the radial distance from the outer perimeter to the exhaust radius. The ideal flow field is one that moves the exhaust at sufficient velocity to keep the walls clean, and that prevents the occurrence of slag-accumulating recirculation zones. Numerical combustion models have also been developed that incorporate empirical reaction correlations derived from measurements in the technical literature, mass transfer, two-phase slip effects, radiation heat transfer, and the effects of high temperature dissociation of the reacting species.

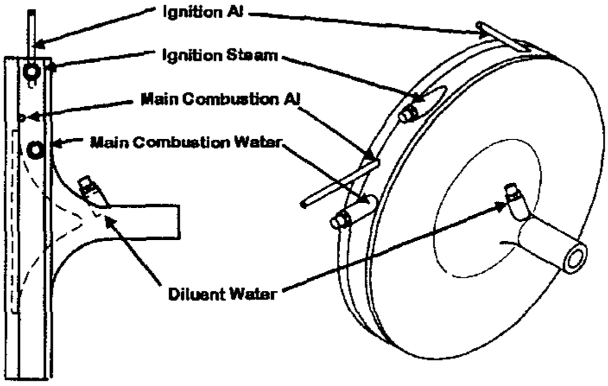

Fig. 7. Concept sketch for a low-rate/long-endurance combustor

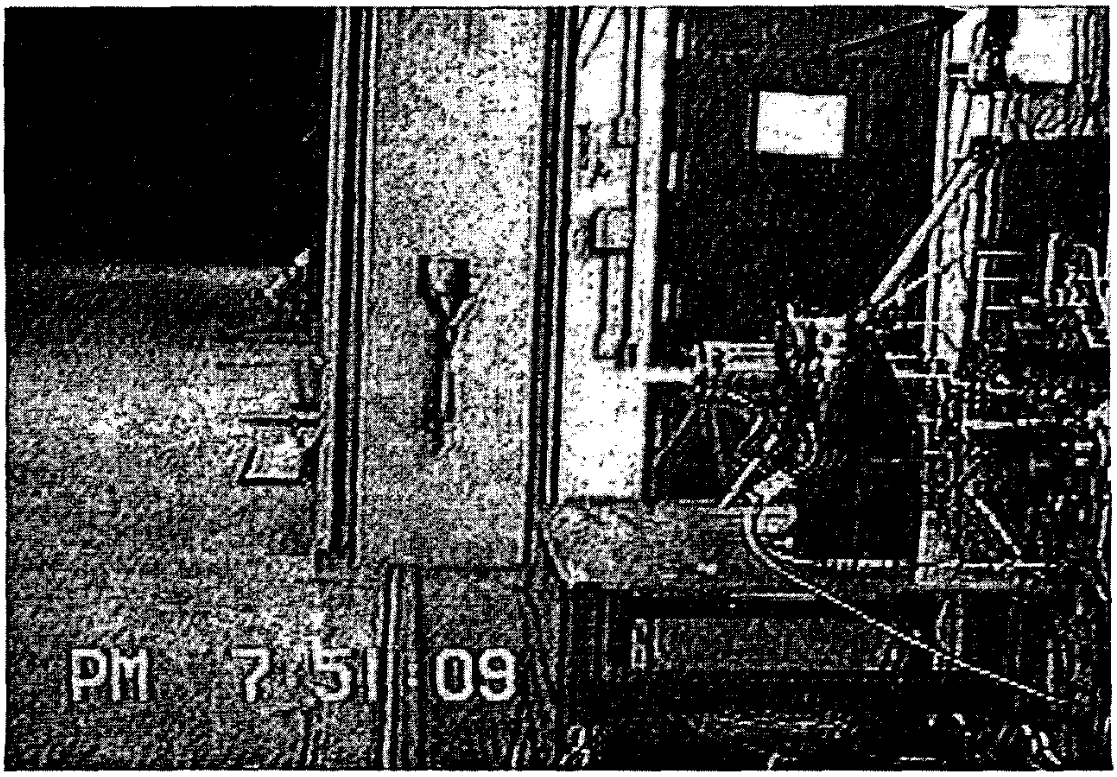

Fig. 6. Photograph of an operating vortex combustor (without water diluent) on a test stand.

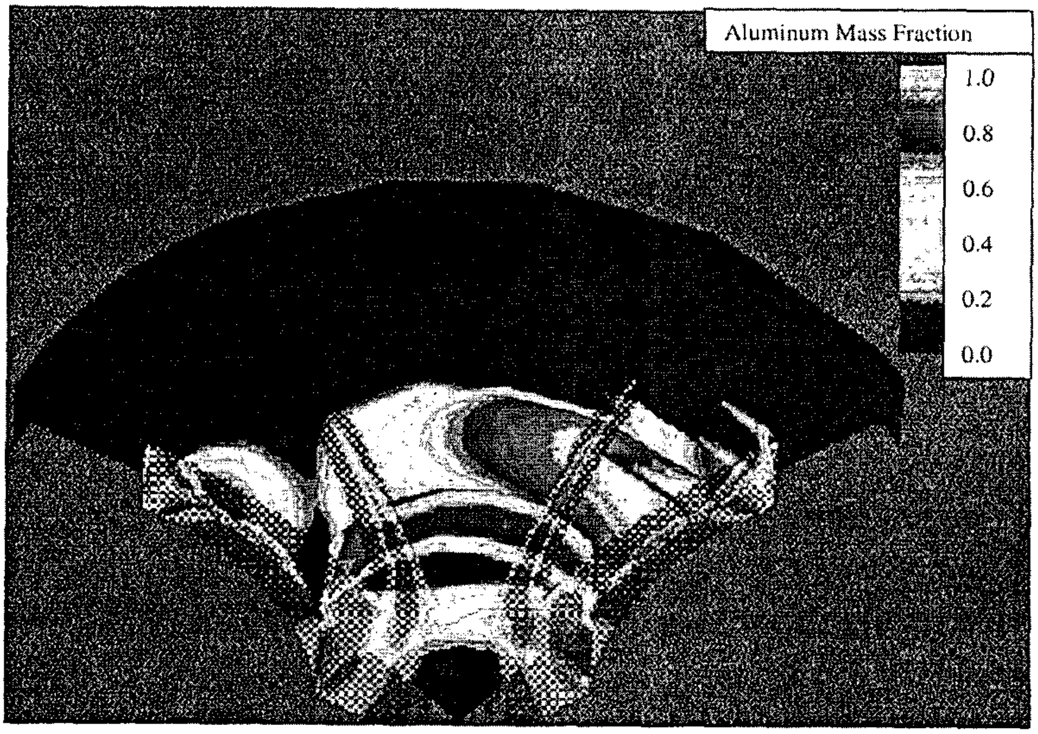

Fig. 8. Illustrative 3-D CFD calculation showing mass fraction of aluminum within a model vortex combustor chamber.

C. Oxide Separator

As mentioned previously, a key requirement of this system is the removal of any large oxide particulate upstream of the turbine. Fig. 9 shows a sketch of a novel cyclone separator developed for this requirement. A successful separator is one that not only has high separation efficiency and low pressure drop, but also maintains the high pressure required of the system, prevents loss of gas, permits uninterrupted operation, and enables the separated material to be conveyed away continuously for disposal overboard.

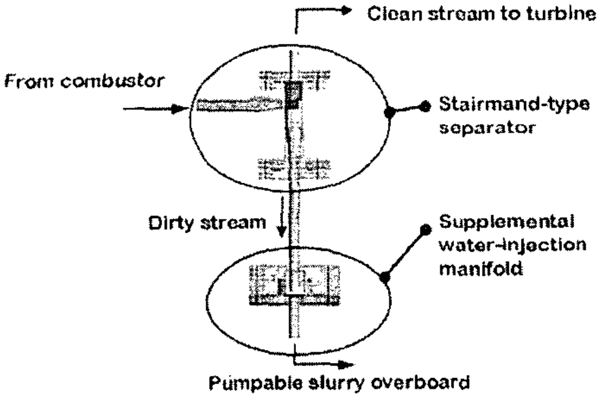

Fig. 9. CAD rendering of the high-pressure, continuous-flow oxide separator.

The oxide separator developed here uses a supplemental water manifold to create a slurry in the oxide exhaust of the separator [8]. The slurry flows through a restriction orifice that enables a high pressure to be maintained. Fig. 10 shows measurements of separation efficiency and pressure drop in a high-pressure cold flow for alumina powder of 7 micron diameter. These measurements show very high separation efficiencies for densely laden flows. For the more moderately laden flows of application here, the separation efficiency is still in the 90% range, and the very low pressure drop (< 6 kPa) across the separator permits a number of separators to be linked in series to obtain the desired degree of oxide removal. An actual separation system would likely consist of a central separator that would remove large "clunker" particles, followed by three or four parallel lines of separators of the type described above.

Any loss of high-temperature and high-pressure gas represents a loss in system efficiency. Fig. 11 shows measurements of operational pressure and the supplemental water flow requirements required to ensure that no gas is lost. The supplemental water flow requirements are quite modest. In fact, under some power requirements, the supplemental water requirement is dictated by that required to rapidly quench the high temperature oxide stream to below the saturation temperature of water.

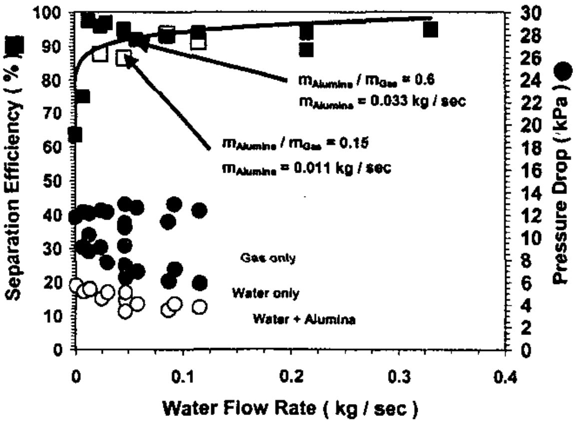

Fig. 10. Supplemental water requirements to maintain pressure and to prevent loss of steam.

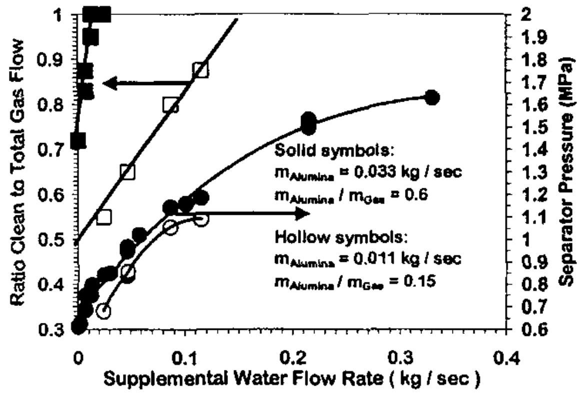

Fig. 11. Separator efficiency and pressure-drop of the particle separator as a function of supplemental water flow rate.

D. *Turbine*

Fig. 12 shows a photograph of a range (from 4 kW to over 1 MW) of full impulse, single-stage turbines designed for power requirements ranging over two orders of magnitude. Roughly, power requirements dictate the size of the turbine wheel and efficiency requirements mandate the maximum rotational speed subject to the ability of the wheel to withstand the centrifugal stress. Consequently, the lowest power wheels have the smallest diameter and spin at the highest RPM. The smaller blades on the smaller diameter wheels may be more susceptible to erosion or clogging. This suggests that the lower power wheels might be more subject to the effects of solid oxide particles and emphasizes the importance of the separation system.

If the oxide separation system is operating perfectly, then no modification of the turbine design relative to those currently used are necessary. If the aluminum oxide particle diameter in the turbine stream can be held to less than 7 microns then sufficient turbine blade life appears feasible [9]. Blade erosion seems tractable, though no test data at completely identical conditions are available.

A pragmatic design should not assume perfect operation. Fig. 13 shows two full impulse turbine blade designs. Single-stage full-impulse blades were selected for simplicity and similarity to torpedo turbines. The first cascade depicts a current blade design typical of a lightweight torpedo engine. The second cascade depicts the design modifications appropriate for operation in a potentially abrasive oxide laden stream. The modified profiles are substantially more massive in order to survive a more abrasive environment. The modified profile has been designed for 75 kW operation, and enables a theoretical turbine efficiency of 71.3% (a two point reduction in efficiency relative to the lightweight torpedo turbine). At higher power levels, this efficiency will increase.

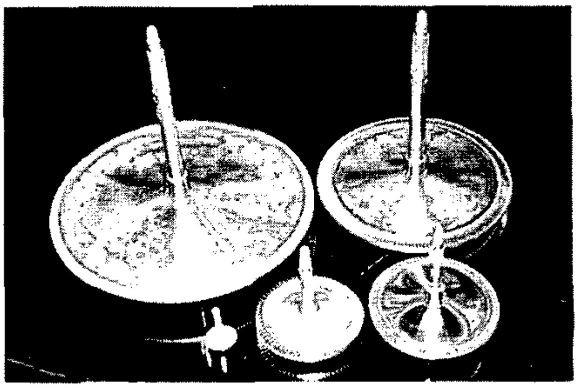

Fig. 12. Photograph of family of single-stage, full-impulse turbines ranging in power from 4 kW to 1 MW.

E. *Heat Exchangers*

Fig. 14 show a photograph of a typical compact heat exchanger used in a Rankine cycle undersea propulsion system. The coiled tubes encircle the exhaust portion of the turbine. Superheated exhaust from the turbine passes over the tubes and transfers heat to the colder fluid flowing through the tubes. Fine heat transfer augmentation fins are attached to the tube exteriors. The requirement of sufficient superheated steam production to ensure ignition dictates the portion of water diverted through both the steam generator and water heater, and through the steam generator alone.

Fig. 15 shows calculations from a first law analysis that illustrates the temperature and relative amount of superheated steam that may be produced from either the turbine or the combustor exhaust. The horizontal coordinate expresses the amount of the stoichiometric reaction water that is diverted through the superheater. The vertical coordinate expresses the superheated temperature that the diverted water can achieve. For example, at one atm pressure, ~90% of the stoichiometric reaction water (if diverted) can be superheated by the turbine exhaust. At a

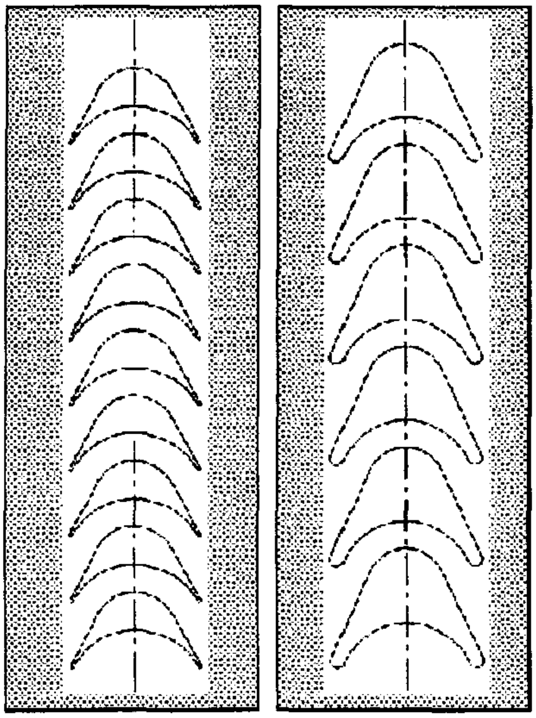

Fig. 13. Sketch of standard lightweight torpedo turbine blade cascade (left) and modified (right) AUV turbine blade cascade.

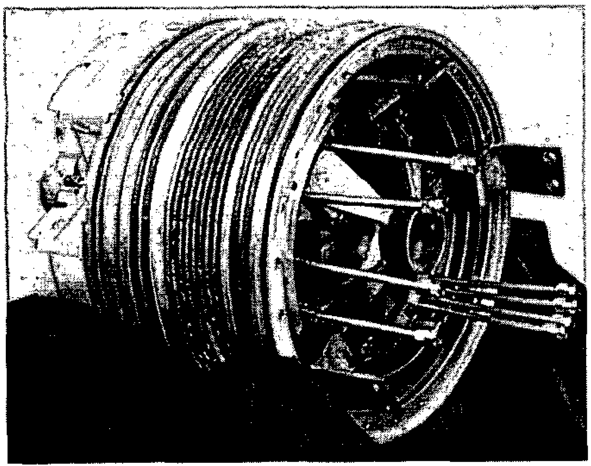

Fig. 14. Photograph showing a regenerative feedwater heater (coiled tube) surrounding the (hidden) turbine exit.

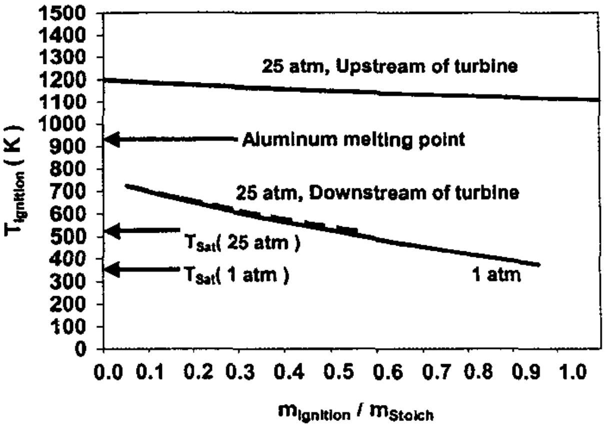

Fig. 15. Results of 1st -law analysis illustrating the relative amount and temperature of ignition (superheated) steam that can be produced by recuperation of the turbine or combustor exhaust steam.

more relevant 25 atm pressure, ~55% of the diverted stoichiometric water can be superheated to produce ignition steam. If larger amounts are diverted then a saturated mixture will be obtained. If reduced amounts of stoichiometric reaction water passes through the superheater, then higher temperature ignition steam is obtainable. An operation point that enables the production of 600 K steam from 20-25% of the reaction water was chosen. It may be possible to locate a steam generator between the combustor exit and the turbine inlet.

If this is possible, the entire stoichiometric reaction water can be transformed to superheated steam at 1150 K (well in excess of the aluminum melting point). This configuration should be viewed as a second choice because the extraction of energy upstream of the work-producing component produces a disproportionate falloff in the thermodynamic efficiency.

V. SUMMARY

This paper described a hypothetical seawater-breathing AUV energy system based on the reaction of powdered aluminum. The reaction of aluminum with seawater offers improvement in energy density that will revolutionize the ability for long duration operation underwater. Although the system is hypothetical, the critical components are currently undergoing active engineering research and development. Consequently, this paper also describes these system components in much more detail. The level of technical maturity of the critical components suggests that the development of a next-generation aluminum-seawater combustion system for AUV applications is feasible.

ACKNOWLEDGMENT

This work was supported by the Office of Naval Research and the Defense Advanced Research Projects Agency. Development of the powder feed system and simulations of the vortex combustor flowfield were performed by M. G. Schmidt and J. J. Cor, respectively, of the Applied Research Laboratory.

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