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Report Title

Optimized Power Generation and Distribution Unit for Mobile Applications

ABSTRACT

This research project focused on determining optimal power generation and distribution within a mobile human-scale power system. The intended application was for a human scale exoskeleton, in particular underwater applications. However, the tools and techniques are applicable for a broad range of mobile systems that carry a finite energy supply and need to optimize both the system performance and system efficiency. A wide survey of appropriate energy storage and power generation technologies was performed. Subsequently, a decision making algorithm was developed that specifically determined the best way to convert stored energy to available power coupled with the best way to distribute this power to multiple needs within the system. A dual stage decision making strategy was adopted whereby fast inner stage would determine both the needed power and the optimal control of the particular power application within the system. A slower second stage would accept the power demands from the first stage and then determine the optimal way generate that power from the stored energy source. The strategy was tested in simulation and experimentally. It was determined that a significant energy savings can be accomplished over conventional power management schemes while still achieving a particular mission's performance requirements.

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(2) Gupta, P. and A. Alleyne, "Centralized and Decentralized Powertrain Controllers for an Earthmoving Vehicle," Proceedings of the 2005 American Control Conference, Portland, OR, 1613-1618, June 8-10, 2005.

(3) Hencey, B. and A. Alleyne, "Stable Gain Scheduling through Bumpless Transfer," Proceedings of the 2005 ASME IMECE, Orlando, FL, IMECE2005-82146, Nov. 2005.

(4) Hencey, B. and A. Alleyne, ""A Static Anti-windup Compensator Design Technique for Robust Regional Pole Placement," Proceedings of the 2006 ASME IMECE, Chicago, IL, IMECE2006-14653, Nov. 5-10, 2006.

(5) Montgomery, A. and A. Alleyne, "Optimizing The Efficiency Of Electro-Hydraulic Powertrains" Proceedings of the 2006 ASME IMECE, Chicago, IL, IMECE2006-16008, Nov. 5-10, 2006.

(6) B. Hencey and A. Alleyne, "A Robust Controller Interpolation Design Technique" accepted for the 2007 American Controls Conference, NY, NY, July 2007.

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(2) Hencey, B. and A. Alleyne, "A Robust Controller Interpolation Design Technique" submitted to IEEE Transactions on Control Systems Technology, December 2006.
(3) Hencey, B. and A. Alleyne, "An Anti-Windup Compensator Design Technique for Robust Regional Pole Placement, submitted to IEEE Transactions on Control Systems Technology, January 2007

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Graduate Students

NAME	PERCENT_SUPPORTED	
Yan Li	0.66	No
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Alexander Montgomery	1.00	No
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Total Number:	**3**	

Names of Post Doctorates

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FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
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Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME	
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Optimized Power Generation and Distribution Unit for Mobile Applications

Andrew Alleyne

0. Abstract

This research project focused on determining optimal power generation and distribution within a mobile human-scale power system. The intended application was for a human scale exoskeleton, in particular underwater applications. However, the tools and techniques are applicable for a broad range of mobile systems that carry a finite energy supply and need to optimize both the system performance and system efficiency. A wide survey of appropriate energy storage and power generation technologies was performed. Subsequently, a decision making algorithm was developed that specifically determined the best way to convert stored energy to available power coupled with the best way to distribute this power to multiple needs within the system. A dual stage decision making strategy was adopted whereby one stage would determine both the needed power and the optimal control of the particular power application within the system. A second stage would accept the power demands from the first stage and then determine the optimal way generate that power from the stored energy source. The strategy was tested in simulation and experimentally. It was determined that a significant energy savings can be accomplished over conventional power management schemes while still achieving a particular mission's performance requirements.

Appendices

Appendix A:

Optimizing The Efficiency Of Electro-Hydraulic Powertrains
by A. Montgomery and A. Alleyne

Appendix B:

A Robust Controller Interpolation Design Technique
by B. Hencey and A. Alleyne

Appendix C:

Power Systems Investigation
by Joseph Macklin

1. Problem Statement:

The goal of this project is to develop tools and methodologies for optimizing the power generation and power distribution in mobile systems of interest to the military. We examine systems that carry their own energy, convert it to useful power, and then apply that power to perform some task against a load. The target systems are those that would be human scale such as an exoskeleton type of device. Primary metrics of success will be overall reduction in system power consumption while maintaining prescribed levels of task performance.

The project produced algorithms, methodologies and general frameworks that can then be applied to specific machine or system configurations. In addition, platform-specific versions of these algorithms were implemented in real-time simulations and in hardware-in-the-loop platforms culminating in implementation on a physical testbed.

2. Summary of Results:

Initially, a detailed investigation was performed to determine the optimal combination of energy storage and power generation systems. The results of this detailed study can be found in Appendix C. The study was originally performed with the constraint that the system be non air breathing. As a result, battery powered electrical systems were found to be the most appropriate. However, as the project progressed, the constraint of non air breathing systems was relaxed allowing for other candidate technologies to be evaluated. The candidate technology that ended up being focused on here followed existing exoskeleton designs [1] and examined internal combustion engines combined with fluid power distribution. Once the candidate technology was settled on, the main results from this work were twofold. First, a strategy for optimizing power generation and power distribution for mobile systems was developed. Second, a framework for extending this strategy over a wide range of system operating conditions was developed. The first set of results is detailed in Appendix A. Examples related to the second set of results are detailed in Appendix B.

2.A Power generation and distribution:

As stated above, the primary goal of this project was to minimize energy consumption, particularly for mobile power systems, while maintaining a prescribed level of system performance. This goal results in a coupled problem where there were competing sub-goals associated with:

- power generation or conversion
- power distribution through a network, and
- load matching with an environment.

First, there was a goal to maximize efficiency in terms of energy converted from some stored source (e.g. chemical fuel) to mechanical energy useful to do work. Depending on the conversion system, there may be different modalities of conversion that may be optimal. Also, it is important to produce only that power that is deemed necessary to perform the given tasks. Secondly, the power generated must be distributed efficiently to the loads. For the types of fluid power systems under consideration, this requires a minimum of energy losses due to factors such as throttling. Finally, it is imperative that the appropriate performance metrics be satisfied insofar as the loads meeting their prescribed displacement paths despite external disturbances. A generic schematic of this type of a system is shown below in Figure 1. In this schematic the assumption is that a human-in-the-loop is monitoring the system performance with respect to the external environment and providing reference commands to the overall system. This would be consistent with exoskeleton usage.

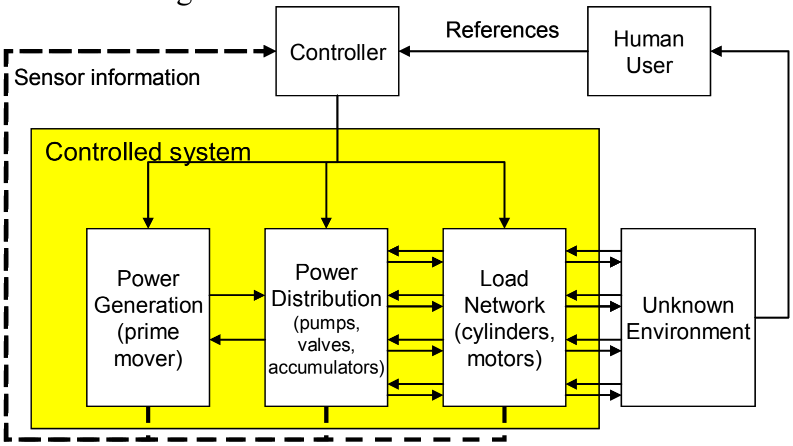
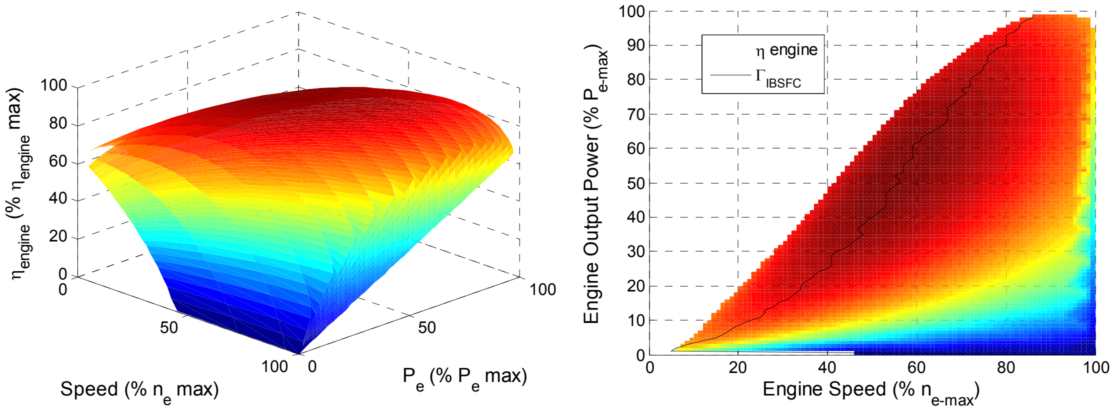


Figure 1. General framework for mobile energy management system with fluid power

The primary challenge for efficient performance of this class of problem is that the exogenous signals (environmental interaction and user commands) are unknown, time varying, and highly coupled to the load network.

The external environment produces time-varying loads to the overall system. These loads are reflected through the load network back to the generation and distribution subsystems. To match these loads, the generation and distribution subsystems must adjust their power output as quickly as the variation in the environment. However, the change in the power output can easily change the efficiency with which the power is either generated or distributed. Therefore, the efficiency strategy must be integrated into the decision making algorithm. The constraints imposed by satisfying both efficiency and performance requirements led to a very challenging power management problem.

The system of Figure 1 is essentially a powertrain (generation and transmission) system and therefore has significant parallels with automotive applications. Fluid power systems, particularly those with variable displacement pumps and motors, are akin to automotive systems with continuously variable transmissions (CVTs) in their ability to vary the ratio of input to output torque or speed. In fact, if Figure 1 were to represent a prime mover, a single variable-displacement pump, and a hydraulic motor, that would be exactly the framework for a CVT system. There has been a significant amount of work done on the control of mobile IC-engine driven CVT systems [2-9]. Several of these works have been very insightful in the appropriate integration of power generation and distribution to a single load. In particular, [3,4,8] examine how to maintain the power production from the prime mover near some maximum efficiency point while simultaneously meeting the load demands at the drive wheels. One of the fundamental approaches was to maintain proximity to an optimal operating path in the prime mover power space. Such a path can be called an Optimal Operating Line (OOL) [4] or an Ideal Brake Specific Fuel Consumption (IBSFC) line [10] as shown in Figure 2.



(a) Steady State Efficiency Map (b) IBSFC Curve (Γ_{IBSFC})

Figure 2. Unit Compression Ignition Engine Maps [11]

While illuminating, the previous CVT studies have all focused on a single transmission path for power; e.g. a single load. What was needed to meet the goal of efficient mobile Fluid power systems was a decision making framework capable of handling multiple distribution and/or load subsystems in an interconnected network.

The early work associated with this project [11-13] focused on the overall MIMO control strategies without explicit regard to optimizing the power generation. More recent work [14] supported by this project provides a framework for explicitly accounting for the power generation and distribution. The basic approach developed was to decouple the problem into an inner loop algorithm focused on performance and an outer loop problem focused on efficiency. The outer loop algorithm estimates the amount of power that is required in the system based on an estimate of the overall power consumed at the loads. Simple approaches would be to estimate the power required based on a pressure-flow measurement at each of the loads [14]. Given *i* total loads in the network,

$$P_{desired} = kP_{load} = k\sum_i p_i q_i ; \quad k \geq 1 \tag{1}$$

A more sophisticated approach [5] would be to calculate the demanded engine power as a function of individual transmission component efficiencies (η_i).

$$P_{desired} = P_{load}\prod_i^n \eta_i\left(Q_p, p_u, p_d\right) \tag{2}$$

Unfortunately, the approach in (2) requires far too much accuracy in the a priori knowledge of system parameters as well as parametric invariance with respect to time. The approach proposed here is to design a <u>*dynamic*</u> demanded engine power estimator that increases when too little power is produced and decrease when the engine is producing excess power. For example, the approach used in [14] for a system with throttling valves gives

$$\dot{\hat{P}}_{desired} = k_1\sum_i^n e_i - k_2\left(u_{v,\max} - \max\left(\underbrace{u_{v1}, u_{v2}, \ldots, u_{vn}}_{\text{valve inputs}}\right)\right) \tag{3}$$

with k_i being design constants to affect the speed of response of the demanded power estimator. For the valves to be replaced by variable displacement devices, as is the focus of the current work, the dynamic demanded power estimator would be modified to be

$$\dot{\hat{P}}_{desired} = k_1 \sum_{i}^{n} e_i - k_2 \left(f \left(d_i, d_{i\_\max} \right) \right) \tag{4}$$

with f a yet to be determined function. If the power distribution network is coupled to a CI engine such as the one shown in Figure 2, the estimated demanded power can then be converted into an engine speed command reference via

$$\hat{P}_{desired} = \int \dot{\hat{P}}_{desired} \;\text{ and }\; n_{reference} = \Gamma_{IBSFC} \left(\hat{P}_{desired} \right) \tag{5}$$

The incorporation of a dynamic power estimator allows the inner loop, consisting of the power distribution and load network subsystems in Figure 1, to focus on MIMO control using available techniques (LQG/LTR, H_{infinity}) [12]. An example of the power savings that can be obtained on a hardware-in-the-loop system [12] representative of an earthmoving vehicle can be seen in Fig 3.

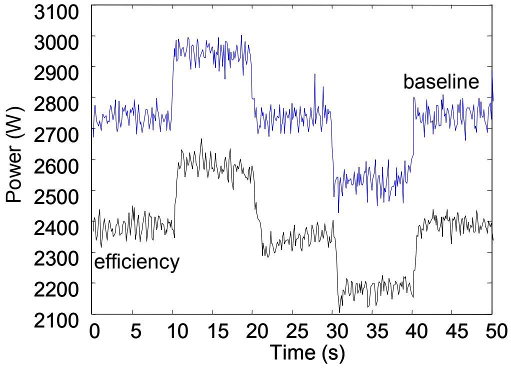
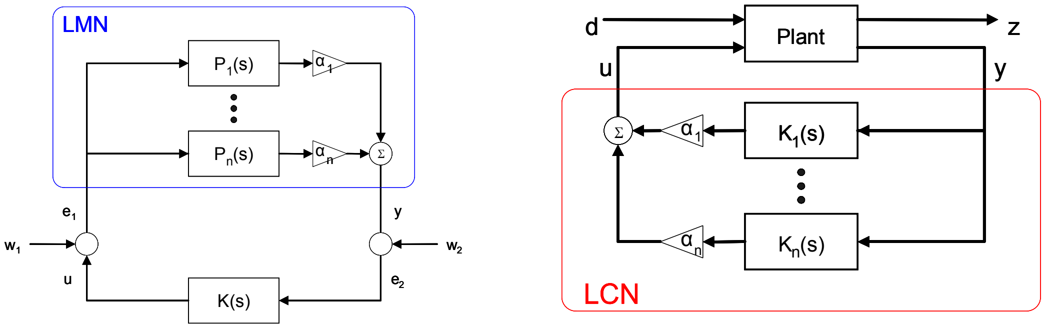


Figure 3. Improved efficiency for an earthmoving vehicle powertrain [14].

Further details are highlighted in Appendix A.

2.B Gain-scheduled control over a large operating regime

The second goal that is related to the overall system efficiency is to ensure that the tools developed are applicable over a wide range of operating conditions. The methodological tools discussed above in Section 2.A are most useful for linear system representations. This allows the full suite of linear computer aided control system design (CACSD) tools to be brought to bear on the design of either portion of the inner-outer loop strategy. Most mobile power systems, particularly fluid power systems, have dynamics that change significantly over the operating range of the system. Therefore, we needed an approach that could handle a widely varying set of dynamics as a function of operating point. One approach is to provide a single robust design. However, that usually leads to reduced system performance. Here, we highlight an approach that allows for the decomposition of the overall system dynamics into multiple local models, as per Figure 5a, and then use multiple local controller approaches, as per Figure 5b, using the inner-outer loop strategy outlined in Equations 1-5 and Figure 4. The use of blending functions (α_i) [16] allows for individual controller designs to be combined in parallel.

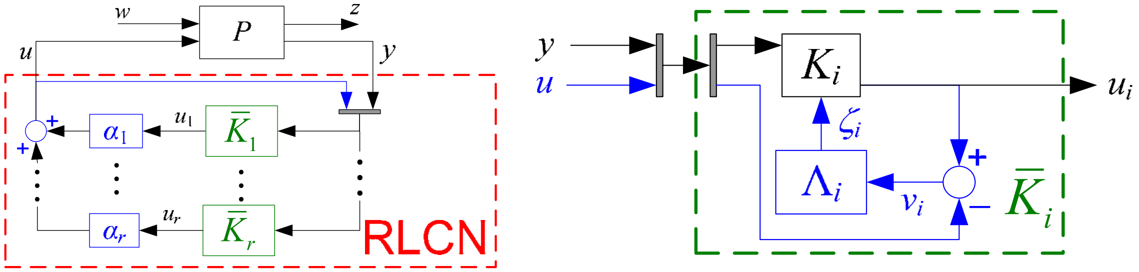


(a) Local Model Network (LMN)

(b) Local Controller Network

Figure 5. Local approaches to solve global control problem

The approach given above can be guaranteed stable for slowly varying operating conditions [16]. Additionally, arbitrary pointwise stability can be guaranteed by using a Youla parameterization [17] of the LCN; termed a local Q network in [18]. However, there is still a challenge to guaranteeing stability under widely and rapidly varying operating conditions. The approach under development within this project, still within the overall framework of optimal power generation and distribution, is to use a form of anti-windup compensators to guarantee that the local models will not 'fight' with each other thereby maintaining stability. Preliminary work in this area, termed a *Robust Local Controller Networks (RLCN)*, is described in [19] and shown schematically in Figure 6. In Figure 6, L_i are the additional compensators to ensure that each controller doesn't 'fight' with any of its neighboring controllers. Details can be found in [19], albeit for a restricted class of systems. Although not covered by the current ARO grant, work is underway by the PI and his students to remove the system constraints introduced in [19].



(a) Robust Local Controller Network

(b) Zoomed in view of local controller

Figure 6. Gain Scheduled approach to controller design

Details on the creation of the local controller networks, and their implementation on a physical testbed representative of the original problem, can be found more completely in Appendix B.

Bibliography

[1] Zoss, A.B.; Kazerooni, H.; Chu, "A Biomechanical design of the Berkeley lower extremity exoskeleton (BLEEX).", IEEE/ASME Transactions on Mechatronics, Vol. 11, No. 2, pp. 128–138, April 2006.

[2] M. Deacon, C. J. Brace, N. D. Vaughan, C. R. Burrows, and R. W. Horrocks, "Impact of alternative controller strategies on exhaust emissions from an integrated diesel/continuously variable transmission powertrain," *Proceedings of the Institution of Mechanical Engineers, Part D (Journal of Automobile Engineering)*, v 213, n D2, 1999, p 95-107.

[3] L. Guzzella and A. M. Schmid, "Feedback Linearization of Spark-Ignition Engines with Continuously Variable Transmissions," IEEE Transactions on Control Systems Technology, vol. 3, no. 1, 1995.

[4] S. Liu, A. G. Stefanopoulou, "Effects of control structure on performance for an automotive powertrain with a continuously variable transmission," IEEE Transactions on Automatic Control, vol. 10, no. 5, pp. 701-9, Sept. 2002.

[5] T. Kim and H. Kim, "Performance of integrated engine-CVT control considering powertrain loss and CVT response lag," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, v 216, n 7, 2002, p 545-553.

[6] P. Gupta, "Powertrain Optimization and Multivariable Robust Controller Design for an Earthmoving Vehicle Powertrain," M.S. Thesis, Dept. of Mechanical Engineering, University of Illinois at Urbana-Champaign, 2004.

[7] S. M. Savaresi, F. Taroni, F. Prevedi, and S. Bittanti, "On the design and tuning of the controllers in a power-split continuously variable transmission for agricultural tractors," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, v 217, n 8, 2003, p 745-759.

[8] R. Pfiffner and L. Guzzella, "Optimal operation of CVT-based powertrains," International Journal of Robust and Nonlinear Control, vol. 11, no. 11, Sept. 2001, pp. 1003-21.

[9] S. Liu and B. Paden, "A Survey of Today's CVT Controls," *Proceedings of the 36th IEEE Conference on Decision and Control*, pp. 4738-43, 1997.

[10] D. Yanakiev and I. Kanellakopoulous, "Engine and Transmission Modeling for Heavy-Duty Vehicles," MOU 124, PATH Technical Note, May 1995.

[11] R. Zhang, E. Prasetiawan, and A. Alleyne, "Modeling and Multivariable Control of an Earthmoving Vehicle Powertrain," *Proceedings of the ASME IMECE*, DSC-24564, New York, NY, 2001.

[12] R. Zhang, A. G. Alleyne, and E. A. Prasetiawan, “Modeling and H2/H-infinity MIMO Control of an Earthmoving Vehicle Powertrain,” *ASME Journal of Dynamic Systems, Measurement and Control*, vol. 124, pp. 625-636, Dec. 2002.

[13] R. Zhang, E. A. Prasetiawan, A. G. Alleyne, and R. Thacher, “Modeling and Coordinated Control of a Multi-Load Earthmoving Vehicle Powertrain,” *Proceedings of the European Control Conference 2001*, Porto, Portugal, 2001. pp.1577-1582.

[14] Montgomery, A. and A. Alleyne, “Optimizing The Efficiency Of Electro-Hydraulic Powertrains” *Proceedings of the 2006 ASME IMECE*, Chicago, IL, IMECE2006-16008, Nov. 5-10, 2006.

[15] Gupta, P. and Alleyne, A., “Powertrain optimization for an earthmoving vehicle,” *Proceedings of the 2004 ASME IMECE*, IMECE 2004-60023, Anaheim, CA, Nov. 2004.

[16] R. Zhang, A. Alleyne, and D. E. Carter, “Generalized Multivariable Gain Scheduling with Robust Stability Analysis,” *ASME J. of Dyn. Syst. Meas. and Control*, vol. 127, pp. 668-687, 2005.

[17] J.D. Bendtsen, J. Stoustrup, and K. Trangbaek, “Bumpless transfer between observer-based gain scheduled controllers,” International J. of Control, vol. 78, no.7, pp. 491-504, 2005.

[18] B.P. Rasmussen and A. Alleyne, "Gain Scheduled Control of an Air Conditioning System Using the Youla Parameterization," *Proceedings of 2006 American Control Conference*, pp. 5336 – 5341, Minneapolis, MN, 2006.

[19] B. Hencey and A. Alleyne, “A Robust Controller Interpolation Design Technique” *submitted for the 2007 American Controls Conference*, NY, NY, July 2007.

[20]

Appendix A

OPTIMIZING THE EFFICIENCY OF ELECTRO-HYDRAULIC POWERTRAINS

A. Montgomery and A. Alleyne,
Proceedings of IMECE2006, Paper IMECE2006-16008, November 5-10, 2006, Chicago, Illinois
USA

Proceedings of IMECE2006
2006 ASME International Mechanical Engineering Congress and Exposition
November 5-10, 2006, Chicago, Illinois USA

IMECE2006-16008

OPTIMIZING THE EFFICIENCY OF ELECTRO-HYDRAULIC POWERTRAINS

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ABSTRACT

The evolution of the hydrostatic transmission system from mechanical systems to electronically controlled systems creates opportunity for improvements in efficiency through the use of intelligent control algorithms. In systems for which the prime mover is an internal combustion (IC) engine, overall system efficiency depends greatly on the prime mover's operating conditions. The use of variable displacement pumps can add a degree of freedom and allow engine operation to be optimized. However, this strategy requires a desired engine power value based on operating states and load references. This paper proposes a novel solution to this problem by using a dynamic engine power demand estimate to meet steady-state load demands using minimal engine power.

1. INTRODUCTION

There is much potential for efficiency gains in electro-hydraulic (EH) systems through the application of intelligent control [1]-[7]. [1] demonstrates fuel economy gains in electro-hydraulic mobile equipment applications by replacing fixed displacement pumps with variable displacement pumps and load sensing. [2] shows that controlling pump supply pressure to minimize power consumption results in near optimum system efficiency. A fully integrated approach is taken in [3] which seeks to minimize hydrostatic losses with the added objective of optimal prime mover operation. Inclusion of the prime mover in the overall efficiency objective is essential because its efficiency varies greatly with respect to its loading conditions [2]. Moreover, the efficiency rate of an IC engine tends to have the strongest influence of all the individual components on the overall system efficiency [4]. Therefore, its optimization is most important.

Optimal operation of IC engines has been an active area of research in the automotive industry for years. One promising method for increasing engine efficiency is through the use of a continuously variable transmission (CVT). A variable displacement pump, which is used in most electro-hydraulic systems, is the hydraulic analogue of the variable diameter pulley or toroidal CVT used in automotive applications []. Therefore, control strategies developed for automotive CVT applications are directly applicable to EH systems with an IC engine and variable displacement pump. Such a system is considered in this paper.

The advantage of using CVT's over traditional fixed gear ratio transmissions is that CVT's offer a continuum of transmission ratios meaning a given power demand can be satisfied over a broad and continuous range of engine torque and speed combinations. Because there exists an optimum torque/speed combination with respect to fuel economy for a given engine power, the added degree of freedom gained from a CVT allows for possible increases in system efficiency.

Typical CVT control strategies rely on knowledge of engine power or a demanded engine power based on external references. However, accurately estimating desired prime mover power based on load power demand is not trivial. This is due to losses throughout the transmission, which are typically nonlinear functions of operating states. Proposed strategies for this include choosing the desired engine power to vary linearly with load power [3] or using output references and the system's individual tabulated component efficiencies to calculate power demand [9]. The problem with these methods is that they must be conservative to ensure load demands are met, meaning excess power is produced at the prime mover and later lost in transmission.

In this paper, a dymanic engine power demand estimator is proposed as a solution to this problem. This engine power demand estimate is then used as part of an integrated approach to maximize overall system efficiency. The test system and its linear model are described in section 2. The efficiency objective is explained in section 3. Section 4 describes the controller design. Experimental results are shown in section 5, and conclusions are drawn in section 6.

NOMENCLATURE

A, B, C	state matrices of the linearized powertrain model
$\widetilde{A},\widetilde{B},\widetilde{C}$	state matrices of augmented linearized powertrain model
H	outer-loop reference generator
K_0	nominal MIMO controller
$\mathrm{K}_{\mathrm{LQR}}$	LQR controller
O	reduced-order observer
P	EVPS system
b_e	engine viscous damping ratio
b_m	motor viscous damping ratio
c_1 and c_2	coefficients in proportional flow valve model
c_u and c_d	upstream and downstream leakage coefficients, respectively
C_m	coulomb friction of the motor
C_o	model coefficient in state matrix A
D_m	displacement of the motor
D_p	displacement of the pump
e	tracking error
J_e	engine moment of inertia
J_m	moment of inertia on the motor shaft
K_e	DC gain of engine delay
K_p	swash-plate spring constant
$\dot{m}_f$	mass flow rate of fuel
n_e	engine speed
n_m	speed of the motor
P_e	engine power
$\hat{P}_e$	estimated minimal necessary engine power
Γ_{IBSFC}	function corresponding to IBSFC curve
P_L	load power
p_d	downstream pressure, pressure after the flow valve
p_u	upstream pressure, pressure before the flow valve
Q_{LHV}	lower heating value of the fuel
Q_m	flow that goes to the motor
Q_p	flow supply from the pump
Q_v	flow through the flow valve
r	system references
T_e	engine torque
u	control inputs
u_v	flow valve input
V_u and V_d	upstream and downstream volume of the hoses
x	system states
y	system outputs
$\bar{\ }_o$	equilibrium value at the operating point
α_{ref}	swash-plate reference angle
β	hydraulic fluid bulk modulus
$\delta-$	deviations relative to the equilibrium point at which the model is linearized
τ_e	engine model time constant
τ_v	flow valve time constant
γ	engine throttle angle input
Δp	pressure difference across the flow valve
η_{mani}	valve manifold efficiency
η_{pump}	efficiency of variable displacement pump
η_{sys}	overall powertrain efficiency

2. SYSTEM DESCRIPTION

A picture of the EVPS is shown in Figure 1 and a schematic is shown in Figure 2. This system consists of power generation, transmission, and load units.

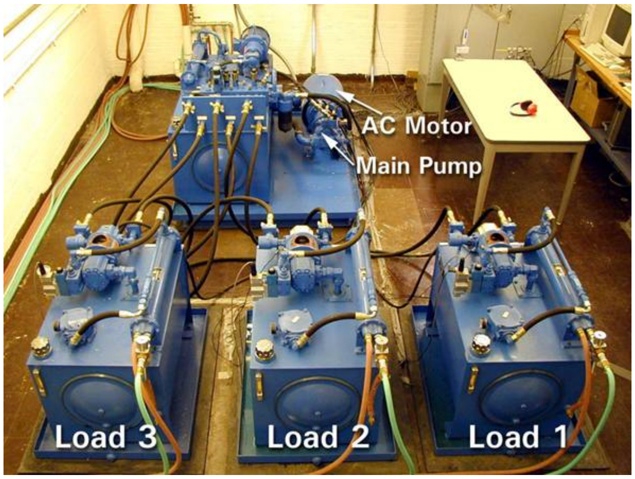

Figure 1: EVPS Electro-hydraulic Powertrain Testbed

The power generation unit is a diesel engine emulated using an AC motor and a PC controller [11]. The distribution unit consists of a variable displacement pump, hydraulic hoses, and proportional flow valves. The load unit consists of hydraulic motors and external loads.

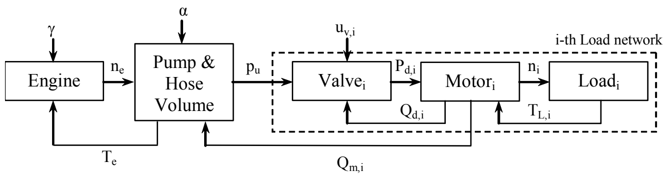

Figure 2: EVPS Schematic

Furthermore, load power demands for this system are simply expressed as hydraulic motor reference speeds. Load power demanded being a flow and pressure combination required to meet a speed reference. Also, any discussion of performance will refer to hydraulic motor speed tracking.

2.1 Linearized System

The EVPS is a nonlinear system best described by a nonlinear model. For the purpose of using linear control techniques, the nonlinear model in [7] is linearized at a certain operating condition (denoted by the subscript "o") for the deviation states (denoted by the prefix "δ"):

$$\begin{aligned} \delta\dot{x} &= A\delta x + B\delta u \\ \delta y &= C\delta x + D\delta u \qquad \left(D = 0_{9\times 5}\right) \end{aligned} \tag{1}$$

$$\begin{aligned} \delta x = [&\delta T_{e,i}, \delta n_e \mid \delta v_1, \delta v_2, \delta v_3 \mid \delta p_u \mid \ldots \\ &\delta p_{d1}, \delta p_{d2}, \delta p_{d3} \mid \delta n_{m1}, \delta n_{m2}, \delta n_{m3}]^T \end{aligned} \tag{2}$$

$$\delta u = \begin{pmatrix} \delta\gamma & \delta\alpha_{ref} & \delta u_{v1} & \delta u_{v2} & \delta u_{v3} \end{pmatrix}^T \tag{3}$$

$$\delta y = [\delta n_e, \delta p_u \mid \delta p_{d1}, \delta p_{d2}, \delta p_{d3} \mid \delta n_{m1}, \delta n_{m2}, \delta n_{m3} \mid \delta P_e]^T \tag{4}$$

The state matrices A, B, C for the overall system with 12 states, 5 inputs and 8 outputs are listed here in detail. The dimensions of the sub-matrices in the partition of A are determined by Eq. (2).

$$A = \begin{bmatrix} A_{11} & 0_{2\times 3} & A_{13} & 0_{2\times 3} & 0_{2\times 3} \\ 0_{3\times 2} & A_{22} & 0_{3\times 1} & 0_{3\times 3} & 0_{3\times 3} \\ A_{31} & A_{32} & A_{33} & A_{34} & 0_{1\times 3} \\ 0_{3\times 2} & A_{42} & A_{43} & A_{44} & A_{45} \\ 0_{3\times 2} & 0_{3\times 3} & 0_{3\times 1} & A_{54} & A_{55} \end{bmatrix} \tag{5}$$

The sub-matrices are:

$$[A_{11} \mid A_{13}] = \left[\begin{array}{cc|c} \dfrac{-1}{\tau_e} & 0 & 0 \\ \dfrac{1}{J_e} & \dfrac{-b_e}{J_e} & \dfrac{-K_p D_{po}}{J_e} \end{array}\right] \tag{6}$$

$$A_{22} = \frac{-1}{\tau_v} I_{3\times 3} \tag{7}$$

$$A_{31} = \begin{bmatrix} 0 & \dfrac{\beta}{V_u} K_q D_{po} \end{bmatrix} \tag{8}$$

$$A_{32} = \begin{bmatrix} \dfrac{-\beta}{V_u} c_1 \sqrt{\Delta p_o} & \dfrac{-\beta}{V_u} c_1 \sqrt{\Delta p_o} & \dfrac{-\beta}{V_u} c_1 \sqrt{\Delta p_o} \end{bmatrix} \tag{9}$$

$$A_{33} = \frac{-\beta}{V_u}\left(c_u + \frac{3C_o}{2\sqrt{\Delta p_o}} \right) \tag{10}$$

$$A_{34} = \begin{bmatrix} \dfrac{\beta}{V_u}\left(\dfrac{C_o}{2\sqrt{\Delta p_o}}\right) & \dfrac{\beta}{V_u}\left(\dfrac{C_o}{2\sqrt{\Delta p_o}}\right) & \dfrac{\beta}{V_u}\left(\dfrac{C_o}{2\sqrt{\Delta p_o}}\right) \end{bmatrix} \tag{11}$$

$$A_{42} = \frac{\beta}{V_d} c_1 \sqrt{\Delta p_o} I_{3\times 3} \tag{12}$$

$$A_{43} = \begin{bmatrix} \dfrac{\beta}{V_d}\left(\dfrac{C_o}{2\sqrt{\Delta p_o}}\right) & \dfrac{\beta}{V_d}\left(\dfrac{C_o}{2\sqrt{\Delta p_o}}\right) & \dfrac{\beta}{V_d}\left(\dfrac{C_o}{2\sqrt{\Delta p_o}}\right) \end{bmatrix}^T \tag{13}$$

$$[A_{44} \mid A_{45}] = \left[\begin{array}{c|c} \dfrac{-\beta}{V_d}\left(c_d + \dfrac{C_o}{2\sqrt{\Delta p_o}} \right) I_{3\times 3} & \dfrac{-\beta}{V_d} D_m I_{3\times 3} \end{array}\right] \tag{14}$$

$$[A_{54} \mid A_{55}] = \left[\begin{array}{c|c} \dfrac{D_m}{J_m} I_{3\times 3} & \dfrac{-b_m}{J_m} I_{3\times 3} \end{array}\right] \tag{15}$$

The coefficient C_o is defined as: $C_o = Q_{vo} / \sqrt{\Delta p_o}$ (16)

$$B = \left[\begin{array}{cc|c} \dfrac{K_e}{\tau_e} & 0 & \\ 0 & \dfrac{-p_{u0}\alpha_0}{J_e} & 0_{2\times 3} \\ \hline \multicolumn{2}{c|}{0_{3\times 2}} & I_{3\times 3} \\ \hline 0 & \dfrac{\beta}{V_u}\alpha_0 n_{e0} & -\dfrac{\beta}{V_u} c_2 \sqrt{\Delta p_o} \times 1_{1\times 3} \\ \hline \multicolumn{2}{c|}{0_{3\times 2}} & \dfrac{\beta}{V_d} c_2 \sqrt{\Delta p_o} I_{3\times 3} \\ \hline \multicolumn{2}{c|}{0_{3\times 2}} & 0_{3\times 3} \end{array}\right] \tag{17}$$

The dimensions of the sub-matrices in the partition of system matrix B are determined by Eq. (2) and (3). The system matrix C is implied by Eq. (4) as:

$$C = \left[\begin{array}{cc|c|ccc} 0 & 1 & & 1 & 0 & 0 \\ 0 & 0 & & 0 & 0 & 0 \\ 0 & 0 & 0_{9\times 3} & 0 & I_{3\times 3} & 0 \\ 0 & 0 & & 0 & 0 & I_{3\times 3} \\ 0 & D_{p0} p_{u0} & & D_{p0} n_{e0} & 0 & 0 \end{array}\right] \tag{18}$$

The parameters in this overall system model were experimentally identified on the EVPS, and the single load open loop experiment in [7] validated these parameters in the time domain. For more information on the EVPS, the interested reader is referred to [11].

3. EFFICIENCY OBJECTIVE

Our objective is to maximize overall system efficiency, which is the ratio of mechanical power at the load units to chemical power delivered to the prime mover (19):

$$\eta_{sys} = \frac{Load \quad Power}{Power \;\; input \;\; to \;\; prime \;\; mover} = \frac{P_L}{\dot{m}_f \times Q_{LHV}} \qquad (19)$$

Equation 1 can be expanded in order to separate power generation efficiency from power transmission efficiency:

$$\eta_{sys} = \overbrace{\left(\frac{P_e}{\dot{m}_f \times Q_{LHV}}\right)}^{\substack{Chemical \;\; to \;\; mechanical \\ conversion \;\; efficiency}} \times \overbrace{\left(\frac{P_L}{P_e}\right)}^{\substack{Power \\ Transmission \\ Efficiency}} \qquad (20)$$

We will assume that load power demand is exogenous and given. Therefore, the strategy for maximizing overall system efficiency will be to determine the minimum engine power required, thereby maximizing the second term of (20), and ensuring that power is generated most efficiently, which maximizes the first term of (20) for a given engine power. This strategy then maximizes overall system efficiency.

3.1 Power Transmission Efficiency

Maximizing power transmission efficiency is equivalent to minimizing engine power subject to a load demand. This can be expressed as the following constrained minimization problem:

$$\begin{aligned} &\min \;\; P_e \\ &s.t. \;\; \sum_i Q_{m,i} = D_m \sum_i n_{m,i-ref} \end{aligned} \qquad (21)$$

Substituting for engine power and assuming negligible volumetric losses:

$$P_e = T_e n_e = \frac{Q_p p_u}{\eta_{pump}} \qquad (22)$$

$$Q_p = \sum_i Q_{m,i} \qquad (23)$$

and, where

$$\eta_{pump} = f\left(n_e, D_p, p_u\right) \qquad (24)$$

We can reformulate (3) as:

$$\begin{aligned} &\min \;\; \frac{p_u Q_p}{\eta_{pump}} \\ &s.t. \;\; Q_p = D_m \sum_i n_{m,i-ref} \end{aligned} \qquad (25)$$

From (25) we see that pump flow is fixed based on load references meaning the objective function in (25) is now only a function of upstream pressure and pump displacement. Figure 3 below shows how pump efficiency varies as a function of these variables for a fixed pump flow.

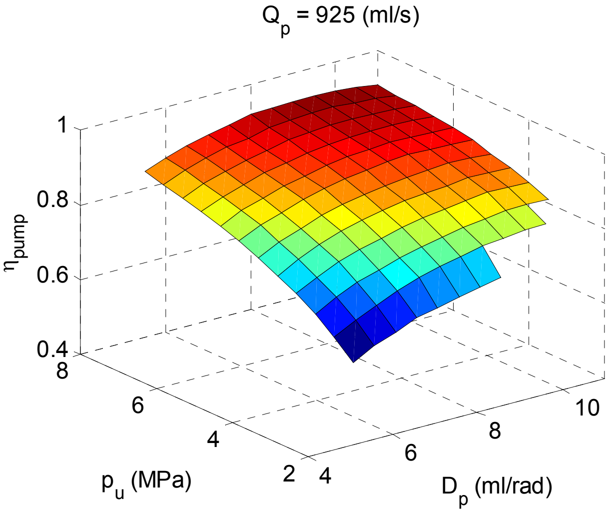

Figure 3: Steady-State Pump Map

Clearly, pump efficiency increases monotonically with both increasing pump displacement and increasing upstream pressure. However, increasing upstream pressure decreases valve manifold efficiency given by:

$$\eta_{mani} = \frac{\sum_i Q_{m,i} p_{d,i}}{p_u \sum_i Q_{m,i}} \qquad (26)$$

To resolve competing objectives, let us consider the plot of how the objective function from (25) varies with respect to upstream pressure and pump displacement show in Figure 4:

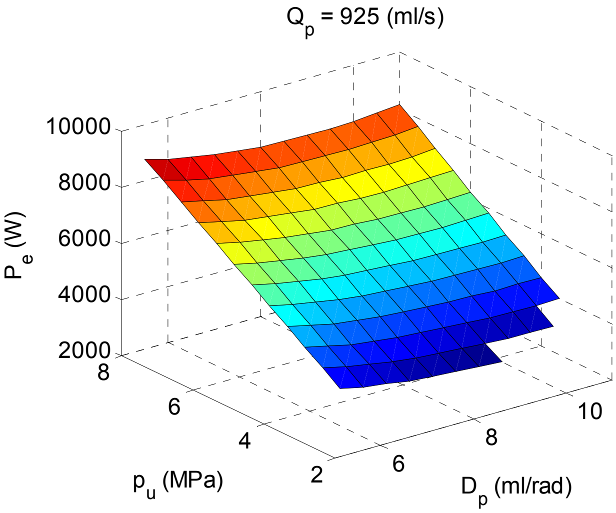

Figure 4: Objective function from Equation 25

This plot indicates that engine power is monotonically decreasing as a function of upstream pressure despite the influence of pump efficiency. Also of note is that for a given flow, engine power needed decreases monotonically with increasing pump displacement. This is significant because it means that maximizing power transmission efficiency requires simply maximizing pump displacement and minimizing upstream pressure subject to load demands.

3.2 Power Generation Efficiency

The previous section has show that, given a load demand, there is a minimum engine power which minimizes transmission losses thus maximizing transmission efficiency. Now, given this engine power demand, we seek to maximize power generation efficiency. This is equivalent to minimizing fuel consumption for a given engine power output. Considering the steady-state power map of the diesel engine prime mover in Figure 5, we see that fuel consumption is strongly dependent on operating conditions.

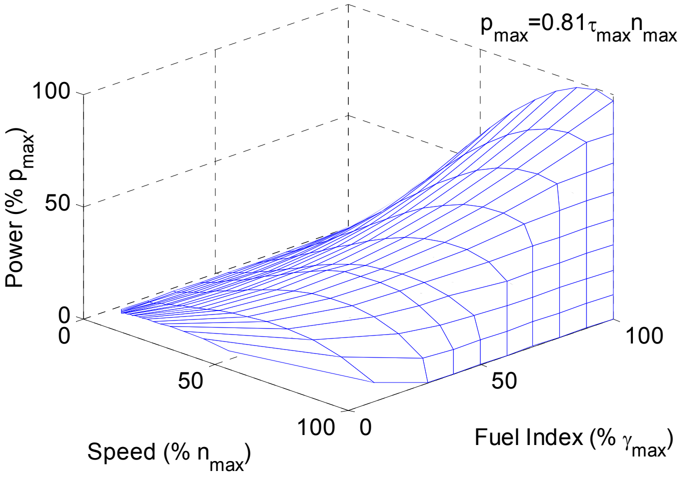

Figure 5: Steady-State Power Map, CI Engine [5]

Furthermore, from this we can construct a curve connecting the points of minimum fuel consumption for each value of engine power which gives the optimal engine speed at each power. This is called the Ideal Brake Specific Fuel Consumption (IBSFC) curve, and it is shown below:

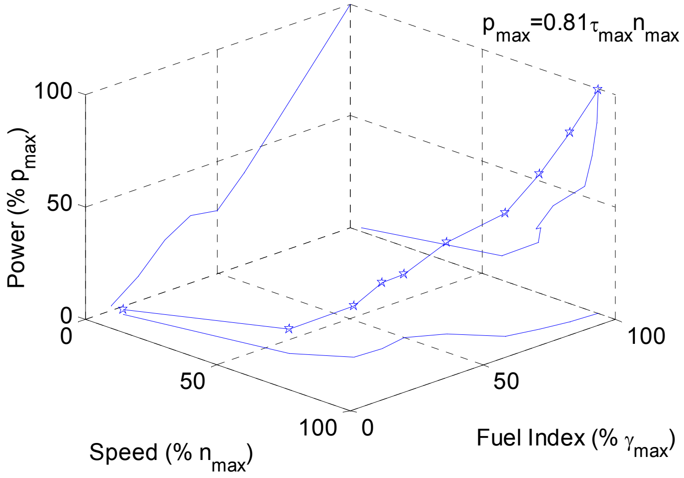

Figure 6: IBSFC curve for CI Engine [5]

Our goal of maximizing power generation efficiency can be summarized as restricting steady-state engine operation to this curve. This is possible because we have an added degree of freedom from the adjustable pump displacement.

Based on the above argument, our efficiency control objectives are:

i) minimize p_u
ii) operate engine on IBSFC curve at steady-state

4. CONTROLLER DESIGN

The control design strategy is as follows: First, design a MIMO, model based controller to track engine speed, engine power, and motor speeds. Second, design outer-loop engine power demand estimator to converge to minimal engine power sufficient to meet load demands. This estimate will then be used to generate engine speed and engine power references for the inner-loop controller. Figure 7 shows the controller structure:

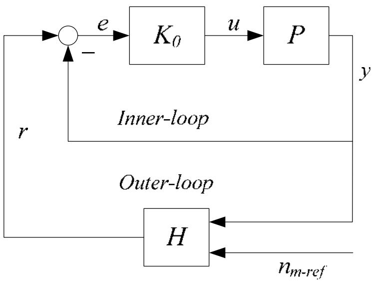

Figure 7: General Controller Structure

Here, K_0 is the nominal, inner-loop controller designed for perfect steady-state reference tracking, and P is the EVPS. System H uses system outputs and the exogenous motor speed references to create internal engine speed and engine power references. This is done by estimating minimal engine power necessary to meet load demands.

4.1 Inner-Loop Controller Design

The nominal controller can be any MIMO controller, based on the plant model, and designed for perfect steady-state tracking of hydraulic motor speeds, engine speed, and engine power. In this study, we design an LQ controller with a reduced order observer to recover the unmeasured states.

We augment the linear system model from section 2 as follows:

$$\widetilde{A} = \left[\begin{array}{ccccc|c} & & A & & & 0_{12\times5} \\ \hline 0 & 1 & & 0 & 0 & \\ 0 & 0 & 0_{5\times8} & I_{3\times3} & 0 & 0_{5\times5} \\ 0 & 0 & & 0 & 1 & \end{array}\right] \qquad (27)$$

$$\widetilde{B} = \left[\begin{array}{c} B \\ \hline 0_{5\times5} \end{array}\right] \qquad (28)$$

$$\widetilde{C} = \left[\begin{array}{c|c} C & 0_{9\times5} \\ \hline 0_{5\times12} & I_{5\times5} \end{array}\right] \qquad (29)$$

Our new state-space model is then given by:

$$\begin{bmatrix} \delta\dot{x} \\ \delta\dot{x}_I \end{bmatrix} = \widetilde{A}\begin{bmatrix} \delta x \\ \delta x_I \end{bmatrix} + \widetilde{B}\,\delta u + \begin{bmatrix} 0_{12\times5} \\ -I_{5\times5} \end{bmatrix}\widetilde{r} \qquad (30)$$

Where:

$$\widetilde{r} = \begin{bmatrix} n_{e-ref} & n_{m1-ref} & n_{m2-ref} & n_{m3-ref} & P_{e-ref} \end{bmatrix}^T \qquad (31)$$

Which is related to the full system reference from figure 7 by:

$$r = \left[\begin{array}{ccc} 1 & 0 & 0 \\ \hline & 0_{4\times5} & \\ \hline 0 & I_{3\times3} & 0 \\ 0 & 0 & 1 \end{array}\right]\widetilde{r} \qquad (32)$$

Adding integrated error states allowing the formulation of the zero-error LQR problem. The LQR controller and reduced order observer are designed independently based the augmented plant model (27)-(30). For more information on multivariable feedback control, the interested reader is referred to [12].

4.2 Outer-Loop Control Design

The goals of the outer-loop controller are to generate engine speed and engine power references based on a dynamic engine power estimate. The engine power estimate is used as the reference engine power (33), and the engine speed reference is determined from the engine power estimate via a lookup table corresponding to the IBSFC curve (34). Calculation of the engine power estimate is done using the following algorithm:

$$P_{e-ref} = \dot{\hat{P}}_e = k_1 \sum_i e_{n_m,i} - k_2\left(P_e - P_L\right) \qquad (33)$$

$$n_{e-ref} = \Gamma_{IBSFC}\left(\hat{P}_e\right) \qquad (34)$$

Where k_1 is chosen to be significantly larger than k_2 so that engine power is more responsive when load references are not met but still converges to a minimum, sufficient engine power at steady-state. Thus, system H from figure 7 may be represented as follows:

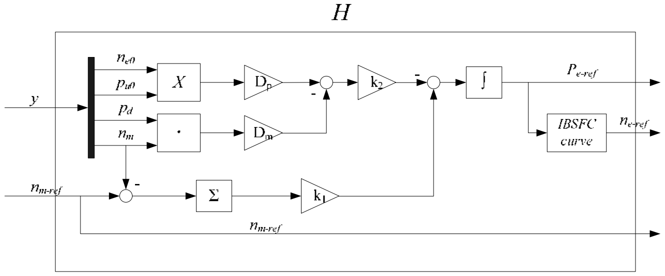

Figure 8: System H schematic

The ratio of k_1 to k_2 can be tuned to affect transient performance and efficiency.

5. EXPERIMENTAL RESULTS

The controller structure proposed in section 4 was implemented on the system described in section 2. The results that follow are compared to those of a baseline controller using the same nominal controller but a power estimator similar to one used in [5] of the form:

$$P_{e-ref} = \hat{P}_e = kP_L \tag{35}$$

$$n_{e-ref} = \Gamma_{IBSFC}\left(\hat{P}_e\right) \tag{36}$$

Where engine power demand is calculated by a static gain on load power demand. Hydraulic motor speed tracking for both controllers during identical load cycles is shown in Figure 9. Motors 1 and 2 are given step changes in reference, and motor 3 is given a constant reference.

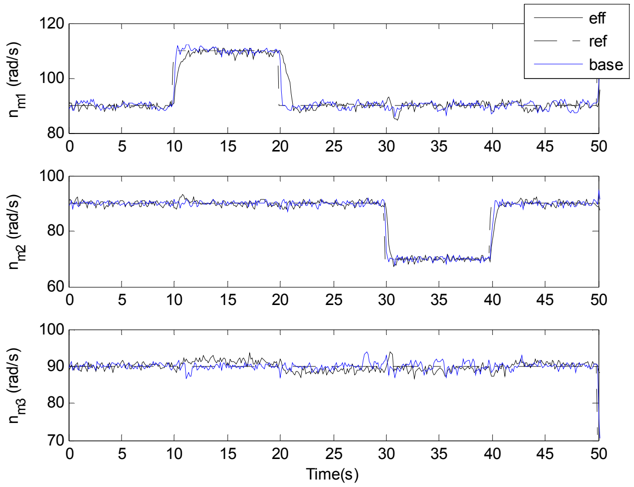

Figure 9: Motor Speed Tracking

Both controllers exhibit good steady-state tracking while the baseline controller appears to have slightly faster transient performance. This is no surprise as the baseline controller operates the system with excess power, Figure 10.

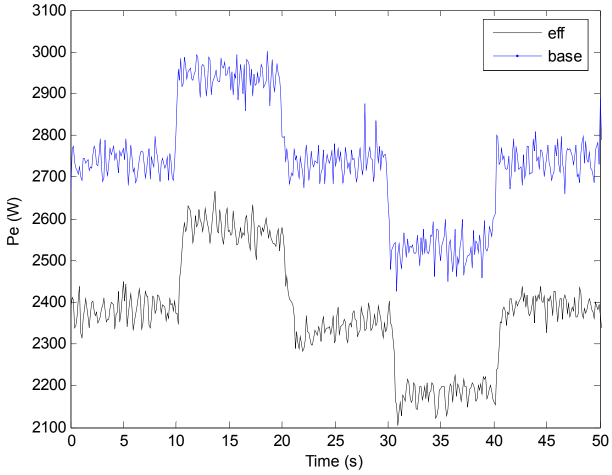

Figure 10: Engine Power

The efficiency controller operates the system at the minimal engine power required to meet the load references. This can be seen from their respective flow valve inputs, shown in Figure 11 below:

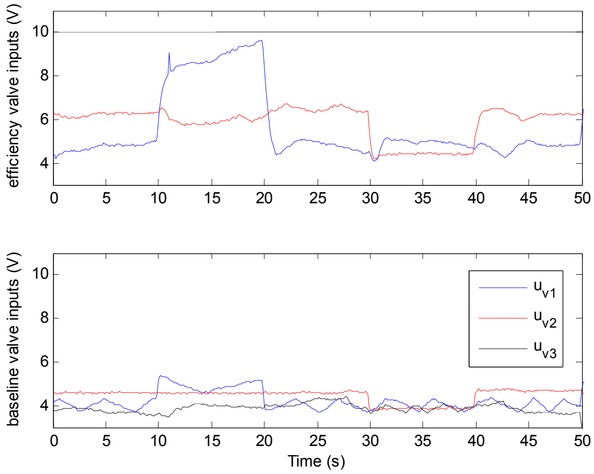

Figure 11: Control Inputs for Proportional Flow Valves

The efficiency controller has larger valve inputs throughout the load cycle. Furthermore, with the efficiency controller, one valve is always fully open. This means that upstream pressure is at a minimum, and as the section 3.1 explains, minimizing upstream pressure is equivalent to minimizing engine power. Figure 12 shows engine speed tracking with the IBSFC reference plotted as a dotted line. Both controllers track the IBSFC curve at steady-state and deviate only at step changes in load references. Therefore, both controllers meet the objective of steady-state IBSFC curve regulation.

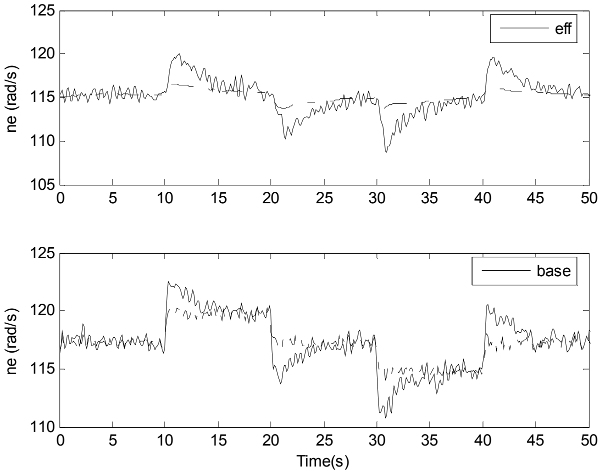

Figure 12: Engine Speed Tracking

Performance and efficiency data for the load cycle was calculated for both controllers and is shown in Table 1 below:

	Baseline Controller	**Efficiency Controller**	**% Change**

Motor Speed $\bar{e}_{RMS}$ (rad/s)	1.5450	2.3276	50.6
Fuel Consumption (kg)	0.2610	0.2385	-8.6
Engine Power (W)	2,736.2	2,371.9	-13.3

Table 1: Comparison of controllers during load cycle

From this data we see that the efficiency controller did in fact reduce fuel consumption over the load. However, this improvement in fuel economy came at a cost of increased average RMS motor speed tracking error. Now we must investigate steady-state behavior to determine how much of the increase in tracking error is due to slower transient response to step changes. Figure 13 below shows fuel consumption and average RMS tracking error for both controllers at steady-state loading conditions over a range of load powers.

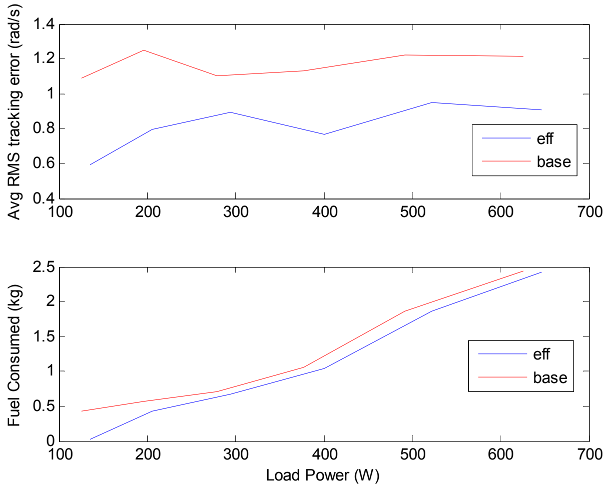

Figure 13: Steady-state comparison

Again, the efficiency controller consumes less fuel per load power delivered. However, here we see that the efficiency controller actually has a lower steady-state tracking error. This is significant because it shows an increase in efficiency with no sacrifice in performance at steady-state.

6. CONCLUSION

This paper has shown that running a powertrain at the minimum power required to meet load demands increases overall fuel economy, and it has proposed a method for estimating minimum drive power required. Experimental results show that running a system at the minimum required power increases fuel economy at the expense of a slower transient response. However, steady-state tracking has been shown to be unaffected.

REFERENCES

[1] Cetinkunt, S., Pinsopon, U., Chen, C., Egelja, A., and Anwar, S. "Positive flow control of closed-center electrohydraulic implement-by-wire systems for mobile equipment applications," *Mechatronics*, v 14, n 4, May, 2004, pp. 403-420.

[2] Davies, R. M. and Watton, J. "Intelligent Control of an Electrohydraulic Motor Drive System," *Mechatronics*, v 5, n 5, pp. 527-540.

[3] Gupta, P. and Alleyne, A., "Powertrain optimization for an earthmoving vehicle," Proceedings of IMECE, ASME 2004-60023, 2004.

[4] Nevala, K., Penttinen, J., and Saavalainen, P. "Developing of the anti-slip control of hydrostatic power transmission for forest tractor and optimisation of the power of diesel engine," *AMC'98 - Coimbra. 1998 5th International Workshop on Advanced Motion Control. Proceedings (Cat. No.98TH8354)*, 1998, p 475-80.

[5] Claussen, J., Maxwell, J. Tran, T., and Gejji, R. "Digital horsepower control of electrohydraulic variable volume pump," *SAE Technical Paper Series - 921742*, 1992, pp. 1-7.

[6] Rogers, R., Horvat, B., Sturtz, A., Magner, D. "Hydrostatic transmissions are evolving," Hydraulics & Pneumatics, September 2005, 58, 9, pp. 26-28.

[7] E. A. Prasetiawan, R. Zhang, and A. G. Alleyne, "Modeling and Coordinated Control of An Earthmoving Vehicle Powertrain," presented at International Mechanical Engineering Congress and Exposition: The Fluid Power and Systems Technology Division, Orlando, FL, 2000. pp.289-296

[8] Guzzela, L. and Schmid, A. M. "Feedback linearization of spark-ignition engines with continuously variable transmission," IEEE Trans. Control Systems Technology, March 1995, v 3, n 1, pp. 54-60.

[9] Kim, T. and Kim H., 2002, "Performance of integrated engine-CVT control considering powertrain loss and CVT response lag," Proceedings of Institution of Mechanical Engineers, Part D, Journal of automobile engineering, 216, pp. 545-553.

[10] Gafvert, M., Arzen, K. E., Pedersen, L. M., Bernhardsson, B. "Control of GDI engines using torque feedback exemplified by simulations" *Control Engineering Practice*, v 12, n 2, February, 2004, pp. 165-180.

[11] E. A. Prasetiawan, R. Zhang, A. G. Alleyne, and T. C. Tsao, "Modeling and Control Design of a Powertrain Simulation Testbed for Earthmoving Vehicles," presented at International

Mechanical Engineering Congress & Exposition: The Fluid Power and Systems Technology Division, Nashville,TN, 1999.

[12] K. Zhou, J. C. Doyle, and K. Glover, *Robust and Optimal Control*. Upper Saddle River, New Jersey: Prentice-Hall, Inc., 1996.

Appendix B

A ROBUST CONTROLLER INTERPOLATION DESIGN TECHNIQUE

B. Hencey and A. Alleyne,
Proceedings of 2007 American Controls Conference, NY, NY, July 11-13 2007

A ROBUST CONTROLLER INTERPOLATION DESIGN TECHNIQUE

Brandon Hencey[1] *Student Member* and Andrew G Alleyne[2] *Senior Member IEEE*

***Abstract*—In this paper, a robust controller interpolation technique is investigated and applied to an experimental test bed. Controller interpolation describes the process of switching or blending among a family of controllers. The proposed approach allows the individual controller designs to be decoupled by designing the controller interpolation after the family of controllers is designed. In contrast, the 'self-scheduled' linear parameter varying techniques simultaneously design the family of controllers and the controller interpolation, thereby coupling the individual controller designs to one another.**

The presented controller interpolation framework uses the classic controller blending framework augmented by a set of stabilizing compensators. The synthesis conditions for the stabilizing compensators locally maximizing robust stability is stated in terms of a set of bilinear matrix inequalities (BMI). In the motivating example, the stabilizing compensators are designed by using a search that is locally minimizing over the robustness metric.

***Index Terms*—controller interpolation, linear parameter varying, matrix inequalities, linear systems**

INTRODUCTION

THE motivation for this paper is the control of a linear time-invariant (LTI) plant where multiple objectives make a single LTI controller unsuitable. One common solution entails designing a family of r stabilizing LTI controllers, where each controller K_i corresponds with an objective. The controllers are designed independent of one another, thereby allowing different types of LTI controllers (e.g. proportional integral, linear quadratic Gaussian, H_∞) to be members of the same controller family. In order to decouple the controller design and controller interpolation design, this paper investigates a robust controller interpolation design technique performed subsequent to the controller design.

A supervisor controller—either implicitly or explicitly—generates an interpolation signal that determines to what degree each controller in the family of controllers is active based upon the current objective. The class of piecewise continuous interpolation signal $\alpha(t) \in [0,\infty) \to \mathbb{R}^r$, satisfying

$$\sum_{i=1}^{r} \alpha_i(t) = 1 \text{ and } \alpha_i(t) \geq 0, \qquad (1)$$

includes prevalent concepts in the literature such as controller switching [1] and controller blending [2]. In contrast with more restrictive classes of interpolation signals, such as switching dwell-time [3] and blending rate-limit, the primary focus of this paper is upon unrestricted interpolation signals satisfying only (1), called *arbitrary interpolation signals*.

Problem Statement

A *controller interpolation technique* describes how information is shared among individual controllers in order to form an interpolated controller. Given a family of controllers, this paper focuses on developing a controller interpolation technique possessing the following *controller interpolation criteria*:

a) The interpolated controller is stabilizing for any arbitrary interpolation signal.
b) The local controller K_i is recovered when $\alpha_i(t) \equiv 1$.
c) The interpolated controller is a continuous function of $\alpha(t)$.

The first requirement stipulates the interpolated controller is stabilizing for all arbitrary interpolation signals generated by the supervisory controller. The second requirement ensures that the attributes designed into each controller are not modified by the controller interpolation technique. The third requirement ensures discontinuities in the control signal are not induced solely by a continuous interpolation signal. Alongside the requirement to satisfy the controller interpolation criteria, this paper also considers maximizing some metric of robust stability.

Literature Overview

Self-Scheduled Approach

Rather than designing the family of the controllers and then designing the controller interpolation, [4] and [5] ensure the satisfaction of the controller interpolation criteria by simultaneously designing the family of controllers and controller interpolation. The 'self-scheduled' approach relies upon linear matrix inequalities that couple the design of the individual controllers to one another, thereby not completely allowing the controller design and controller interpolation design to be completely decoupled.

Ad-Hoc Approaches

As discussed in [6], the gain scheduling problem has motivated many forms of ad hoc controller interpolation techniques including: interpolation of poles and zeros, interpolation of balanced realizations, and interpolation of the control signals [7] and [8]. In this paper, an interpolated controller constructed by interpolating control signals of the

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individual controllers will be a called local controller network (LCN) [7]. Despite the intuitive motivation behind ad-hoc controller interpolation techniques, as shown by an example in [9], such approaches do not guarantee stable for even the class of static interpolation signals $\|\dot{\alpha}(t)\| = 0$.

Youla Parameterization

Another controller interpolation technique is based upon Youla parameterization [10]. For a given coprime factorization of the LTI plant, Youla parameterization maps all stabilizing controllers to a class of stable systems, thus for each LTI controller there exists a corresponding LTI Youla parameter Q_i. As a result, interpolating among stabilizing controllers may be reduced to interpolating among the corresponding Youla parameters. In particular, [1] discusses interpolating the state space matrices to form the interpolated Youla parameter. Similarly, [2] and [11] interpolate the Youla parameters outputs to form a local Youla parameter network (LQN). Although the controller interpolation criteria are satisfied for a Youla-based controller interpolation technique, the maximization of robust stability is directly linked to the choice of the coprime factorization.

Bumpless Transfer

Although the bumpless transfer technique in [2] guarantees stability for an arbitrary interpolation signal, not all bumpless transfer techniques guarantee stability for arbitrary interpolation signals. As discussed in [12] and [13] bumpless transfer focuses on minimizing the transient induced by a single switch among controllers. Many anti-windup and bumpless transfer techniques in the literature are described using the unified coprime factorization frameworks discussed in [14] and [15]. Recent work has focused using metrics to measure the quality of the bumpless transfer. For example, [12] is a model-based approach that focuses on recovering an ideal target response in an $\mathcal{L}_2$ sense, whereas [13] does not rely upon the plant model for controller input matching.

Paper Outline

The following section proposes a controller interpolation framework consisting of stabilizing compensators as its primary design element. The synthesis conditions for the stabilizing compensators are presented in the form of bilinear matrix inequalities, and an algorithm for the solution of the bilinear matrix inequalities is briefly discussed. The controller interpolation design technique is successfully used to design and implement a robust local controller network for the experimental test bed.

CONTROLLER INTERPOLATION DESIGN

For the following discussion let the LTI plant be described as

$$P \triangleq \begin{cases} \dot{x} = Ax + B_w w + B_u u \\ z = C_z x + D_{zw} w + D_{zu} u \\ y = C_y x + D_{yw} w + D_{yu} u \end{cases}, \qquad (2)$$

where $x_p \in \mathbb{R}^{n_p}$, $w \in \mathbb{R}^{n_w}$, $u \in \mathbb{R}^{n_u}$, $z \in \mathbb{R}^{n_z}$, and $y \in \mathbb{R}^{n_y}$. Without a loss of generality, assume D_{yu}=0. The proposed controller interpolation technique uses the controller blending

$$u_\alpha(t) = \sum_{i=1}^{r} \alpha_i(t) u_i(t) \qquad (3)$$

where $u_i(t)$ is the output of the augmented local controller

$$K_i \triangleq \begin{cases} \dot{x}_{Ki}(t) = A_{Ki} x_{ki}(t) + B_{Ki} y(t) + \zeta_{i1}(t) \\ u_i(t) = C_{Ki} x_K(t) + D_{Ki} y(t) + \zeta_{i2}(t) \end{cases}, \qquad (4)$$

$x_{ki} \in \mathbb{R}^{n_{ki}}$, and $\zeta_i(t) = \begin{bmatrix} \zeta_{i1}(t) & \zeta_{i2}(t) \end{bmatrix}$ is some *stabilizing signal* that is used to ensure the interpolation criteria is satisfied. Note the special case $\zeta_i(t) \equiv 0$ corresponds with the local controller network framework [7]. Let the LPV description of the closed loop system with the LCN be described as

$$T_{o,zw}(\alpha) \triangleq \begin{cases} \dot{x}_{CL} = A_o(\alpha) x_{CL} + B_o(\alpha) w \\ z = C_o(\alpha) x_{CL} + D_o(\alpha) w \end{cases}, \qquad (5)$$

where

$$x_{CL} = \begin{bmatrix} x_p^T & x_{K1}^T & \cdots & x_{Kr}^T \end{bmatrix}. \qquad (6)$$

Stabilizing Compensators

Consider a stabilizing signal generated by

$$\zeta_i(t) = \Lambda_i v_i, \qquad (7)$$

where $v_i(t) \triangleq u_i(t) - u_\alpha(t)$ and Λ_i is a system called a *stabilizing compensator*. The control signals of the augmented controllers, shown in Figure 1, are blended to form a robust local controller network (RLCN), shown in Figure 2. Note the local controller K_i is not compensated when $\alpha_i(t) \equiv 1$, and v_i is a continuous function of $\alpha(t)$; therefore, the stabilizing signal generated by (7) satisfies part (b) and (c) of the controller interpolation criteria.

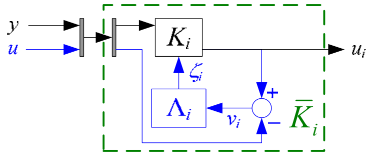

Figure 1: Augmented controller with stabilizing compensator

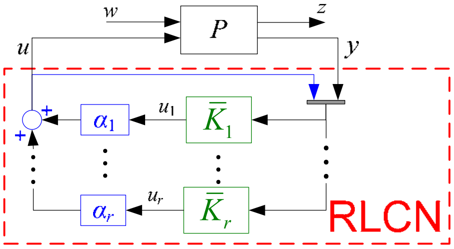

Figure 2: Closed loop with robust local controller network

Much of the anti-windup and bumpless transfer literature [14], [15], and [16] uses a similar framework motivated by coprime factorization. Furthermore, it may be shown that a

Youla parameterization based controller interpolation yields a stabilizing compensator of the form

$$\Lambda_i = \begin{bmatrix} B_{Ki}N \\ I-M \end{bmatrix} \text{ for } i=1,\ldots,r, \tag{8}$$

where $[N\ M]$ is a coprime factorization of the LTI plant $P_{yu}=NM^{-1}$. Since the proposed controller interpolation framework includes a class of stabilizing compensators (8) that may be shown to satisfy the interpolation criteria, the proposed controller interpolation framework is considered to be adequate for the maximization of a robust stability objective.

Stabilizing Compensator Synthesis

For the development of the stabilizing compensator synthesis conditions, the induced $\mathcal{L}_2$ norm is used as a ubiquitous example of a robustness metric that can be used for controller interpolation design. Although the interested reader may design a set of dynamic stabilizing compensators that minimize the induced $\mathcal{L}_2$ norm using the results of Theorem 17.1 in [17], the induced $\mathcal{L}_2$ norm is one of many LMI-based robust stability metrics in the literature [19] that are addressable with the proposed controller interpolation framework.

This paper focuses on the simpler static stabilizing compensators. Also, in order to avoid complexities with algebraic loops created by $\zeta_{i2}(t)\neq 0$, the following discussion will only consider Λ_i such that $\zeta_{i2}(t)\equiv 0$.

Given static stabilizing compensators Λ_i for i=1,…,r, let the LPV description of the closed loop system be described as

$$T_{CL,zw}(\alpha) \triangleq \begin{cases} \dot{x}_{CL} = A_{CL}(\alpha)x_{CL} + B_{CL}(\alpha)w \\ z = C_{CL}(\alpha)x_{CL} + D_{CL}(\alpha)w \end{cases}, \tag{9}$$

where

$$\begin{bmatrix} A_{CL}(\alpha) & B_{CL}(\alpha) \\ C_{CL}(\alpha) & D_{CL}(\alpha) \end{bmatrix} \triangleq \sum_{i=1}^{r} \alpha_i \begin{bmatrix} A_{CL,i} & B_{CL,i} \\ C_{CL,i} & D_{CL,i} \end{bmatrix}, \tag{10}$$

$$\begin{aligned} &A_{CL,i} \triangleq A_{o,i} + \mathbf{B}_\lambda \mathbf{\Lambda} \mathbf{C}_{\lambda,i},\ B_{CL,i} \triangleq B_{o,i} + \mathbf{B}_\lambda \mathbf{\Lambda} \mathbf{D}_{\lambda,i}, \\ &C_{CL,i} \triangleq C_{o,i},\ D_{CL,i} \triangleq D_{o,i}, \end{aligned} \tag{11}$$

$$\begin{aligned} &\mathbf{B}_\lambda = \begin{bmatrix} B_{\lambda 1} & \cdots & B_{\lambda r} \end{bmatrix}^T,\ \mathbf{C}_{\lambda,i} = \begin{bmatrix} C_{\lambda 1,i}^T & \cdots & C_{\lambda r,i}^T \end{bmatrix}^T, \\ &\mathbf{D}_{\lambda,i} = \begin{bmatrix} D_{\lambda 1,i}^T & \cdots & D_{\lambda r,i}^T \end{bmatrix}^T, \text{ and } \mathbf{\Lambda} = \operatorname{diag}(\Lambda_1,\ldots,\Lambda_r). \end{aligned} \tag{12}$$

For r=2, i.e. two local controllers, the matrices (12) may be written as

$$\begin{aligned} &B_{\lambda 1} = \begin{bmatrix} 0 & I & 0 \end{bmatrix}^T,\ B_{\lambda 2} = \begin{bmatrix} 0 & 0 & I \end{bmatrix}^T, \\ &C_{\lambda 1,2} = \begin{bmatrix} (D_{K2}-D_{k1})C_y & -C_{K1} & C_{K2} \end{bmatrix}, \\ &C_{\lambda 2,1} = \begin{bmatrix} (D_{K1}-D_{k2})C_y & C_{K1} & -C_{K2} \end{bmatrix}, \\ &C_{\lambda 1,1} = C_{\lambda 2,2} = 0, \text{ and } D_{\lambda j,i} = \begin{bmatrix} (D_{Ki}-D_{Kj})D_{yw} \end{bmatrix}. \end{aligned} \tag{13}$$

Lemma 1: *Quadratic Performance*—The closed loop (9) has an induced $\mathcal{L}_2$ norm less than γ if there exists $Q=Q^T>0$ such that

$$\begin{bmatrix} A_{cl,i}Q + QA_{cl,i}^T & B_{cl,i} & QC_{cl,i}^T \\ B_{cl,i}^T & -\gamma I & D_{cl,i}^T \\ C_{cl,i}Q & D_{cl,i} & -\gamma I \end{bmatrix} < 0 \text{ for } i=1,\ldots,r. \tag{14}$$

Proof: See [5] and [18] for details.

Note (14) is a BMI in terms of a structured $\mathbf{\Lambda}$ and Q, thus a globally minimizing structured $\mathbf{\Lambda}$ and Q is not always readily available. One method often used to eliminate variables from special types of BMIs is the Elimination Lemma [18].

Lemma 2: *the Elimination Lemma* [18]: There exists unstructured Λ satisfying the matrix inequality

$$\Psi + H^T\Lambda G + G^T\Lambda^T H < 0 \tag{15}$$

if and only if the matrix inequalities

$$\mathcal{N}^T(G)\Psi\mathcal{N}(G) < 0 \tag{16}$$

and

$$\mathcal{N}^T(H)\Psi\mathcal{N}(H) < 0 \tag{17}$$

are satisfied, where $\mathcal{N}(H)$ is the null space operator such that $H\mathcal{N}(H)=0$.

Although the Elimination Lemma will not be directly used to construct a set of stabilizing compensators represented by a structured $\mathbf{\Lambda}$, the Elimination Lemma is useful in ascertaining a lower bound for the induced $\mathcal{L}_2$ norm γ. For the ensuing application of the Elimination Lemma, let

$$G_i = \begin{bmatrix} \mathbf{C}_{\lambda,i} & \mathbf{D}_{\lambda,i} & 0 \end{bmatrix} \operatorname{diag}(Q,I,I), \tag{18}$$

$$H = \begin{bmatrix} \mathbf{B}_\lambda^T & 0 & 0 \end{bmatrix}^T, \tag{19}$$

and Ψ_i is the left side of (14), when Λ_i=0 for i=1,…,r.

Lemma 3: *Necessary Conditions for Synthesis*—There exists structured $\mathbf{\Lambda}$ satisfying (14) only if

$$\mathcal{N}^T(G_i)\Psi_i\mathcal{N}(G_i) < 0 \tag{20}$$

and

$$\mathcal{N}^T(H)\Psi_i\mathcal{N}(H) < 0 \tag{21}$$

for all i=1,…,r.

Proof: Since we are seeking a structured $\mathbf{\Lambda}$, (20) and (21) are only necessary conditions. Matrix inequality (21) is a direct result of the application of the Elimination Lemma. Concerning (20), it may be shown for any given i=[1,r] the matrix

$$\begin{aligned} &\Psi_k + J(\beta)G_k + G_k^T J^T(\beta) \\ &+\sum_{j=1}^{r}\beta_j H^T \mathbf{\Lambda} G_j + \sum_{j=1}^{r}\beta_j G_j^T \mathbf{\Lambda}^T H \end{aligned}, \tag{22}$$

where β_i=1 and β_j=0 for $j\neq i$ and

$$J(\beta) \triangleq \begin{bmatrix} \beta_1 B_p & \beta_2 B_p & \cdots & \beta_r B_p \\ 0 & 0 & \cdots & 0 \\ \vdots & \vdots & & \vdots \\ 0 & 0 & \cdots & 0 \end{bmatrix}, \tag{23}$$

is equivalent to the left hand side of (14) for any k=1,…,r,. It also may be shown that for any i,j=1,…,r G_i and G_j are linearly dependent, thus

$$\mathcal{N}\left(G_i\right)=\mathcal{N}\left(G_j\right). \tag{24}$$

As a result, (22) and (24) imply

$$\mathcal{N}^T\left(G_i\right)\Psi_i\mathcal{N}\left(G_i\right)=\mathcal{N}^T\left(G_j\right)\Psi_j\mathcal{N}\left(G_j\right) \tag{25}$$

for all i,j=1,…,r thereby proving (20). ■

Static Output Feedback Substitutive LMI Formulation

The BMI (14) takes the form of a static output feedback synthesis problem which is considered to be a subset of the BMI problem [19]. This paper utilizes the substitutive LMI algorithm presented in [20] for the purposes of searching for Q and $\mathbf{\Lambda}$. The reader should note this is one of many possible algorithms that could have been used from the LMI based static output feedback synthesis literature, e.g. [21] and [22].

The following uses a direct adaptation of the $\mathcal{H}_\infty$ static output feedback synthesis discussed in [20] for the problem at hand. The closed loop system (9) has a induced norm less than γ if there exists $Q=Q^T>0$ and $\mathbf{\Lambda}$ such that

$$\begin{bmatrix} \Phi_i\left(Q,L_i\right)+\Delta_i & * & * & * \\ C_{o,i}Q & -\gamma I_q & * & * \\ \left(B_{o,i}-\mathbf{B}_\lambda\mathbf{\Lambda}\mathbf{D}_{\lambda i}\right)^T & D_{o,i}^T & -\gamma I_r & * \\ \left(\mathbf{B}_\lambda\mathbf{\Lambda}-Q\mathbf{C}_{\lambda i}^T W^{-1}\right)^T & 0 & 0 & -W^{-1} \end{bmatrix}<0, \tag{26}$$

for i=1,…,r, where * indicates the elements are inferred by symmetry,

$$\Delta_i \triangleq L_i W L_i^T + NWN^T - NW\left(\mathbf{B}_\lambda\mathbf{\Lambda}\right)^T - \mathbf{B}_\lambda\mathbf{\Lambda}WN^T \text{ and} \tag{27}$$

$$\Phi_i\left(Q,L_i\right)\triangleq\left(A_{o,i}-L_i\mathbf{C}_{\lambda,i}\right)Q+Q\left(A_{o,i}-L_i\mathbf{C}_{\lambda,i}\right)^T. \tag{28}$$

For a given N, L_i, and W, (28) becomes a LMI, thus enabling the use of conventional LMI solvers such as [23]. As discussed in [20], the substitutive LMI formulation (26) penalizes (14) with a positive semi-definite term using the substitutive variables L_i and N. In particular, the penalizing positive definite term disappears when

$$L_i=Q\mathbf{C}_{\lambda,i}^T W^{-1} \text{ and } N=\mathbf{B}_\lambda\mathbf{\Lambda}, \tag{29}$$

thereby recovering (14). The iterative LMI algorithm proposed in [20] is described as follows:

Step 0) Starting with iteration k=1. Choose a weighting matrix W>0 and select the initial value of $L_i^{(k)}=L$ such that $\Phi_i(Q,L)<0$ is satisfied and set $N^{(k)}$= $L^{(k)}$.

Step 1) Minimize $\gamma^{(k)}$ over $Q^{(k)}$>0 and $\mathbf{\Lambda}^{(k)}$ such that (26) is satisfied.

Step 2) Set $L_i^{(k+1)}=Q^{(k)}\mathbf{C}_{\lambda,i}^T W^{-1}$ and $N^{(k+1)}=\mathbf{B}_\lambda\mathbf{\Lambda}$ for the next iteration.

Step 3) Check for the convergence to a minimum using the induced $\mathcal{L}_2$ norm bound $\gamma^{(k)}$. If the solution has not converged, proceed to Step 1 for iteration k=k+1.

Two consequences of the choice of L in step 0 are (a) (26) may not be feasible on step 1, and (b) the choice impacts which local minimum the iterative LMI converges upon. The next section briefly discusses an ad-hoc technique for initializing the algorithm in the process of designing the controller interpolation for the motivating example.

EXAMPLE

Experiment Setup

The Earthmoving Vehicle Powertrain Simulator (EVPS) at the University of Illinois at Urbana-Champaign was utilized as a test bed to demonstrate the utility of using a robust local controller network for controller interpolation in practical applications. The EVPS is a hardware-in-the-loop setup capable of emulating earthmoving powertrains [24] and similar hydraulic equipment [25]. Consequently, the EVPS allows the flexibility to develop and validate new control concepts through hardware-in-the-loop testing for a variety of systems. In the following experiment, the EVPS was utilized to emulate a hydrostatic powertrain with a continuously variable transmission (CVT).

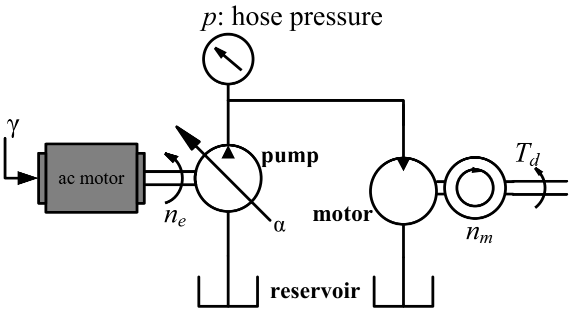

Fig. 3: Hydrostatic powertrain schematic

The prime mover for the powertrain, shown in Fig. 3, consists of a compression ignition engine emulated through a three-phase induction motor [24]. The induction motor drives the variable-displacement pump, i.e. the CVT in the powertrain, and the hydraulic fluid pumped by the CVT drives a hydraulic motor.

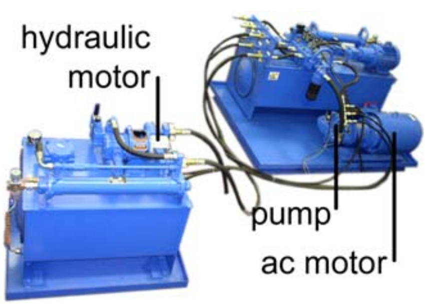

Fig. 4: Experimental test bed photo

The following linearized model is based upon the model structure presented in [24]. The engine speed n_e and hydraulic motor speed n_m are measurements available to the controller, as well as the reference engine speed $n_{e,r}$ and hydraulic motor speed $n_{m,r}$. The powertrain is controlled through the engine throttle angle γ, and swash plate angle α. The resulting reduced-order model linear model is:

$$P_{yu} \triangleq \begin{cases} \delta \dot{x}_p = A_p \delta x_p + B_{p,u} \delta u \\ \delta y = C_{p,y} \delta x_p + D_{p,yu} \delta u \end{cases} \tag{30}$$

where

$$\delta u = \begin{bmatrix} \delta\gamma & \delta\alpha \end{bmatrix}^T, \ \delta x_p = \begin{bmatrix} \delta n_e & \delta p & \delta n_m \end{bmatrix}^T, \tag{31}$$

$$A_p = \begin{bmatrix} -0.8409 & -9.699 & 0 \\ 0.1803 & 0.8461 & -0.5271 \\ -2.03 & 2440 & -28.01 \end{bmatrix}, \ C_{p,y} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \tag{32}$$

$$B_{p,u} = \begin{bmatrix} 29.15 & -22.11 \\ 0.01547 & 6.976 \\ 0.02799 & -11.54 \end{bmatrix}, \text{and } D_{p,wu} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}. \tag{33}$$

Controller Design

This example has two conflicting objectives associated with managing the trade-off between performance and efficiency. Efficiency is typically managed by tracking an optimal engine speed for the current load-power condition **Error! Reference source not found.**. Consequently, efficiency is related to tracking a reference engine speed $n_{e,r}$, whereas performance is directly related to tracking a reference motor speed $n_{m,r}$.

Rather than designing one LTI controller that compromises between the two objectives, the following discusses the design of two separate LTI controllers. Given the plant uncertainty and plant nonlinearities associated with this class of plant, one may also consider conflicting objectives such as high robustness versus high performance. For the purposes of this paper, the robustness characteristics associated with $\mathcal{H}_\infty$ controllers are used.

In order to fulfill robust performance requirements, $\hat{K}_i$, shown in Fig. 5, was designed to minimize the $\mathcal{H}_\infty$ gain of the system from w to z, where

$$w = \begin{bmatrix} w_1^T & w_2^T \end{bmatrix}^T \text{ and } z = \begin{bmatrix} z_1^T & z_2^T & z_3^T \end{bmatrix}^T. \tag{34}$$

The weighting matrices on the various signals in Fig. 5 are as follows

$$\hat{W}_r = \operatorname{diag}(40,40), \ W_u = \operatorname{diag}(0.30, 0.15), \tag{35}$$

$$W_{e,1} = \operatorname{diag}(0.0667, 0.400), \ W_{e,2} = \operatorname{diag}(0.267, 0.200), \text{ and} \tag{36}$$

$$W_n = \left\{ \begin{bmatrix} \dot{x}_{Wn} \\ z_3 \end{bmatrix} = \left[\begin{array}{c|cc} -65.13 & -3.256 & 32.56 \\ \hline -1 & -0.05 & 0.5 \end{array} \right] \begin{bmatrix} x_{Wn} \\ y \end{bmatrix} \right. . \tag{37}$$

The frequency weightings are constructed to reflect engine and motor speed tracking objectives and high frequency model uncertainty.

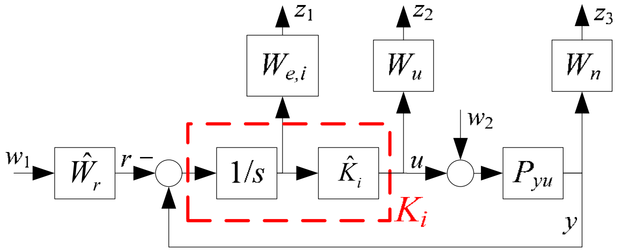

Fig. 5: Closed loop design model

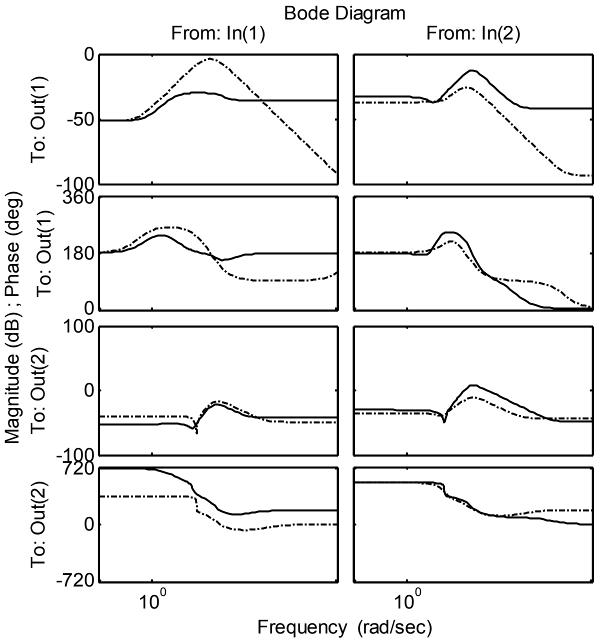

Fig. 6: Bode plot of $\hat{K}_i$ for i=1,…,r, $\hat{K}_1$ solid and $\hat{K}_2$ dot dashed

Implementation of the continuous-time controller designed involves an approximate discretization of the controller using the Runge-Kutta fixed-step solver in Wincon 3.2, software produced by Quanser Consulting Inc. Since many robust control techniques can yield large closed loop poles, the controller $\hat{K}$ was designed using the robust regional pole placement technique discussed in [26]. The LMI region was chosen as the open left half plane intersected with the disk centered at the origin with a radius of 300 rad/s, a fraction of the Nyquist frequency $\omega_s=\pi/T_s$, where T_s=0.001 s, in order to limit input/output signal distortion of the implemented controller. Using the algorithm discussed in [26] and a balanced realization based model reduction, Bode plots of the resulting controllers are shown in Fig. 6.

Stabilizing Compensator Design

Naturally, it is desirable to maintain some level of robust stability while interpolating controllers to form the interpolated controller K_α. The robust stability metric is the induced $\mathcal{L}_2$

norm from w to z, shown in Fig. 7, which is similar to the metric used for the controller design discussed previously. The frequency weightings on the signals in Fig. 7 are given by (35), (36), (37), and

$$W_r = \hat{W}_r \operatorname{diag}\left(W_{PI}, W_{PI}\right) \qquad (38)$$

where

$$W_{PI} = \{\left(0.001s+1\right)/\left(s+0.001\right). \qquad (39)$$

Note the frequency weighting function W_{PI} is designed as a stable integrator-like frequency weighting function to reflect the frequency content of the references.

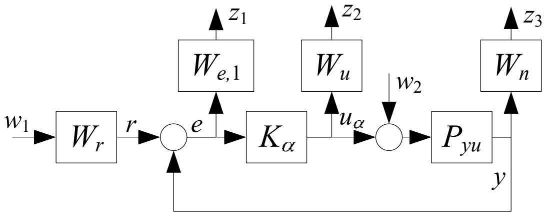

Fig. 7: Controller interpolation design model

Since the BMI algorithm utilized is effectively a local search, the initialization is an important factor in feasibility and convergence. The ad-hoc initial condition

$$L = \left[\beta_1 B_{K1} \bar{P}_{yu} \quad \cdots \quad \beta_r B_{Kr} \bar{P}_{yu}\right], \qquad (40)$$

where $\bar{P}_{yu}$ is the DC gain of the plant and β_i is a positive scaling parameter found through trial and error, was found to be particularly effective for this example. The ad-hoc initial condition is motivated by the dynamic stabilizing compensators constructed using a Youla parameterization, corresponding with the coprime factorization $[N\ M]=[P_{yu}\ I]$. In general, a search for L may be constructed by reformulating the matrix inequality $\Phi_i(Q,L) < 0$ in terms of $Q^{-1}=Q^{-T}>0$ and the LMIs

$$Q^{-1}\left(A_{o,i} - L_i \mathbf{C}_{\lambda,i}\right) + \left(A_{o,i} - L_i \mathbf{C}_{\lambda,i}\right)^T Q^{-1} < 0, \text{ for } i=1,\ldots r. \qquad (41)$$

Applying the iterative LMI technique discussed above, the induced $\mathcal{L}_2$ norm quickly converges very close to the lower bound estimate, as shown in Fig. 8. The induced $\mathcal{L}_2$ norm bound for the LCN case is infinite because each controller contains integrators.

Table I: Induced L_2 norm for different controllers

	K_1	K_2	LCN	RLCN
$\|\|T_{zw}\|\|$	2.198	2.152	∞	2.199

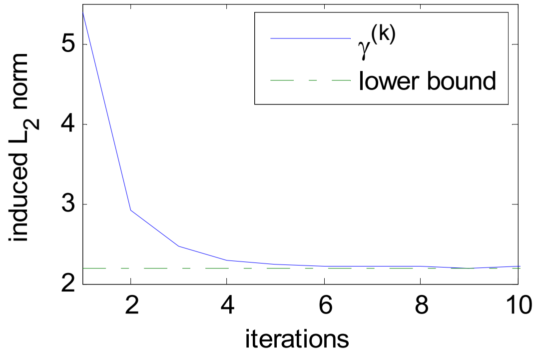

Fig. 8: Convergence of iterative LMI algorithm

Experimental Results

The following experiment evaluates the tracking performance of the controller interpolation designed in the previous section. A switching signal with a period of 2 seconds was chosen as the interpolation signal to represent a harsh example of a controller interpolation signal.

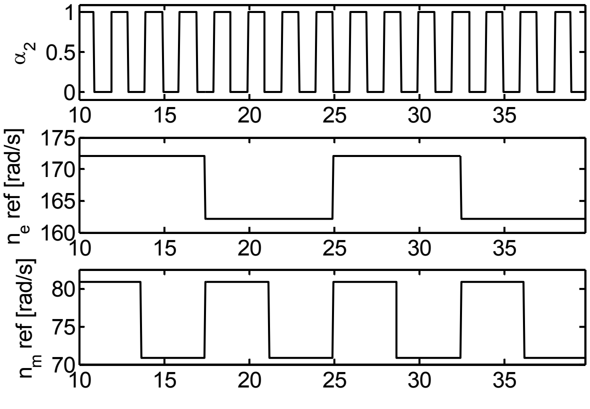

Figure 9: Switching signal and references

Table II: Performance measures from experimental data, where e_1 is n_e error and e_2 is n_m error

	K_1	K_2	LCN	RLCN
$\|\|e_1\|\|_\infty$	10.7	10.9	11.5	11.0
$\|\|e_2\|\|_\infty$	10.8	10.4	15.3	10.6
$\|\|e_1\|\|_1$	41.0	27.3	41.8	33.8
$\|\|e_2\|\|_1$	36.4	39.7	79.2	38.0
$\|\|e_1\|\|_2$	13.5	10.7	12.2	11.6
$\|\|e_2\|\|_2$	12.1	14.2	21.6	12.7

As shown in Figure 10, the RLCN closed loop system has vastly greater tracking performance than the LCN closed loop system. For the LCN case, the switching between controllers caused large deviations away from the reference value, whereas in the RLCN case, the switches were nearly imperceptible. Table II confirms the tracking performance of the RLCN closed loop a significant improvement over the LCN closed loop. Also, Table II shows that the RLCN closed tracking performance lies between the tracking performance of K_1 and

K_2, thereby indicating the controller interpolation results in some level of compromise between the two controllers.

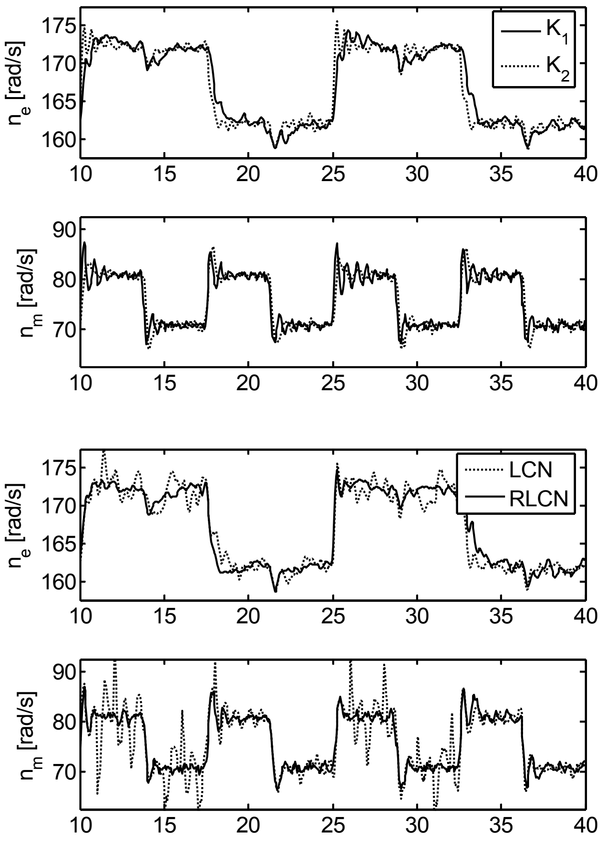

Figure 10: Comparison of closed loop outputs

CONCLUSION

For a given family of controllers, possibly consisting of different types of controllers, this paper discussed a controller interpolation design technique that considers the controller interpolation criteria and a robust stability metric. In particular, the controller interpolation framework consisted of controller blending augmented by a set of stabilizing signals. The set of stabilizing signals are produced by a corresponding set of stabilizing compensators that are designed using a set of BMIs. Although the stabilizing compensator synthesis involves a set of BMIs, which only guarantees local sub-optimal convergence; the demonstrated proximity to the optimal solution in the example is promising for the future work using this controller interpolation framework. Furthermore, the presented experimental results suggest the controller interpolation technique presented is a useful controller interpolation design tool.

REFERENCES

[1] J.P. Hespanha and S.A. Morse, "Switching between stabilizing controllers," *Automatica*, vol. 38, pp. 1905-1917, 2002.

[2] J.D. Bendtsen, J. Stoustrup, and K. Trangbaek, "Bumpless transfer between observer-based gain scheduled controllers," *International J. of Control*, vol. 78, no.7, pp. 491-504, 2005.

[3] D. Liberzon, *Switching in Systems and Control*, Boston, Birkhauser, 2003.

[4] A. Packard, "Gain scheduling via linear fractional transformations," *Systems and Control Letters*, vol. 22, pp. 79-92, 1993.

[5] P. Apkarian and P. Gahinet, "A convex characterization of gain-scheduled H_∞ controller," *IEEE Trans. Automat. Contr.*, vol. 40, pp. 853-864, 1995.

[6] W.J. Rugh and J.S. Shamma, "Research on gain scheduling," *Automatica*, vol. 36, pp. 1401-1425, 2000.

[7] R. Zhang, A. Alleyne, and D. E. Carter, "Generalized Multivariable Gain Scheduling with Robust Stability Analysis," *ASME J. of Dyn. Syst. Meas. and Control,* vol. 127, pp. 668-687.

[8] D.A. Lawrence, J.H. Kelly, and J.H. Evers, "Gain Scheduled Missile Autopilot Design Using a Control Signal Interpolation," *AIAA Guidance, Navigation, and Control Conference*, Washington, DC, 1998, pp. 1394–1402.

[9] H. Niemann, J. Stoustrup, and R.B. Abrahamsen, "Switching between multivariable controllers," *Optim. Control Appl. Meth.*, vol. 25, pp. 51-66, 2004.

[10] B.D.O Anderson, "From Youla-Kucera to identification, adaptive, and nonlinear control", *Automatica*, vol. 34, pp. 1485-1506, 1998.

[11] B.P. Rasmussen and A. Alleyne, "Gain Scheduled Control of an Air Conditioning System Using the Youla Parameterization," in *Proceedings of American Control Conference*, Minneapolis, MN, 2006.

[12] Zaccarian, L. and Teel, A.R., "The L2 (l2) bumpless transfer problem for linear plants: Its definition and solution," *Automatica*, vol. 41, pp. 1273-1280, 2005.

[13] M.C. Turner and D.J. Walker, "Linear quadratic bumpless transfer," *Automatica*, vol. 36, pp. 1089-1101, 2000.

[14] M.V. Kothare, P.J. Campo, M. Morari, and C.N. Nett, "A unified framework for the study of anti-windup designs," *Automatica*, vol. 30, pp. 1869-1883, 1994.

[15] C. Edwards and I. Poslethwaite, "Anti-windup and bumpless-transfer schemes," *Automatica*, vol. 34, pp. 199-210, 1998.

[16] P.F. Weston and I. Postlethwaite, "Linear conditioning for systems containing saturating actuators," *Automatica*, vol. 36, pp. 1347-1354, 2000.

[17] K. Zhou, J. Doyle, and K. Glover, *Robust and Optimal Control*, Upper Saddle River, New Jersey: Prentice Hall, Inc.

[18] S. Boyd, L. El Ghaoui, E. Feron, and V. Balakrishnan,, *Linear Matrix Inequalities in System and Control Theory.* Philadelphia, PA: Society for Industrial and Applied Mathematics, 1994.

[19] L. El Ghaoui and S.-I. Niculescu, *Advances in Linear Matrix Inequality Methods in Control.* Philadelphia, PA: Society for Industrial and Applied Mathematics, 2000.

[20] A. Fujimori, "Optimization of static output feedback using substitutive LMI formulation," *IEEE Trans. Auto. Contr.*, vol. 49, no. 6, pp. 995-999, 2004.

[21] C.A.R. Crusius and A. Trofino, "Sufficient LMI conditions for output feedback control problems," *IEEE Trans. Automat. Contr.,* vol. 44, pp. 1053-1057, 1999.

[22] F. Leibfritz, "A LMI-based algorithm for designing suboptimal static H_2/H_∞ output feedback controllers," *SIAM J. Control Opt.*, vol. 39, no. 6, pp. 1711-1735, 2001.

[23] P. Gahinet, A. Nemirovski, A.J. Laub, and M. Chilali, *LMI Control Toolbox*, Natick, MA: The MathWorks, Inc., 1995.

[24] R. Zhang, A. Alleyne, and E. Prasetiawan, "Modeling and $\mathcal{H}_2/\mathcal{H}_\infty$ MIMO Control of an Earthmoving Vehicle Powertrain," *ASME J. of Dyn. Syst. Meas. Control*, vol. 124, no. 4, pp. 625-636, 2002.

[25] Zhang, R. and Alleyne, A.G., 2002, "Dynamic Emulation Using a Resistive Control Input," *Proc. of the ASME International Mechanical Engineering Congress and Exposition Conference*, New Orleans, LA, pp. 137-147.

[26] M. Chilali, P. Gahinet, and P. Apkarian, "Robust Pole Placement in LMI Regions" *IEEE Trans. Automat. Contr.*, vol. 44, no. 12, pp. 2257-2270, 1999.

[27] A. Montgomery and A. Alleyne, "Optimizing the efficiency of electro-hydraulic powertrains," *Proceedings of ASME International Mechanical Engineering Conference and Exposition*, IMECE20

<u>Appendix C</u>

POWER SYSTEMS INVESTIGATION

J. Macklin,
Senior Undergraduate Thesis Report

ME 393: Special Projects – FINAL REPORT
Power Systems Investigation

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EXECUTIVE SUMMARY

This report looked at the problem of powering a mobile underwater unit, closely focusing on energy sources and methods of power generation.

In the first report, Energy Sources, different types of energy sources were evaluated against a list of constraints for underwater use by the U.S. Navy. These included miniaturization, non-air breathing, noise production, minimizing bubble exhaust and increasing efficiency. Areas of technologies included nuclear, chemical, mechanical and electrical.

Conclusions yielded a ranked list of sources for the system, putting batteries as a firm favorite, but a nuclear source was close behind.

The second report, Power Generation, looked at different methods to generate power from the energy sources described in the first report, again applying the same list of constraints.

The conclusions to this report again produced a ranked list, similarly with batteries on top.

The overall analysis of this report concluded that if the weight and volume problems of batteries could be sufficiently overcome with advancing technology they should be preferred to other methods. But, failing to do so, a couple of other options are still available including the combination of a fuel cell with a battery to reduce weight and increase efficiency, and the use of RTGs where adequate shielding for the operator was provided.

CONTENTS

ENERGY SOURCES

A1. INTRODUCTION

A1.1 Title of Project

"A Systems-Level Investigation for Self-Contained Energy Storage System and Power Generation Device"

A1.2 Introduction to Power Systems

Energy storage and power generation have been huge topics of interest for many years now. There are plenty of ways of doing both, but it depends on exactly what the consumer is looking for as their optimum output that decides what the best combination will be. **Figure 1** shows the general block diagram for this energy process.

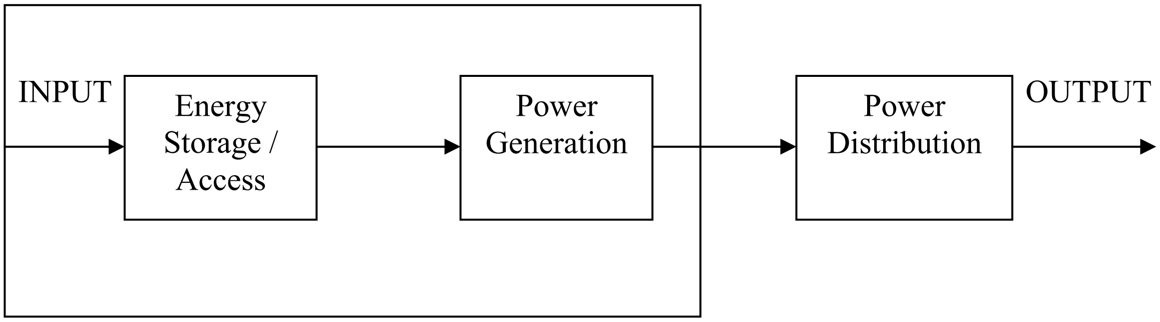


Figure 1: General Block Diagram for this Energy Process

This project aims to look at the processes involved that occur within the box in **Figure 1** only.

Case Study Background:

With the largest navy in the world, the US has its fair share of submarines. They are known as Attack Submarines and come under The Carrier Strike Group of the navy.

The main purpose of these submarines is ‘to seek and destroy enemy submarines and surface ships’. But there are other secondary objectives as well, ranging from ‘intelligence collection and special forces delivery to anti-ship and strike warfare’ **[1]**.

Part of intelligence collection, for example, might involve leaving the submarine whilst submerged, either alone or with equipment, based on (i) the oxygen supply, and (ii) the power available to them to operate any equipment they have.

As far as mobile power for underwater experimentation goes, the current favored solution is the use of batteries, which can be charged by the nuclear reactor in the modern submarines. This may not be the most efficient method of operation though.

A self-contained energy storage and power generation system could help increase the efficiency and reduce the time of underwater operations, thus increasing the number of operations that could be carried out (or the total time you could spend under water).

It should be noted though that there are many factors that would contribute to a better final solution as all submarines and their dependents are ‘required to meet all of the CINCs and national intelligence community’s highest operational and collection requirements’**[2]**.

A1.3 Aims of Project

The overall aims of this project are to:

- Deal with the issue under the two report headings of Energy Storage & Access and Power Generation.
- Look at existing technologies or prototypes for storing energy under the different types of sources (chemical, mechanical etc.).
- Apply a list of constraints to each to determine their suitability for underwater use.
- Repeat the last two points for methods of power generation.
- Determine the best combination of these under the final problem specifics and/or suggest other paths of possible progress using alternative technologies i.e. technologies that as of yet have not been used in the same field.
- Produce list(s) in order of ranking for different properties required i.e. depending on the conditions a certain pair may be favored to another.

Each aim will be broken down into sub-sections as we progress through the report so as to whittle down the technologies to the optimum pairing.

A1.4 Possible Constraints

- Non-Air Breathing:

The most obvious constraint that comes to mind when thinking about underwater power generation is the lack of oxygen for combustion. Old submarines used to only run on dieselengines to combat the very fussy petrol engine stoichemetric ratio.

Submarines of late have moved on to having their very own small nuclear reactors in the back end (see ***A2.2.1***).

Equipment or vehicles underwater outside the submarine, it seems, would have no possibility of working on a combustion cycle due to this lack of air.

But is there really a complete lack of air?

The answer is obviously no, as the people in the submarine need air to breathe, and so do those venturing outside of it. So equipment could be powered by a combustion cycle that utilizes oxygen from the diver's oxygen tank…

I think that ruling out the possibility of air-breathing equipment at this stage is short-sighted, but recognize the fact that pursuance in this line of thought will probably be to no avail.

The constraint would be better described as ‘Finite Oxygen’

- Low Noise:

Stealth is an important part of the military forces’ tactics, and nothing is worse than giving away the co-ordinates of your position by sending a noisy signal.

The water itself will have a large damping effect on the noise of high-frequency mechanical parts, but will not always be enough to contain the low frequency sounds. The choice of materials, as well as the actual physical design of the system is important here.

Summarizing, the important areas are:
- motors;
- other moving parts;
- chemical reactions;
- noise reduction;
- choice of materials.

- Compactness:

The idea of mobile equipment and instrumentation for human use underwater indicates that a certain amount of maneuverability is required. Therefore having a system that is as large as, or larger than, the existing submarine is pointless.

But just how small can energy storage and power generation systems go?

Each existing system will be looked at, and what reasons, if any, they have for their limiting or preferred sizes.

- Minimal Bubble Exhaust:

The topic of exhaust is connected to the stealth issue raised for the ‘low noise’ constraint. If bubbles are released into the water they cause a disturbance with a detectability that depends on the size of the bubbles themselves.

Bubble release can also increase the noise of the system, and so resistance to this needs to be included in the design from an early stage.

For the examples in this project, there will be a variety of waste products including toxic gases from chemical reactions and nothing for electric systems.

- Efficiency:

Efficiency is a big business. In fact, some businesses make all their money from taking other people's products and making them run smoother, using less fuel or less parts, but always with the intention of saving a few bucks.

Although cost may not seem like much of an object to the US Navy, the lifetime of a system is. The money will always be there to replace broken equipment, but when you're several thousand feet under the surface of the sea, getting new parts to you isn't easy. It can be said that a more efficient system should have a longer life span, and maximizing the efficiency should give more flexibility to underwater operations.

The main efficiency criterion is about how much power you get for your energy input. This, along with expected lifetime will be examined more closely for each piece of technology.

A2. ENERGY STORAGE & ACCESS

A2.1 Introduction to Energy Storage

Dr. Johannes Jensen highlights the two most important features of a system when looking at possible energy storage solutions as:

1) the amount of energy to be stored

2) the length of time for maintaining the storage **[3]**

These parameters are affected by the system's individual characteristics and the solutions are often standardized (closest solution to required ideal) rather than customized (optimum solution). There are other factors too that attribute to the solution and these will be dealt with in due course.

A2.2 Energy Sources

There are growing concerns about the fact that, what we call 'fossil fuels' (oil, coal, natural gas etc.) are rapidly diminishing as we are starting the new century and it will be many, many years before they are naturally formed again.

But until renewable energy sources prove to be capable of supplying the majority of the world's energy needs, there will be no significant slowing down of fossil fuel use until it's too late.

Both renewable and non-renewable energy sources will be considered in this project and examples of each will be given. **Figure 2** shows my interpretation of the energy storage block diagram, and each block will be discussed separately.

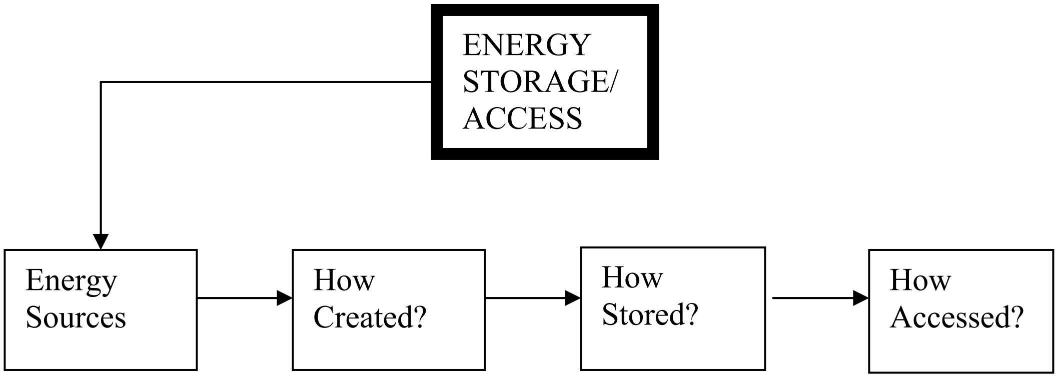


Figure 2: An Energy Storage Block Diagram

A2.2.1 Methods of 'Creation', Storage & Access

There are four main categories of energy conversion that will be discussed in this project:

- Electrical
- Chemical
- Mechanical
- Nuclear

<u>Electrical:</u>

This group includes electric fields, magnetic fields and superconducting coils.

Capacitors are electrical devices that are defined by the amount of charge they can take up and store per unit of voltage. An electric field is established and so energy is stored due to the potential energy of the charges. Some materials are polarisable e.g. dielectrics, and so the potential total charge will increase (and thus the stored energy likewise).

For an electromagnet connected to a constant voltage source, the energy flow into the magnetic system varies with time. Energy is required to build the field up and this can be released again in an output circuit as an electric current at a later point.

Superconducting coils can carry high currents (when magnetic fields are around) with zero resistance, but must be operated at liquid-helium temperature. Their main advantage is that they can 'store energy at a lower power level for later discharge at a higher power level' **[3]**.

Chemical:

The main source in this category is electrochemical sources like batteries and fuel cells but there are a few other important types:
a) Synthetic Fuels
b) Hydrogen
c) Solar

With electrochemical energy sources, chemical energy is converted into electrical energy. The difference between batteries and fuel cells is that batteries use the chemicals that are contained within them and fuel cells have fuel energy in the chemical form supplied to them form the outside. There are other specific requirements for the optimization of an electrochemical system that include (but not exclusively) the temperature and the electrode activity. The problem of battery 'life' is still the biggest drawback as far as batteries are concerned. A more detailed look at electrochemical energy sources can be found in section **D1**.

Synthetic fuels are generally substitutes for hydrocarbon fossil fuels (oil, natural gas) and include methanol, ethanol and methane. Methane is generally stored as a gas in cylinders and so is relatively easy to mobilize.

Being surrounded by water it would be frustrating to think that the hydrogen in the water could not be utilized to power equipment. Hydrogen is seen by many, as the 'ultimate fuel and energy storage medium' as it can be formed in the water-splitting process and combusted back releasing no pollution **[3]**. This process however, is very expensive due to the high temperatures required in the electrolytic decomposition of water. Most hydrogen production is at present done by either reforming natural gas or by partial oxidation of heavy oils. But a system that could run off the seawater around – now that sounds appealing.

One of the less likely solutions might be the use of solar or photovoltaic cells. In fact, so little light penetrates to a submarines depth that all trails of thought regarding this idea will end here.

Mechanical:

Mechanical systems are those that can generally be split into two groups, namely:

(i) Those that are based on potential energy;
(ii) Those that are based on kinetic energy.

Examples that work using potential energy are springs, compressed gas and hydro storage. Flywheels are an example of a kinetic energy source.

Unfortunately, any type of mechanical device's movement is going to be hindered dramatically by the water, and so may suffer from a decreased efficiency. If the mechanical system could however be isolated from the water e.g. in a vacuum, then this problem could be avoided. Compressed gas could be used to drive a small motor underwater. The problem with hydropower is that is requires the 'movement of water' to turn a turbine, so a gradient would have to somehow be established.

Nuclear:

The most recent of the categories is nuclear power, which now provides 'about 17% of the world's electricity' **[4]**. The raising and lowering of 'control rods' allows the rate of nuclear fission taking place to vary, thus increasing or decreasing the amount of heat produced respectively. Permanent nuclear reactor plants are very large when compared to their submarine sibling. Just how small nuclear sources can go will be researched in this project – nuclear reactor backpack anyone…?

A3. CONCLUDING REMARKS A

A lot of the briefly mentioned areas of energy storage deal with large-scale applications. People are interested in storing large amounts of energy top be dealt out in small installments

when needed. The problem of power generation underwater for such a small-scale application will have to look at whether any of these larger examples can in fact be scaled down.

Also, as we delve further into the subject matter, the exact specific requirements of the experimentation will become more important and generalizations will become harder to make.

The *amount of energy and time required to complete operations* will dominate the problem though.

B1. MINIATURIZATION

B1.1 The Concept of Miniaturization

Billed as the 'second industrial revolution' by some, the science of miniaturization has only been around since 1948, when the transistor replaced vacuum tubes. It is national defense programs that give modern miniaturization its greatest impetus and it is estimated that 'anywhere from 50 to 80 per cent of all miniaturization production today is designed either directly or indirectly for defense'. **[5]**

The focus on today's missions is all based on efficiency. As Lt. Gen. Arthur G. Trudeau, Ex Chief of Research and Development in the Army once stated:

‘Reduced size and weight and power requirements are factors that are becoming more and more important in the development of new weapon systems and equipment’

For external missions in the submarine case, this improved efficiency could be represented by an increase in the number of missions or the length of each mission. Basically, more bang for your buck.

It is important to note as well, that although miniaturization has had most success and practice in the electronics industry, other manufacturing industries are keen to utilize the science and progress has been made in other areas, such as the mechanical segment.

B1.2 General Problems in Design

“A little knowledge is a dangerous thing’ should be interpreted as “The maximum amount of knowledge is the minimum required” according to Raymond H. Carter, former Chief Engineer at Miniature Precision Bearings, Inc.**[6]** Applying pre-existing templates when attempting to achieve optimum miniaturization is foolish as the inter-relation of things varies with each application of apparently identical mechanisms. Confining a mechanism to a specified volume and weight are not the only problems facing the design engineer. Carter also gives a list of general operating conditions that he recommends should be consulted on approaching the design:

- Temperature
- Environment
- Speed
- Load
- Lubrication
- Characteristics and Performance
- Life
- Reliability **[6]**

Cold, high-pressure seawater applies to the first two (and possibly the fifth) items, but the others will depend entirely on what the mobile unit physically comprises of.

B1.2.1 Note on Biomimetics

Biomimetics is the imitation of life in engineering design from the Greek words *bios* (life) and *mimesis* (imitation). Just looking around, the wonders of Nature are the epitome of engineering design. For example, gram for gram, bone is stronger than steel; spider silk is one of the strongest materials on earth with an elasticity 30% better than the most elastic of nylons. Whale blubber provides excellent insulation against the cold of the ocean and is also a great food reserve during non-feeding migrations over thousands of miles.

Man has strived to compete with such engineering superiority, and to some extent has produced its own marvels in modern day society. But when you go small, nature always seems to win. This section of the project aims to look miniaturization in energy storage. A lot of the factors in the above list relate more to the power generation and distribution parts of the cycle, and some to both these and the energy storage part. Attempts will be made to keep the systems separate when dealing with the issue of miniaturization – or *compactness*.

B2. ENERGY STORAGE & MINIATURIZATION

The size of an energy storage system depends on all of the factors highlighted in **Figure 1** below:

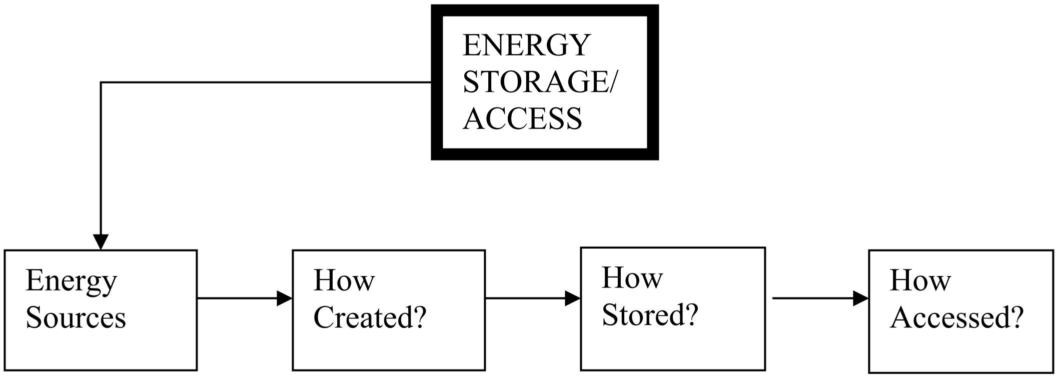


Figure 1: An Energy Storage Block Diagram

Different energy sources will be created in different ways, and if the energy source is seawater it does not have to be created or stored, merely utilized. The energy source may be created on land, it may be created on the submarine, or it may be done within the actual mobile unit itself.

B2.1 Nuclear Energy

The most fantastical of energy sources shall be dealt with first, as the thought of a nuclear power plant the size of a backpack is a scary thought, even for the most ambitious of engineers.

How Created?

The atomic nucleus consists of neutrons and protons collectively known as nucleons. It is special, complex nuclear forces that keep the nucleons in fixed positions relative to each other in the nucleus. The energy that must be expended to perform the work of dissociating the nucleus into its component nucleons is known as the nuclear binding energy. This energy has to overcome the nuclear forces for *fission* to occur. In the reverse process, *fusion*, the binding energy is defined as the energy released in the formation of the nucleus from the nucleons.

The binding energy of a nucleon differs from atom to atom (of different atomic weight). **Figure 3** shows how the nucleon binding energy (y-axis/Mev) varies with atomic weight (x-axis).

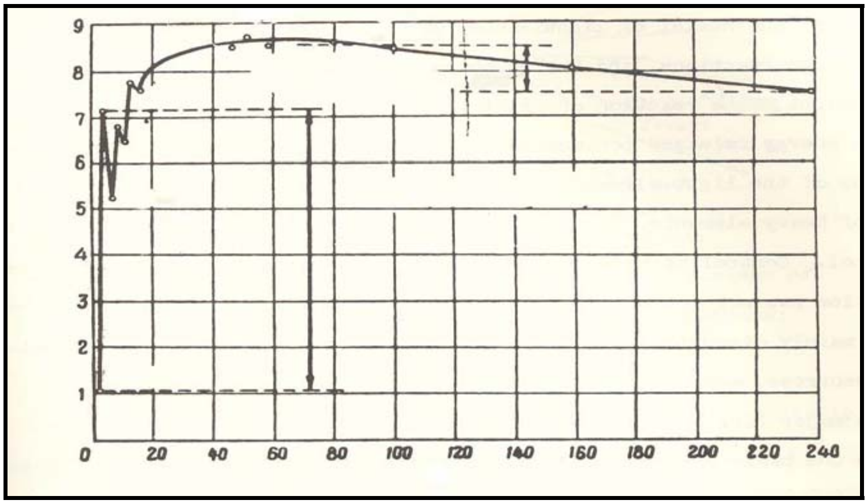


Figure 3: Ratio of Energy per Particle in the Nucleus to the Atomic Weight [7]

From the above graph, the binding energy available per nucleon is a maximum for elements with an atomic weight of around 60. Either side of this maximum the energy available deteriorates, notably more so for the lighter elements.

Fusion does not occur automatically but must be initiated by giving extremely high kinetic energy to suitable light substances - normally deuterium and tritium.

Fission on the other hand, results when a supercritical (if, on average, more than one of the free neutrons hits another atom, then the mass is **supercritical**. It will heat up) mass of suitable heavy material is rapidly formed. The reaction occurs automatically as

soon as the free neutrons, already present in the fissionable material, are supplied with a large enough number of atoms to support the process. **[8]**

The most common isotope used as fuel for nuclear power plants is Uranium^{235}, although others, like plutonium, are used as well. **Figure 4** shows the fission reaction of the U^{235} nucleus.

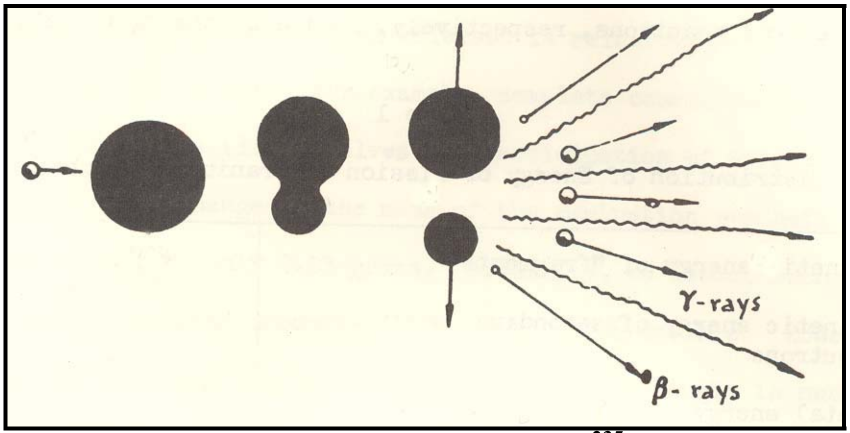


Figure 4: Fission Reaction of Uranium^{235} Nucleus [7]

The nucleus is sent into a state of excitation by a free neutron that collides with it and splits into two unequal fragments. When a U-235 atom splits, it gives off two or three neutrons known as secondaries. The fragments collide with surrounding nuclei and in the process heat the medium in which the fission is taking place. As illustrated above gamma and beta rays are also emitted in the process.

The total energy release from the fission of one kilogram of U^{235} is 19.7 billion kcal., as opposed to one kilogram of chemical aviation fuel (kerosene) that yields only 10,300 kcal! The size of one kilogram of U^{235} is also desirable – being the equivalent to the size of a softball.

So, as far as miniaturization is concerned, nuclear fuel is an extremely good concentrated energy source.

How Stored?

Usually, the uranium is formed into pellets with approximately the same diameter as a dime and the length of an inch or so.**[9]** The pellets are arranged into long rods, and the rods are collected together into bundles which are then submerged in water inside a pressure vessel.

In a nuclear bomb, the mass of uranium is very supercritical, so that all the atoms split instantaneously causing an explosion. In a reactor though, the mass should only be slightly supercritical so that the plant operators can control the heat being produced. If too

many neutrons are being emitted, the reactor will heat up too quickly and explode.

The amount of uranium^{235} in the mass (the level of enrichment) and the shape of it control the criticality of the sample. A **sphere** is the optimal shape.

To prevent this, **control rods** (made of a material that absorbs neutrons) are inserted into the bundle using a mechanism that can raise or lower them. Raising and lowering the control rods allows operators to control the rate of the nuclear reaction.

How Accessed?

When an operator wants the uranium core to produce more heat, the rods are raised out of the uranium bundle. To create less heat, the rods are lowered into the uranium bundle. The rods can also be lowered completely into the uranium bundle to shut the reactor down in the case of an accident or to change the fuel.**[9]**

It is a heat exchanger system that allows the heat generated by the reactor to be carried away to produce useful work. The water surrounding the reactor is continuously pumped, so that on passing it, it carries heat away. This heat can then be utilized to cause cold water in another tank to evaporate, producing steam that can be used to drive a turbine.

Existing Examples

1) The "Atomic Battery"

The atomic battery allows the direct conversion of atomic energy into electricity, and has been around since the 1950's. **Figure 5** shows a typical arrangement of the first atomic batteries:

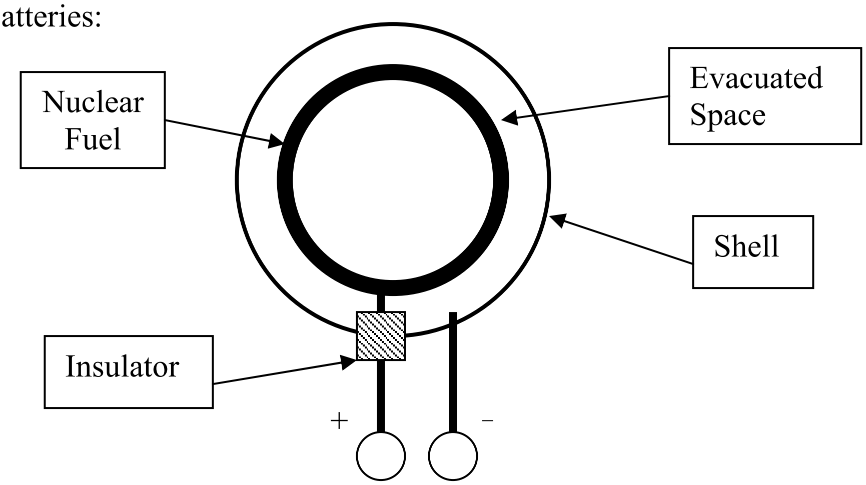


Figure 5: Diagram of an "Atomic Battery"

One of the electrodes is the spherical metal shell, and the other is the internal shell coated with a thin layer of radioactive substance that emits beta particles. A vacuum is created between the two shells, and so a positive charge is gained by the internal electrode, and a negative one by the outer shell.

This type of battery could 'yield high-voltage currents, but the current strength would be very small due to the thin surface layer of radioactive substance'.**[7]**

In recent years though progress has been made in this area. An Oct. 18th, 2002 web post on www.spacedaily.com revealed that 'Cornell University researchers have built a microscopic device that could supply power for decades by drawing energy from a radioactive isotope.'**[10]**

A description of the prototype is as follows:

*"The prototype is made up of a copper strip 1 millimeter wide, 2 centimeters long and 60 micrometers (millionths of a meter) thick that is cantilevered above a thin film of radioactive nickel-63 (an isotope of nickel with a different number of neutrons from the common form). As the isotope decays, it emits beta particles (electrons)."***[10]**

The researchers have chosen only isotopes that emit beta particles (whose energy is small enough not to penetrate skin) to be used in their device.

A negative charge is built on the copper strip as the emitted electrons collect there, and a positive charge results on the isotope film from where it has lost electrons. This opposite attraction bends the rod down, and when it is close enough to the isotope a current flows that compromises the charge. Therefore the rod springs back up and the whole process starts over.

This direct energy conversion also allows direct actuation of linear devices or rotary motion from cams or wheels by the moving cantilever action. Attaching a magnetized material to the rod as it moves through a coil could generate electricity. Other versions of the device that have also been built include one in which 'the cantilever is made of a piezoelectric material that generates electricity when deformed, releasing a pulse of current as the rod snaps up'.**[10]**

The researchers say that an entire device, including a vacuum enclosure, could be made to fit in less than one cubic millimeter in the future.

2) Plasma-Volt ™ Power Cell

It's not quite out in the market just yet, but the company Betavoltaic predict that it is 'straight to market achievable within 9 months to a year at most'.**[11]**

The Plasma Volt 400 Watt Power-Cell will be the first stand-alone power source to be offered by. **Figure 6** shows a picture of the 19" system.

Figure 6: PV-400 19" Rackmount

It is meant to offer the customer 400-Watts continuous power for 2 years constant load conditions! Unfortunately (but understandably) not much information was available on their website at the time of research, but reference number **[11]** is definitely one to keep an close eye on.

3) Micro Electro Mechanical Systems (MEMS)

As some engineers strive to create bigger and better systems, others concentrate on working in the microdomain. Working on 'machines so small they are imperceptible to the human eye and with gears no bigger than a grain of pollen' **[12]**.

Sandia National Laboratories, a leader in the development of micromachines, uses polycrystalline silicon as the basis of their systems – a material stronger than steel and extremely flexible.

Radioisotope Thermoelectric Generators (RTG's) use technology that converts the heat generated by the decay, to electricity. 'Thermoelectric conversion uses a thermal gradient between two different materials to create a current via the *Seebeck* effect.'**[13]** This is as opposed to betavoltaic technology that utilizes the direct energy released. RTG's are already used for underwater power and currently measure approximately 42 cm in length and 114 cm in diameter.

According to the National Academy of Engineering (NAE):

"The modules produce 276 W of electric power at the beginning of life and, despite decay of the isotope, will produce approximately 216 W after 11 years of unattended operation. Current research is focused mostly on the miniaturization of RTGs for many applications, such as MEMS; in addition, efforts to improve the efficiency of existing RTGs are ongoing."

B3. CONCLUDING REMARKS B

Many applications, (including pumps, motors, and actuators) can be improved by onboard power supplies, and current research is dedicated to improve existing technologies. No alternative energy source can match radioisotope power for long, unattended operation, due to the larger energy density available with nuclear sources.

Future research is required to optimize nuclear systems, but as an energy source, nuclear fuel will definitely compete when it comes to miniaturization. The only possible hindrances as far as size would go, would be the shielding required for a human in close contact with the power generation cycle.

C1. ENERGY STORAGE & MINIATURIZATION

Once again we will refer to the figure used earlier as shown in **Figure 1** below:

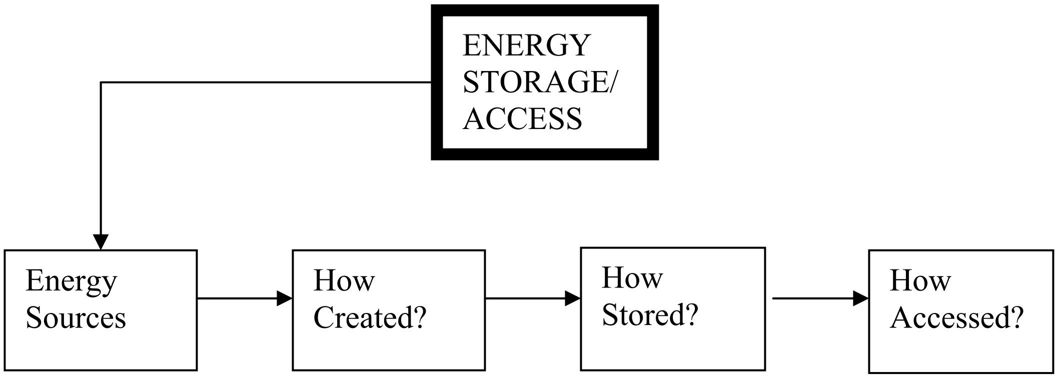


Figure 1: An Energy Storage Block Diagram

C2.1 Mechanical Energy

Flywheels

A flywheel is a circular disc that rotates to convert energy from it’s inertia to useful energy for storage i.e. energy is stored by the rotating mass. From basic physics:

- $W = \frac{1}{2} I \omega^2$ where W = Amount of energy in system

I = Moment of inertia of flywheel
ω = Angular velocity of flywheel.

→ The faster the mass spins, the higher the energy stored, and

→ As the moment of inertia is proportional to the mass of the flywheel, as the mass increases, likewise does the amount of kinetic energy stored.

Flywheels have been around for a long time, and have found use in windmills and steamboats in the past. A flywheel can be designed to either release a small amount of energy over a long period or a large amount of energy in a very short period - steel flywheels can produce up to 1650 kW of power which is released for a few seconds.**[14]** The latter used to dominate early flywheel technology applications, and only recently has progress been made into the development of longer lasting flywheels. These developments have come through material science and bearing technology – it is the material properties of a flywheel that determine the maximum energy that can be stored.

Figure 7 shows a cross-section of a modern flywheel. Fibre composites are generally used as they have tensile strengths higher than steel and much lower mass densities.

There is a problem with size though – as the miniaturization of a flywheel would require a huge angular velocity (and dense material) to store any useful energy.

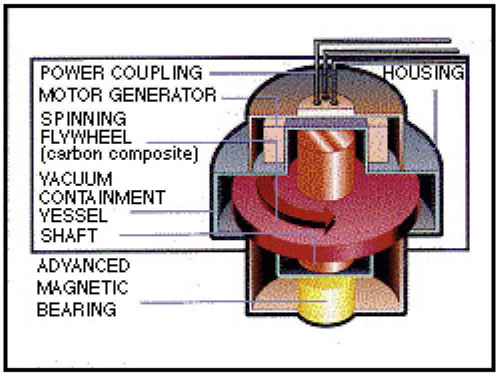


Figure 7: A Cross-Section of a Modern Flywheel [14]

Even more problematic is that flywheels generally run in air. There are appreciable aerodynamic frictional energy losses that would be huge when the system is considered in water (unless of course the flywheel is isolated from the water in a container)…

"At the moment a 'consumer-size' flywheel costs about $10,000 and spins at 50,000 rpm. The flywheel is about the size of a cabinet and occupies about a square metre of floor space."**[14]** Research is ongoing into smaller flywheels, even portable devices, although there are many practical problems, some of which have already been highlighted.

The biggest factor that will affect a flywheels miniaturization though is the input energy source it requires to start or keep spinning. Either the power coupling (see **Figure 7**) would have to be attached to the submarine, and extend as the mobile unit moves away, or the power source would have to be with the flywheel – adding to the bulk of the system.

Flywheels are being looked at for backup purposes these days, for example in power cuts they would supply the surge in energy required for a short period of time. Therefore I think their practical application in a mobile underwater unit is severely limited.

Compressed Air Energy Storage

This is mainly used on a large scale using big underground caverns under high pressure. Air is pumped into them and kept there for peak use. The high pressure of the compressed gas drives turbines to generate power when needed.

The compressed air will lose less energy if it is burnt together in a mixture with natural gas, thus increasing the efficiency.

The smaller-scale approach to compressed air storage uses fabricated high-pressure vessels. The tensile strength of the tank walls and characteristics of the valve determine the ability of a vessel to store fluids at high pressure.

Fluids stored in a tank under pressure can either be:

- Released through a valve creating a direct thrust that can propel something e.g. a turbine on a generator, or
- Mixed with something else that causes a heat-producing chemical reaction (that might then create steam that drives a turbine).

As the latter deals with a chemical reaction it shall be dealt with in the next installment of this report.

Obviously, the more gas you have, the more fuel you have, hence the more energy you have stored and so miniaturization will always reduce the potential storage amount. From the Ideal Gas equation:

$pV = nRT$ where p = pressure
V = volume
→ $V = (nRT)/p$
n = number of moles
R = gas constant **[3]**

So;

- An increase in pressure,
- A decrease in temperature, and
- A gas with a low gas constant

are required to optimize the miniaturization of a high-pressure tank.

The first point depends on the strength of the tank walls as mentioned above. The second point is helped by the fact that the water deep below the surface is very cold. Then the third point will depend on the gas you choose.

The amount of energy stored in a fixed volume of gas at fixed temperature is therefore dependent only on the pressure that the walls of the container can withstand.

For example, “high pressure cylinder oxygen is regulated to 50 psi (345 kPa) before passing through the flow control valve and outlet fitting”.**[15]**

Although the pressure is high, the amount of gas in a small volume (i.e. miniaturization) would not be enough to directly propel a mobile underwater unit for a long time. Gas cylinders could be used however for short bursts every now and then to take sharp turns when necessary.

Pumped Hydro Storage

This is a method of energy storage that is designed to be on a large-scale basis, and so miniaturization of the concept will prove difficult. The system consists of two reservoirs, one at a higher elevation than the other, connected by high-pressure shafts that water drops down through. The water passing through turbines generates electricity. Factors that affect the amounts of energy storage are the ‘head’ (vertical distance that the water drops) and the flow rate, and so reducing the size of one of these systems seems to be counter-productive.

Deep underwater, a water ‘head’ would have to be created artificially by creating a waterless environment for it to flow into. This is hard to do, especially as the water will keep on trying to reach equilibrium with the unit.

All in all, I think that pumped hydro storage is not an option for future consideration based on miniaturization criteria.

Marine Current Turbines

Marine Current Turbines Ltd. is a company that has developed turbines that operate under the principle of ‘submerged windmills’. When installed, they intend to utilize the energy that huge volumes of flowing seawater possess in their currents. They will therefore be positioned where the tidal currents are high. **Figure 8** shows an artists impression of a row of tidal current turbines.

The advantage of these flows is that they are more consistent than those of say wind flows, which are more random in both direction and strength and are generally harder to predict patterns in.

MCT’s technology is basically described by:

- Twin axial flow rotors → 15-20m diameter

- Each drives a generator via a gearbox.
- The twin power units of each system are mounted on wing-like extensions either side of a tubular steel monopole
- The monopole is about 3m in diameter and is set into a hole drilled into the seabed from a jack-up barge. **[16]**

Figure 8: Artist's Impression of a Row of Tidal Current Turbines [16]

The world's first offshore tidal current turbine was installed by MCT Ltd. in June 2003 just north of Devon in England. "It has a rated power of 300kW – enough to meet the electricity needs of about 200 typical UK households."**[16]**

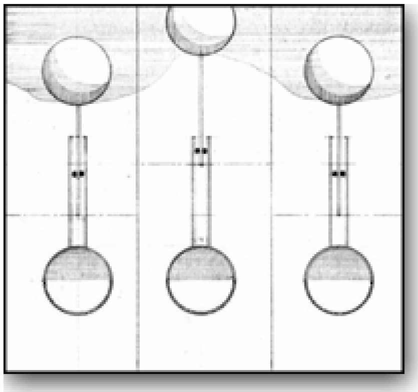
Obviously, for mobility, a smaller rotor would be needed to power an underwater unit – countering the large area that was used to 'collect' the tidal current, and the actual mobility of the unit itself may cause some disruption to the reliability of it as an energy source.

Ocean Wave Energy Converter (OWEC)

A rather novel way of generating useful energy from the sea has been developed by the Ocean Wave Energy Company (OWECO). They utilize the movement of a buoy on the hydroface (sea level) connected to a buoy suspended underwater (see **Figure 9a**). "Reciprocation occurs with the rod inside the tube as a result of ocean wave troughing and cresting".**[17]** Unfortunately horizontal motion of the waves on the hydroface push the floating buoy away so that it cannot return to the vertical position in which it started.

The resulting configuration was that resembling a cone. **Figure 9b** shows a diagram of an interconnected OWEC module array.

This technology, although neat in the way it harmonizes with nature, requires a network of buoys to be floating on the surface above you as you move, and so is just not feasible as a military option.



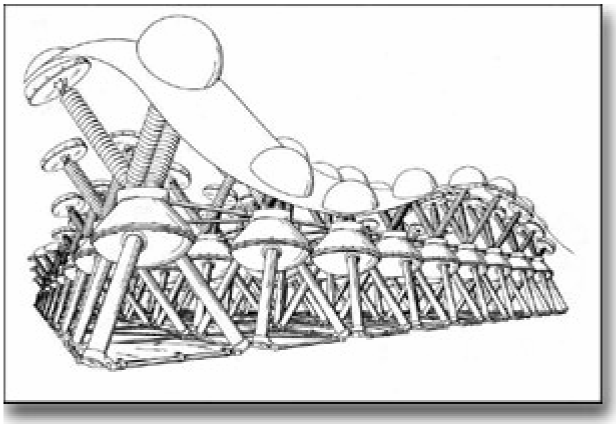
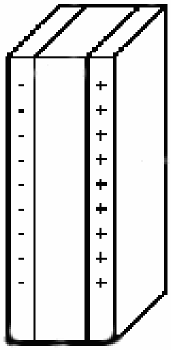


Figure 9a: Schematic of Physics Behind Ocean Wave Energy Converter (OWEC)
Figure 9b: Diagram of an Interconnected OWEC Module Array [17]

C2.2 Electrical Energy

Capacitors



- Two outer metal electrodes
- Dielectric material sandwiched in middle
- Distance between electrodes is **d**.
- Area of metal electrode is **A**.
- Voltage applied over metal electrodes

Figure 10: Schematic Diagram and Description of a Capacitor

A capacitor consists of two outer parallel plates separated by a dielectric insulator. The plates hold opposite charges, which generates an electric field. Capacitors store energy in this field by the accumulation of charge.

Capacitance is defined as: $C = q/V_c$ where q = charge
V_c = voltage across capacitor

→ $V_c = q/C$

As voltage is defined as the energy per charge unit;

→ $dW_c = (1/C)\, q\, dq$ where W_c = energy stored

→ $W_c = \frac{1}{2} (q^2/C)$

→ $\underline{\mathbf{W_c = \frac{1}{2} CV^2}}$

So, increasing the capacitance and the voltage drop across the capacitor are both ways of increasing the amount of energy that can be stored. The voltage is limited to a maximum where the dielectric breaks down and starts to conduct (known as the energy field strength, E_b). Materials with higher dielectric constants can be used to increase the capacitance. A normal capacitor has an specific energy of approximately 0.5 Wh/kg – this is low when compared to lead-acid cell batteries that typically have an specific energy of about 22 Wh/kg.

Supercapacitors

"A supercapacitor is basically a capacitor which is able to hold significantly more charge using thin film polymers for the dielectric layer." **[14]** The electrodes of a supercapacitor are made of carbon nanotubes that give the polymer small spaces to sit in the tube acting like a dielectric, due to their nanoporosity properties. The dielectric polyethylene terephthalate (PET) has a good dielectric constant, and an specific energy of about 1.86 Wh/kg (nearly four times that of a normal capacitor).

Overall, supercapacitors are bulkier and heavier than the equivalent battery, but exceed a battery's lifetime as they can be charged and uncharged an unlimited amount of times. As far as miniaturization is concerned, this isn't good, but if a quick boost of power is needed then they are another alternative to the battery.

Magnetic Energy Storage

When a constant voltage is applied across an electromagnet, the energy flow into the magnetic system varies with time. The magnetic field is generated by the current flowing through a coil wrapped around the magnet as it cuts through the lines of flux. Part of this energy is dissipated as heat due to the resistance of the wire to current flow, and part of it is the energy content of the magnetic field which can be built up and released again as an electric current in an outer circuit. **Figure 11** shows a copy of the magnetic circuit.

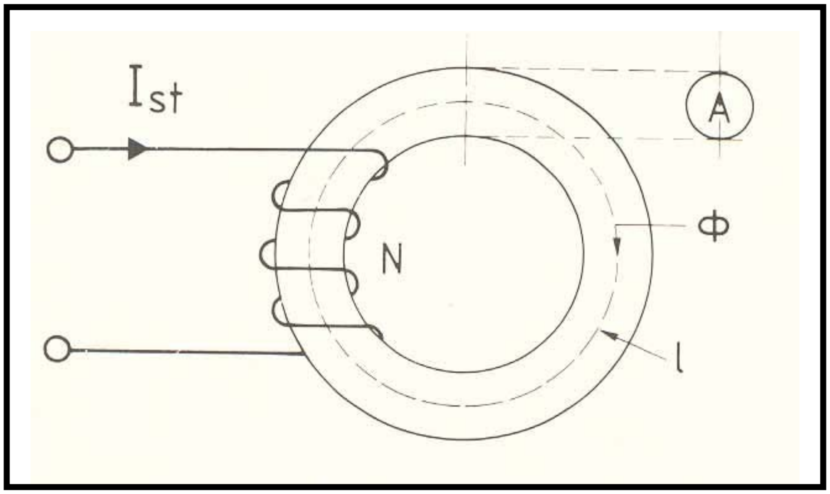


Figure 11: The Magnetic Field Circuit [3]

The amount of stored energy a magnetic field holds can be determined by the magnetomotive force (θ), which is the product of the stable current (I_{st}) and the number of coils of the magnet (N). Relating to **Figure 11**,

$\theta = \phi.R$ where ϕ = Magnetic flux
R = Magnetic resistance
and $\phi = B.A$ (for const. B) B = Strength of magnetic field (induction)
A = Area of magnetic field
and $R = 1/(\mu.A) = N^2/L$ L = Length of magnetic field
μ = Material permeability constant.

→ $\theta = (B.A.\ N^2)/L$ [and $I_{st} = (B.A.\ N)/L$]

It is actually the flux though that enables the higher energy content for higher values of itself.

Rearranging the above equations:

→ $\phi = \theta\ /R = (I_{st}.N.\mu.A)/L$ (1)

It can therefore be seen that very low values of resistance and very high values of permeability are required for a conducting material. Modern ferromagnetic alloys have very high μ.

Superconducting Magnetic Energy Storage (SMES)

When the wire around the coil is of a superconducting nature (i.e. no resistance), the energy can be stored virtually indefinitely until required. All conductors have a critical temperature, T_c, below which they have zero resistance. The discovery of superconductivity began in 1911 when it was found that mercury had zero resistance below 4.2K. Since the 1980's research into superconductivity has thrived, and the quest for a room-temperature superconductor is ongoing. At present, the "superconductor with the highest critical temperature ever recorded is Mercury Barium Thallium Copper Oxide or $Hg_{0.2}Tl_{0.8}Ca_2Cu_3O$, which has a critical temperature of 139 K (-124°C) at one atmosphere."**[18]**

The temperature of seawater deep down does not reach anywhere near this cold, in fact, in areas like the Mariana Trench (deepest ocean trench) the water temperature ranges from 1-4°C (274-277K). So a refrigeration unit would still be required to keep the superconductor cool enough.

The high current density of superconductors allows a unit to be a lot more compact, and as such, SMES have only operated on a relatively small scale so far. So the actual superconductors themselves are not a problem when it comes to miniaturization (example sizes and facts of a superconductor can be found at: http://www.roithner-laser.com/All_Datasheets/Superconductors/super_YBCO-disks.pdf), but it is the methods required to keep them cool that are.

Efficiency wise, SMES have a greater than 97% efficiency at storing electricity, and more importantly can store energy at a lower power level for later discharge at a higher level. Current sizes of refrigeration units start at about 0.5m x 0.25m.

C2. CONCLUDING REMARKS C

Both mechanical and electrical energy were dealt with together here, as I was not expecting anything to jump out as a definite cert for miniaturization.

There are numerous practical problems with flywheels and pumped hydro storage, as they simply aren't designed to operate deep underwater. Their uses in this project I feel are severely limited.

Compressed air storage, marine turbines and the ocean wave energy converter are all meant to be large-scale processes for optimum power output, and miniaturization will cause problems in loss of efficiency. High-pressure tanks will probably be more effective for chemically reacting processes, rather than a fixed amount of direct thrust.

The electrical world was the pioneer of miniaturization, and so components like capacitors and magnetic circuits started out small. Unfortunately though, the energy density when compared to batteries is still unfavorable, and I can only see uses for them when short bursts of power are needed, rather than a sustained energy source.

D1. ENERGY STORAGE & MINIATURIZATION

Once again we will refer to the figure used earlier as shown in **Figure 1** below:

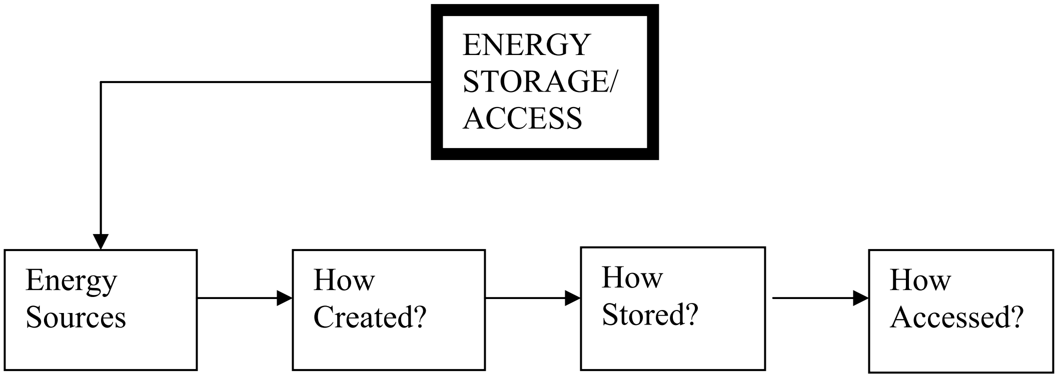


Figure 1: Energy Storage Block Diagram

D1.1 Chemical Energy

The final energy source group under consideration is probably also the most researched. It is thought that chemical energy sources are the way forward for compact, yet energetically dense solutions to some of the world's problems. But technological advances are not fast in all the chemical energy fields. The big areas of interest in chemical energy storage shall be considered below, starting with the most obvious – batteries.

D1.1.1 Batteries

The word 'battery' in the dictionary is described as being 'a device that produces electricity' **[19]**, but more succinctly, it is an *energy converter* – from chemically stored energy to electrical energy.

Alessandro Volta is credited with the creation of the world's first ever battery, produced in 1800. It consisted of alternating layers of zinc, silver, and blotting paper soaked in salt water. **Figure 12** shows a diagram of this battery:

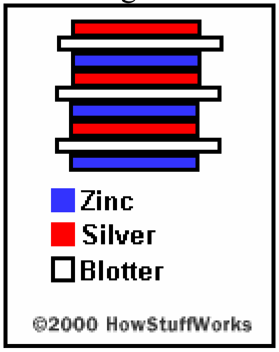


Figure 12: Arrangement of Volta's Battery – Known as a Voltaic Pile [20]

Batteries come under the category of electrochemical reactions – chemical reactions that produce electrons. Another energy process that falls under this category is fuel cells and these shall be dealt with later. Electrons, being negative, are attracted to positive poles and so flow towards these in a reaction – but the reaction only occurs if the circuit is complete, hence why batteries can be left on the shelf for a long time. It is the flow of electrons that 'creates' useful electrical energy that is utilized in circuits and/or motors.

The battery's internal resistance decides the speed of electron production by the chemical reaction and thus how many electrons flow between the two terminals. Chemical reactions are different for different metals and electrolytes used, and each combination has its own characteristic voltage, which it controls.

Batteries can generally be split into two types – primary and secondary. When the active chemicals in the battery have been used up, primary batteries cannot be recharged i.e. their only useful cycle of reactions is their primary one. Secondary batteries can be recharged and are the focus of today's technological advances.

Obviously, the bigger your electrodes or electrolyte, the more electrons that will be flowing and hence the greater the electric potential between the two electrodes. It is this difference in electric potential that is known as the electromotive force of the batteries, which is related to the energy density. So the more cells you have, the greater the potential, and the greater the energy storage possible. “Battery capacity is directly proportional to the area and thickness of the thin-film (anode-electrolyte-cathode) layers that form it”.**[21]** Over the years, the battery industry hasn’t progressed very far, and as **Table 1** shows, even the best of today’s batteries are nowhere near as energetically dense as gasoline.

BATTERY TYPE	***SPECIFIC POWER*** *(W-hr/kg)*	***SPECIFIC ENERGY*** *(J/kg)*
Lead-acid	22	79,200
Nickel-cadmium (Ni-Cd)	44	158,400
Silver-Zinc (Ag-Zn)	110	396,000
Sodium-sulfur (Na-S)	220	792,000
Lithium-Sulfur (Li-S)	220	792,000
Iron-titanium hydride (Fe-Ti-H)	590	2,124,000
Magnesium hydride with Ni catalyst (Mg-H (Ni))	2300	8,280,000
Gasoline (for comparison)	13200	47,500,000

Table 1: Specific Energy for Various Battery Types [22]

Flexible Batteries:

The Mitsubishi Materials Corp. have developed what they call flexible batteries. One of their aims was to develop a “tape-like flexible shaped battery that (could) be pasted to or wound around the inside or outside of the wall of a micromachine”. **Figure 13** shows a schematic and a real image of this battery.

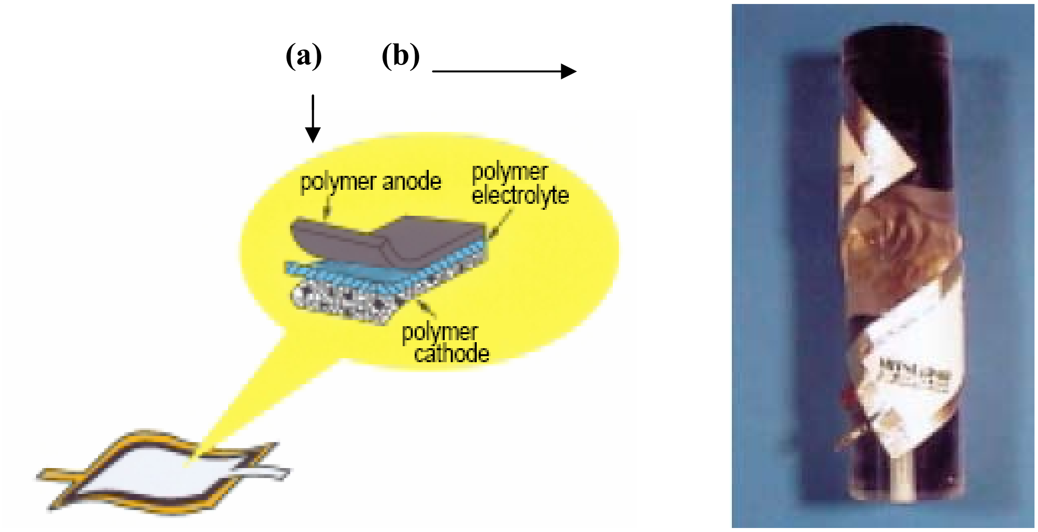


Figure 13: (a) Schematic of flexible shaped battery concept (b) Flexible shaped battery folded round a tube [23]

The prototype shown in **Figure 13(b)** uses flexible polymer materials for the electrodes and the electrolyte (it's a lithium electrochemical system). The battery is 14 cm long, 2 cm wide, and 0.5 mm thick and is shown wound around a 2-cm-radius cylinder, in action.

A battery with such flexibility could find huge uses in military equipment – if the specific energy could be made right. If the entire lining of a vehicle could be pasted with a battery 'strip', then it could lead to huge space reductions in design. Unfortunately, there is no current data on the specific energy of these flexible batteries at present.

D1.1.2 Fuels and Synthetic Fuels

Fuels:

Oil, coal and natural gas are the big three energy resources that the world at present relies on. And while the emphasis these days is on renewable sources of energy, it is foolish to overlook them as possible sources for our underwater unit.

Useful work is generated from them pretty much the same way – burning them to produce heat.

→ *Oil* – Oil is a mixture of long chain (complex) hydrocarbons (hydrogen and carbon atom only compounds) that undergo the process of cracking to produce useful compounds. One of these useful products is petroleum oil (or gasoline), and is what the majority of the world uses to power the car engines in today's world. As **Table 1** shows, the specific energy of gasoline is good (**47.5 MJ/kg**), but as the utilization of this energy is through burning it, miniaturization could be a problem. The burning of any fuel needs to be controlled, and the waste products dealt with accordingly, so already we are looking at a device that can burn oil under control and filter the waste products out – which is now looking slightly bigger than the battery concept.

→ Natural Gas – Natural gas is also a mixture of hydrocarbons, predominantly methane, with some ethane, propane, butane and pentane. The initial specific energy of natural gas is low, which is why it is used in its compressed or liquefied form. "When stored at a pressure of 3,600 psi, Compressed Natural Gas (CNG) provides about one-fourth the specific energy of gasoline (approximately **12 MJ/kg**)".**[24]** Sturdy, heavy tanks are used for safe high-pressure storage, and so any miniaturization is going to battle against this factor (as well as other factors like leakage, waste products etc.).

→ Coal – Coal is not a hydrocarbon, as it contains some oxygen, nitrogen and sulfur. The typical chemical formula for coal is $C_{135}H_{96}O_9NS$. "Coal has a relatively high specific energy of approximately **24 MJ/kg**" **[25]**. This is about half that of gasoline. Because of the impurities in coal, pollutants are formed in the waste products upon burning it.

Overall, the fossil fuels are very energetically dense per unit mass, much more so than batteries (350 kg of batteries is equivalent to 1 kg of gasoline **[26]**), but combustion of them is not simple (in fact the machines are quite bulky) and there are waste products that have to be dealt with.

More notably, as the unit is underwater, a separate supply of oxygen would have to be used to allow combustion to take place – again with this adding to the bulk size of the unit.

Synthetic Fuels:

Synthetic fuels are substitutes for fossil fuels that are manufactured out of coal or biological waste. They include syncrude (synthetic crude oil) and some of the alcohols (methanol, ethanol etc.). Methanol has about half the volumetric energy density of petrol. There are similar problems (to fossil fuels) in the miniaturization of systems that use synthetic fuels.

D1.1.3 Hydrogen

Hydrogen is the Universe's most abundant element, but it is found mainly in water on Earth. When water undergoes electrolysis hydrogen can be separated from oxygen, in a process that is about 67% efficient **[27]**. There are several other methods of producing hydrogen, which include:

- Catalytic steam reforming of natural gas;
- Partial oxidation of heavy oils;
- Water gas reaction i.e. chemical reduction by means of coal;
- Biochemical i.e. industrial photosynthesis;
- Ultraviolet radiation;

- Thermal decomposition of water, utilizing thermochemcial cycles. **[3]**

No pollution is released when hydrogen is combusted back into water in a closed chemical cycle.

There are two ways an underwater unit could use hydrogen as an energy source:
(1) – By giving energy to the sea water to split it, and filtering out the pure hydrogen for use as a fuel *(this takes as much energy to split as it harnesses).*
(2) – By taking reserves of hydrogen onboard to use in a chemical reaction that produces water.

Hydrogen has an energy content of about **135-140 MJ/kg** – 3 times as much as gasoline. As a liquid, hydrogen's energy content per unit volume is 1000 times higher, and so as a fuel would be used in it's liquefied form (at ≈ -253°C) unless produced from the seawater. A disadvantage of gaseous hydrogen is that it takes up a lot of space (3 times as much as natural gas), which again is counter-productive in the art of miniaturization. It is also explosive, which, if in close proximity to a combustion process could be dangerous.

As cryogenic hydrogen storage is energy intensive, the overall efficiency after useful work is produced is only about 25%. This percentage can be increased dramatically by running the hydrogen through a fuel cell.

D1.1.4 Fuel Cells

A fuel cell, like a battery, is an electrochemical energy conversion device, but the fuel store is external rather than internal. The first fuel-cell was around before the first battery, demonstrated by an English lawyer in 1839. **[28]** This original fuel cell was of the hydrogen-oxygen kind, where using a catalyst, hydrogen reacts with oxygen to produce water, electricity and heat. Experimental efficiency values of 85% have been achieved in the laboratory for hydrogen-oxygen fuel cells, and car manufacturers at present are working on prototype hydrogen powered cars. **Figure 14** shows two models that were presented at the North American International Auto Show in January 2003.

Figure 14: (a) The Toyota FINE-S **(b) The Ford Model U**

Toyota's FINE-S (Fuel Cell Innovative Emotion-Sport) is based on fuel cell technology and represents "what fuel cell cars will be like in the future" said Toyota president Fujio Cho. Unfortunately, no technical details "such as weight, range, mileage equivalents, fuel cell output or whether it uses compressed, liquid hydrogen or some other storage technology" **[29]**.

The most common type of fuel cell is the proton exchange membrane fuel cell **(PEMFC)**. **Figure 15** shows an exploded cross-section of a PEMFC.

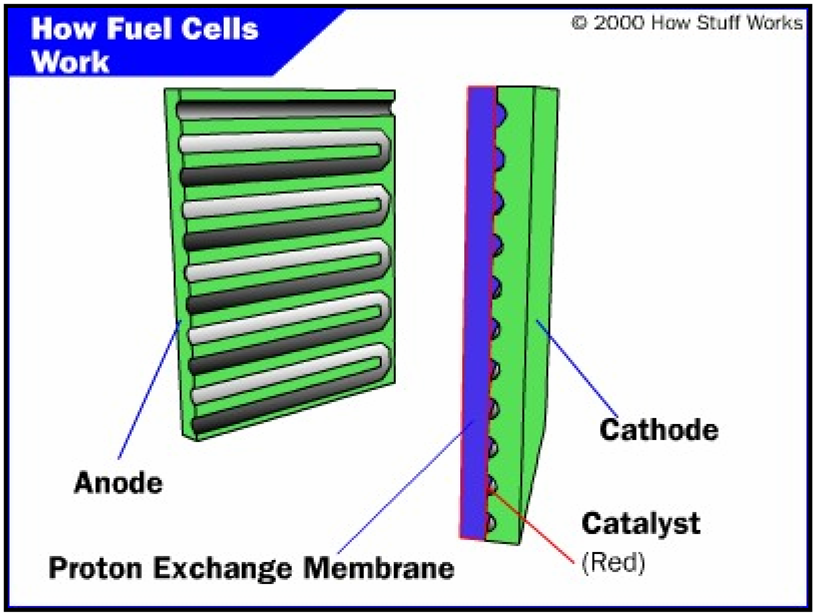


Figure 15: An Exploded Cross-Section of a PEMFC [28]

- The **proton exchange membrane** acts as the electrolyte. It only conducts positively charged ions while blocking electrons.

- The **catalyst** facilitates the hydrogen-oxygen reaction. It usually consists of thinly coated platinum powder on a thin carbon material. To maximize the surface area exposed to the reactants the catalyst is made rough and porous. The catalyst is marked as a red line in **Figure 15**.

Process:

Pressurized hydrogen gas enters the fuel cell at the anode. The pressure forces the gas through the catalyst where the H_2 molecules comes into contact with the platinum and split into two H^+ ions and two electrons (e^-). The anode conducts the electrons, which then travel through an external circuit and return to the cathode.

Simultaneously, at the cathode, oxygen gas (O_2) is forced through the catalyst, where it too splits and forms two oxygen atoms. Because each oxygen atom has a strong negative charge they attract the two H^+ ions through the membrane, and hence combine with two of the electrons from the external circuit to form a water molecule (H_2O).

The reaction in a single fuel cell produces only about 0.7 volts.**[28]** Many single fuel cells have to be connected to produce any reasonable level of power – this is known as a 'fuel-cell stack'.

Due to recent advances, a device 'about the size of a small piece of luggage' can power a car these days.**[28]**.

The equations below summarize the transport of electrons that occurs in the process:

- At the anode: $\mathbf{2H_2 \rightarrow 4H^+ + 4e^-}$
- At the cathode: $\mathbf{O_2 + 4H^+ + 4e^- \rightarrow 2H_2O}$

- Overall Reaction: $\mathbf{2H_2 + O_2 \rightarrow 2H_2O}$

As hydrogen is difficult to store and distribute, a device called a reformer is used to produce it from hydrocarbons or alcohol fuels, which is then fed to the fuel cell. The efficiency of the fuel cell is lowered though by impurities generated due to the non-ideal reformer.

Natural gas, propane and methanol are some of the popular fuels used with reformers. Steam is reacted with the fuel to produce firstly carbon monoxide and hydrogen. The carbon monoxide then reacts further with the water vapor to produce carbon dioxide and hydrogen.

Other types of fuel cell technologies being developed include:

- Alkaline fuel cell (AFC)
- Solid oxide fuel cell (SOFC)
- Phosphoric-acid fuel cell (PAFC)
- Molten carbonate fuel cell (MCFC)

D2. CONCLUDING REMARKS D

Chemical energy storage at present is recognized as the most promising form energy storage for the future. Batteries and gasoline have long dominated this field, with the idea of harnessing energy from a box to power our machines. But now, with the emergence of hydrogen as the 'ultimate fuel and energy storage medium'**[3]** technology is drifting towards high specific energy fuels capable of powering equipment longer, and cleaner in the process.

Hydrogen has three times the energy content of gasoline, and with so much of it around us (especially in the sea), it would be frustrating to think that it could not be utilized. There is even a company (Powerball Technologies) that wants to use little plastic balls full of sodium hydride, which produce hydrogen when opened and dropped into water. The byproduct of this reaction, liquid sodium hydroxide, is a commonly used industrial chemical **[30]**.

It is energy *density* that hydrogen suffers with, as it is the lightest of the elements and so is has poor respective value.

Combining hydrogen and fuel-cell technology is clearly a positive step towards greater energy densities, although the acquisition of hydrogen from seawater is an unlikely scenario, as it takes about as much energy to split the water as the final hydrogen product can produce.

A possible solution would be a *fuel-cell stack with a reformer*.

E1. NOISE & EXHAUST CONTROL

E1.1 The Concept of Underwater Noise

"Noise is the *unwanted* sound that *interferes* with the normal functioning of a system" **[1]**. The field of underwater noise is really only of concern to one area of modern-day life – the military. The effectiveness of the military's naval systems is threatened by sound in water as the bigger a signal you give off, the quicker you are detected. As such, there are two research areas ongoing in the field:

- Noise reduction, or *noise control,*
- Noise detection, or noise amplification.

So, the relative degree of seriousness of noise is more to do with the amount of interference it has with other systems as opposed to the decibel level. For our mobile unit, not much is known about other systems or levels of noise allowed, but it is safe to say that the lower these levels, the better for the system.

There are several types of noise, and most of this is associated with moving parts found in *Power Generation*/*Distribution*. By the Second Law of Thermodynamics, no useful mechanical process can take place without generating some heat – and by consequence also some vibration and thus some noise – so noise is unavoidable. But it can be controlled.

Table 2 shows the definitions of the types of underwater noise according to the American Standards Association.

The amount of sound power that a mechanism radiates varies depending on the mechanism and the medium within which it operates. Power levels in water are generally a lot lower – a ‘modern’ (1970’s) submarine moving slowly in water produces about 10mW acoustic power, whereas surface ships radiate from 5-100W. But the low *levels* of noise radiated by these systems do not mean that they cannot be detected. Just 1W of acoustic power can be detected long-range by passive sonar underwater, whereas the same power in air would carry for only a fraction of the same distance. This is because low power levels are associated with high acoustic pressures and it is pressures that systems respond to.

Water, although most of the time treated as incompressible, is actually slightly to the contrary – after all, ‘it is the compressibility of a medium that makes sound possible’.**[31]**

The process of noise-production can be split into three parts:

- the generation of vibratory motion
- the transmission of this vibration to a radiating surface
- the radiation of sound into the medium.

Noise Type	***Description***
Radiated Noise	Noise radiated into the water that can be used by a passive listening sonar to detect the presence of a vehicle at a considerable distance
Ambient Noise	All noises associated with the medium in which a sonar operates that would exist in the medium if the sonar platform or vehicle itself were not present
	Noise measured by a single, omnidirectional, platform-mounted hydrophone

Platform Noise	in the presence of an operational platform. Conceptually, platform noise should be simply noise attributable to the presence of the platform, but actual measurements of platform noise invariably include the contribution of ambient ocean noise
Sonar Self-Noise	Noise associated with a platform and its sonar hydrophones and pre-amplifiers, as measured through the sonar hydrophone array
Sonar Background Noise	All noise at the output of a sonar array that limits the detection of signals by a signal processor. Sonar background noise includes the contribution of the medium as well as platform noise and any noises contributed by hydrophones, cables, or pre-amplifiers.

Table 2: Definitions of the Types of Underwater Noise [31]

It is the radiation term that is controlled by the Mach number, hence why it differs so much between air and water.

E1.2 Energy Conversion Exhausts

Much like noise, the exhaust of a system is usually unwanted, but very necessary to allow it to continue functioning properly. An exhaust is the expulsion of waste products from a system, and it is often this that contributes a lot of the noise produced by the system. But an exhaust is more than noise; it is also visible and of substance. Therefore an exhaust causes a disturbance by both sound and sight.

As we want as much energy from a source as possible, we hope for little or no exhaust on accessing it. We anticipate that most will come from the power generation stage, and sometimes none will occur at all.

Therefore the topic of exhaust (minimum bubbles etc.) shall be dealt with in the ***Power Generation*** installments.

E2. ENERGY STORAGE & NOISE CONTROL

While underwater units will no doubt produce some noise, most of it will result from the power generation and distribution phases. As this first part of the project deals with energy *storage* it is inherent that the fraction of the systems noise that it will contribute will be small. However, each method of energy storage previously discussed will be considered regardless of this, unless stated where appropriate.

The best way to assess noise control methods required for this project is to first look at a set of established noise control techniques and apply them to each part of **Figure 1** for each energy source so far discussed.

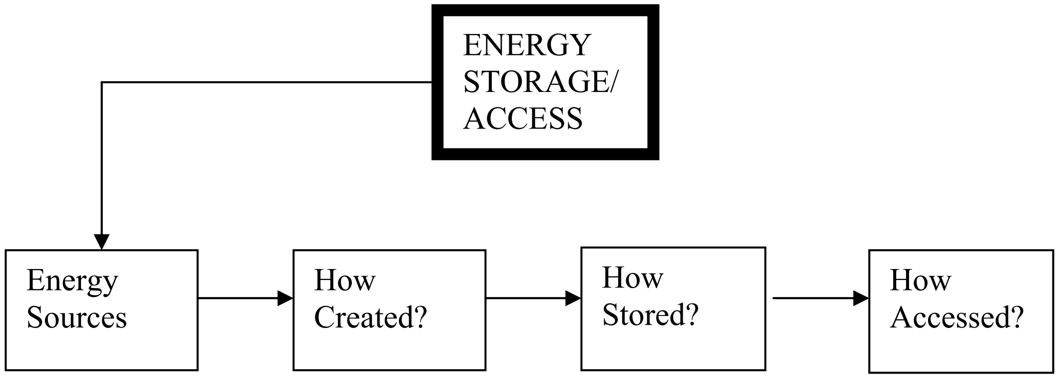


Figure 1: Energy Storage Block Diagram

E2.1 Nuclear Noise

'Nuclear noise' is caused by gamma ray disturbances. Gamma rays have the highest energy and shortest wavelength of all the electromagnetic radiations.**[32]** A radioactive isotope is continuously decaying and giving off gamma rays; it is only the rate at which they are ejected that changes. Nuclear submarines have to give shielding to this gamma ray ejection for two reasons: **1)** it is harmful to human health, **2)** if allowed to radiate far enough they could be detected by an enemy.

Due to the high energy density of gamma rays (the highest in the electromagnetic spectrum), they do not stop for long distances i.e. until all of their energy has been spent. Similar shielding would be required for a mobile underwater unit to protect the operators and reduce the emitted nuclear noise. Unfortunately though this extra weight (often lead products) adds to the problem of miniaturization, as well as that of trying to not sink.

Existing Examples:

All of the nuclear energy examples in *Intermediate Report #2* would suffer from nuclear noise, as the decay of the isotope is unavoidable. The **atomic battery** uses direct energy conversion (using electrons) to produce electrical energy and **micro electro mechanical systems (MEMS)** use radioactive thermal generators to convert the heat produced in the reaction to electricity (see **Electrical Noise**). No information was available on the **Plasma Volt Power Cell** at the time of research (11/13/03).

E2.2 Mechanical Noise

Moving parts probably contribute the most noise out of any of the parts of a system. Whether it is actual moving gears or rushing air through ducts, both the design and materials used are factors in the amount of noise produced.

DUCTS:

Obstructions:

Ducts without obstruction produce the least amount of noise from turbulence "During flow in ducts or pipes there is always some turbulence against the duct walls. The noise from turbulence is increased if the flow must rapidly change direction, if the flow moves at a fast rate, and if objects blocking the flow are close together".**[33]** Connecting strip flanges in long pipes and sharp bends can cause turbulence. An example of this can be seen under **E2.5**.

Exit Noise:

Noise is produced when a flowing gas mixes with a non-flowing gas, especially if it is a disturbed flow as it hits the outlet. The speed of flow is also a factor; the lower the outlet speed the lower the sound level. **Figure 16** shows this principle:

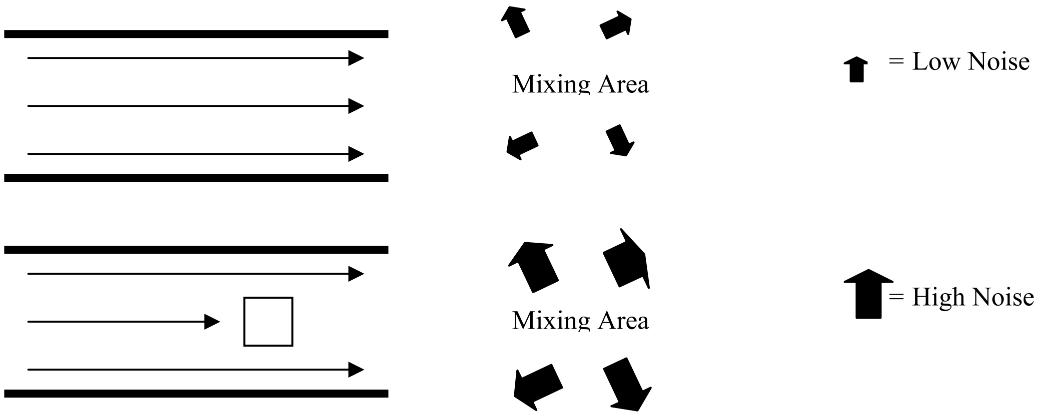


Figure 16: Exit Noise for Undisturbed and Disturbed Flows

For high speed flows, exit air streams slower than the bulk flow can be used to reduce the exit speed relative to the surrounding medium, and hence the exit noise.

Examples of these can also be seen under **E2.5**.

CAVITATION:

When the pressure of a liquid drops rapidly turbulence forms – such is the case in a rapid change of volume, like from an exit pipe into the sea. In this process bubbles of gas form and produce a roaring noise, known as cavitation noise. This noise can be avoided by a slow rate of change of volume i.e. tapered outwards (a diffuser) or staggered exits pipes help reduce cavitation noise (see **Figure 17 (a)** and **(b)**).

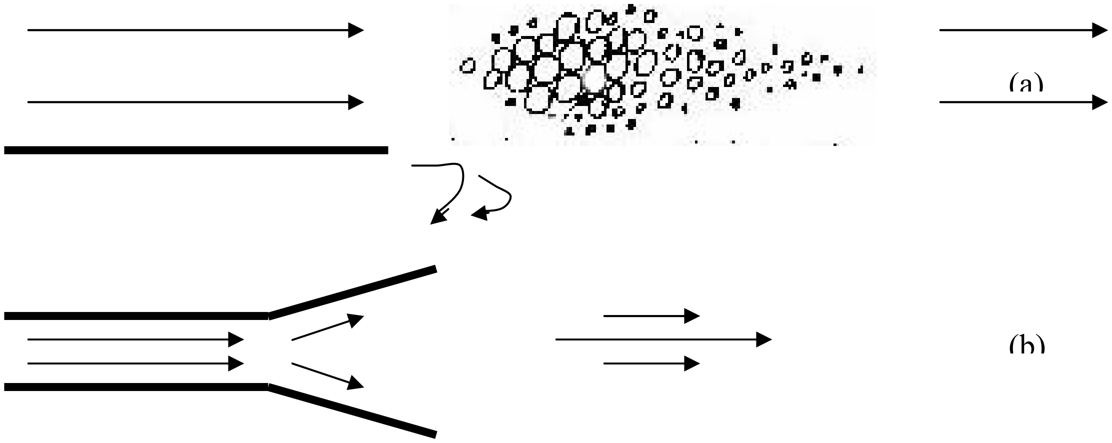


Figure 17: Example of Cavitation (a) and Possible Reduction Method (b)

Existing Examples:

For the impractical **flywheel**, wind tones but be created if allowed to run in a sealed area, and huge pressures would build up. If it just ran in water then it risks vortices being generated causing problems for those operating it, and a clear signal to where you are for anyone looking for you. The drag would be so great on a flywheel in the water, that very low frequency sounds would be created that would travel many miles through the sea.

Compressed air used for direct thrust would exit from its high-pressure chamber through a small nozzle – this would cause high frequency sounds (which, though quite loud to those in the vicinity would die away in the water quite quickly as they dispersed), but also cavitation from the rapid change in pressure and volume.

Pumped hydro storage is just not feasible underwater and the **marine current turbines** would suffer similar cavitation problems (see ***Power Generation***).

E2.3 Electrical Noise

Electrical noise is also known as the electromagnetic interference (EMI) of a system. ‘It is unwanted electrical signals that produce undesirable effects and otherwise disrupt the control system circuits’**[34]**. This noise is silent to the human ear, and only detectable by other circuits. Because this noise is due to how good the design of the circuit is though, it won’t be dealt with in this report as it is assumed that the military will have the best in circuit designers.

As far as sound is concerned, electrical circuits when compared with the other types of energy storage systems are known as *silent sources*.

Existing Examples:

All of the earlier covered examples will be virtually silent. A sound often associated with electrical circuits though is a transformer hum, due to an effect known as 'lamination rattle'. “'Lam' rattle occurs in all transformers to some degree, that degree being related to the quality of the transformer and the quality of the line voltage.”**[35]**

E2.4 Chemical Noise

Chemical reactions provide us with varying amounts of noise, depending on the quantities and type of chemicals used. They range from silent to roaring explosions.

Existing Examples:

Batteries are at the silent end of this reaction sound scale, and so no or little special treatment is given to the reduction in their operation noise. **Fuel cells** are similarly very quiet, due to the similarities in operation (except the fuel store is external).

The noisiest of the chemical reactions are those that are in full force today – **fossil fuels and synthetic fuels** that are used in the combustion process. The high pressures in the combustion chambers and the volatility of the fuel burning creates continuously loud explosions that average out to the rapid chugging sound that we are all familiar with.

E2.5 Basic Noise Control Techniques

Unfortunately ‘water is the best conductor of sound and sound can travel long distances underwater. Sound travels approximately 4 1/2 to 5 times faster in water than in air’ **[36]**.

A few of the ways to reduce sound in the energy storage part of the system are given below:

Duct Lining and Pipe Wrapping:

Figure 18 shows how a steam pipe system’s noise problem can be reduced.

→ Sharp bends produce turbulence and so are replaced by smooth ones.

→ The short distance between cut-off valves also causes turbulence and so this distance is lengthened.

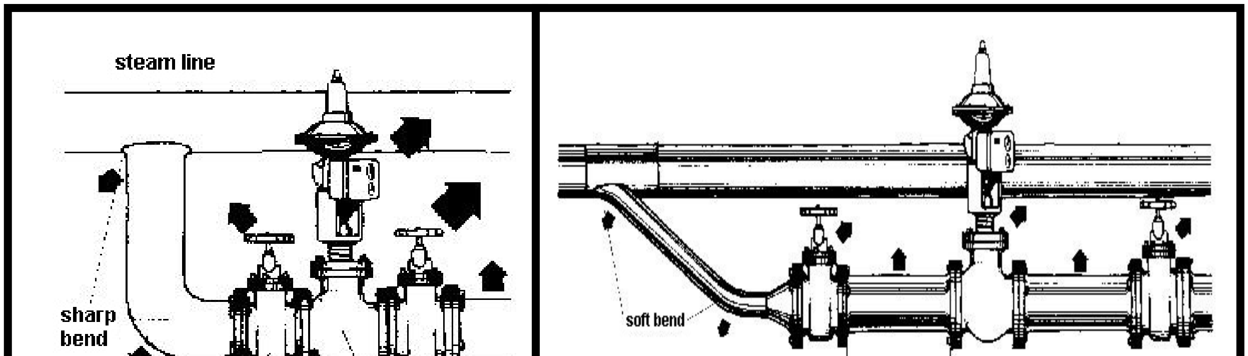


Figure 18: Noise Reduction for a Steam Line (a) before (b) after [33]

The lining of pipes and ducts with a sound absorbent material also reduces the exit noise of a flow.

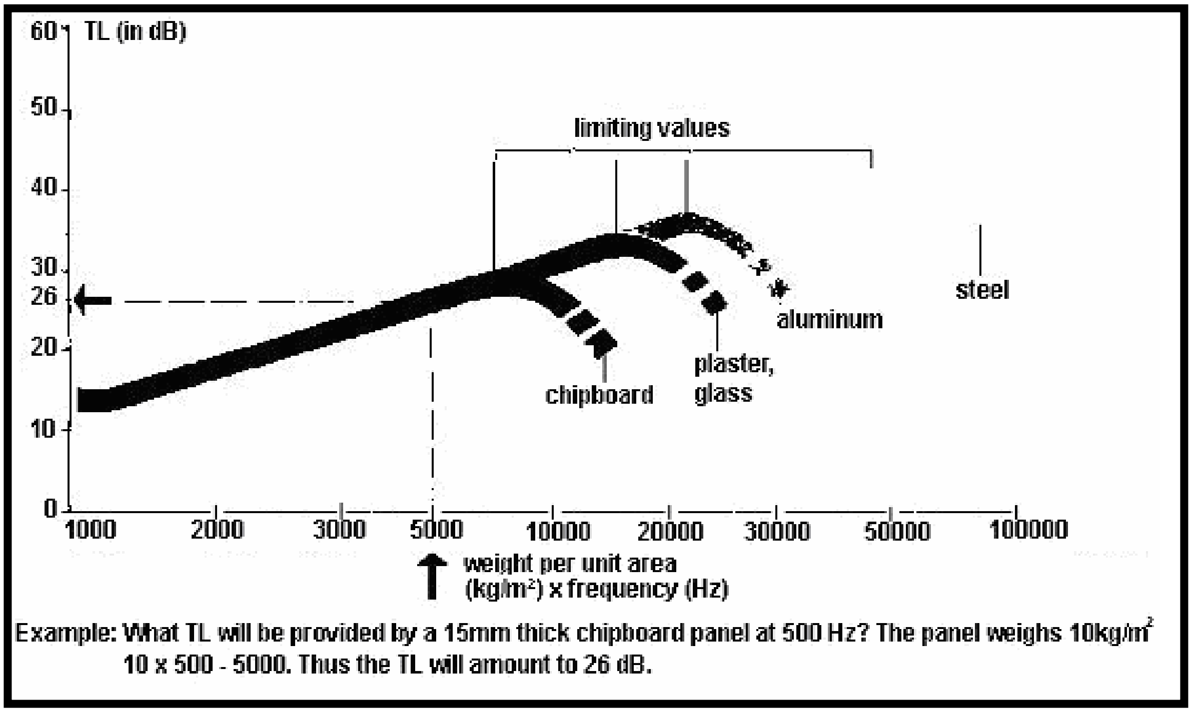
Silencers:

Sometimes known as mufflers, silencers can reduce noise actively or passively. They could consist of a series of plates with different perforations – this way the flow is blocked in certain directions, and channeled the way you want it – or a pipe with many holes that the flow travels parallel with or a combination of both.

Isolation & Absorption of Sound and Vibration:

“Transmission loss" (TL) indicates a wall's ability to absorb sound-producing vibrations. TL is expressed in decibels (dB). The TL of a homogeneous single layer wall can be estimated by its surface weight, that is, kg/m^2.”**[33]**

Figure 19 shows the transmission loss for different materials used to block sound.



Example: What TL will be provided by a 15mm thick chipboard panel at 500 Hz? The panel weighs 10kg/m^2
10 x 500 - 5000. Thus the TL will amount to 26 dB.

Figure 19: Transmission Loss for Different Materials

E3. CONCLUDING REMARKS E

There are many types of sounds that can occur from systems – but only the unwanted noise needs to be dealt with.

The covered examples tend to emit different types of noise, which can be dealt with in different ways.

Overall, electrical sources of energy seem to be the quietist, with volatile chemical sources being the loudest.

This noise can be reduced by absorption and re-design for smooth flow.

F1. NOTE ON MONOPROPELLANTS

F1.1 The Concept of a Monopropellant

According to an online dictionary, a monopropellant is “*a rocket propellant consisting of a single substance or mixture that contains both fuel and oxidizer*” **[37]**.

> *Engines that are based on monopropellants only need one fuel line - an oxidizer line would be redundant as the oxidizer is bound into the molecule itself. The "mono" implies that it can function (i.e. burn) by itself as opposed to bipropellants that require more than one chemical being mixed with another. Having fewer parts in the engine makes it lighter, less expensive, and more reliable. ‘Monopropellant designs are typically used in control thrusters but not in actual propulsion units’* ***[38]***.

‘A monopropellant may be a pure compound or a mixture of two or more substances which react under the conditions of the reaction chamber’ **[39]**. The development of monopropellants hasn’t yet exploded, and today's monopropellants are toxic and have low performance.

F1.2 Types of Monopropellants

Hydrazine:

Hydrazine is a family of compounds that are used in the rocket industry as monopropellants.

Compound	Chemical Formula
Hydrazine	N_2H_2
Monomethyl hydrazine(MMH)	CH_3NHNH_2
Unsymmetrical dimethyl hydrazine	CH_3NNH_2

(UDMH)	

Table 3: Different Types of Hydrazine [38]

When hydrazine is placed in contact with platinum group metal catalysts it spontaneously decomposes (or ignites). It is very popular because its properties save:

- Weight – Only one set of plumbing
- Space – No separate oxidizer
- Complexity – Both of the above.

So from this perspective, monopropellants are better than those that use a separate oxidizer as risk analysis shows they are less likely to encounter a problem.

A NASA scientist, Dale Reed recently designed the MiniSniffer™ - a small, remote-controlled vehicle powered by a unique hydrazine engine.

'Hydrazine blows itself apart in the presence of the right catalyst, a trait that has long made it a popular fuel for spacecraft thrusters. Reed's design used heat given off by this reaction to run a little steam engine; that engine in turn drove a propeller' **[40]**.

Hydrogen Peroxide:

Hydrogen peroxide is an alternative monopropellant used in the engine industry. It does not quite have the same potential specific energy as hydrazine or gasoline, but is a lot easier to store than hydrazine, as it is non-toxic. **Table 4** shows a comparison of the above fuels energy densities. The main hazard with H_2O_2 is that it is classed as an oxidizer for concentrations of 8% upwards.

Compound	Specific Energy MJ/kg
Gasoline	47.5
Hydrazine + Nitrogen Tetroxide	5.0
Hydrogen Peroxide + Silver Rhodium	2.9

Table 4: Specific Energy Comparison of Three Fuels [41]

The reaction that this specific energy relates to is:

$$2\ H_2O_2 + \text{Catalyst} = 2\ H_2O + O_2$$

An existing H_2O_2 engine lists some of its benefits as:

- Light weight due to high stored specific energy;

- Low cost;
- Low exhaust signature potential and temperature **[42]**.

Experts at Purdue University say that fuel cells that utilize hydrogen peroxide can reach energy densities of about 1.6MJ/kg; about 20 times that of a lead-acid battery and twice that of a lithium-ion battery. "That means a 20-kilogram lead-acid battery would put out the same amount of energy as a one-kilogram hydrogen peroxide fuel cell"**[43]**.

The U.S. Navy apparently attempted early development of these cells but abandoned the idea when a thick sludge formed from the pure aluminium catalyst that hindered the flow of electricity. However the Purdue engineers used an aluminium alloy that didn't result in the formation of any such sludge.

F2. ENERGY STORAGE WITHOUT AIR

The storage of most of the energy sources of concern in this project is related to high-pressure cylinders to maximize on the energy density. In fact, the use of air to aid in energy storage is not required for the most part for any of the sources and so only really becomes of concern in the power generation phase where combustion plays a part. Therefore I shall pick up on this topic later on.

F3. CONCLUDING REMARKS F

Monopropellants show much promise as fuels where space and weight are limiting factors (and where a lack of oxygen for combustion occurs – see Power Generation).

Hydrazine is very dense energetically, but is problematic in storage for safety reasons – it is very toxic and cumbersome to handle.

There is still skepticism over the use of H_2O_2, as people say that you just can't carry that much H_2O_2 for a long time, although it is safer than hydrazine.

Also, regardless of the concentration, H_2O_2 is continuously decomposing in a so-called auto-decomposition process and so safety and control measures would need to be implemented.

Monopropellants tend to be best utilized for short term applications, and their specific power drops drastically after an hour or so.

Neither of the above monopropellants have a better specific energy than gasoline, but as far as a trade-off between energy density and weight is concerned, many believe that monopropellants provide the optimum balance.

G1. CONCLUSIONS

G1.1 Description of Summarizing Techniques

In this concluding section I aim to come up with at least one recommended energy source for mobile underwater units. Due to the complexity of the problem, with the constaints concerned and the energy sources available, there may well be several options open to the final solution and I'm sure they will depend on the chosen method of generating power too.

I shall first attempt to rank the energy sources in order of feasibility for each constraint, with a '1' meaning best. This number shall then equate to a point score. The source with the lowest score will emerge as the best solution for these ***unweighted*** constraints.

In order to get a better idea for the actual 'best' energy source I shall need to weight each constraint in order of importance – a problem shall be left until the power generation analysis. bSo, here below is the ranking for each source, and following that a summarizing table for the 'technically best' solution.

G1.2 Ranking of Energy Sources for Each Constraint

Miniaturization:

Nuclear →	Atomic Battery	- 1
	Plasma-Volt^{TM} Power Cell	- 2
	Radioisotope Thermoelectric Generators	- 2
Mechanical →	Flywheel (fused silica)	- 13
	Compressed Air	- 5
	Pumped Hydro	- 16
	Marine Current Turbines	- 14
	Ocean Wave Energy Converter	- 15

Electrical → Capacitors & Supercapacitors - 12
Superconducting Magnets - 11

Chemical → Batteries - 2
Gasoline - 8
Natural Gas - 9
Coal - 10
Hydrogen Fuel Cells - 7
Monopropellants - 5

Noise:

Nuclear → Atomic Battery - 5
Plasma-Volt$^{\text{TM}}$ Power Cell - 5
Radioisotope Thermoelectric Generators - 5

Mechanical → Flywheel (fused silica) - 8
Compressed Air - 14
Pumped Hydro - 16
Marine Current Turbines - 9
Ocean Wave Energy Converter - 9

Electrical → Capacitors & Supercapacitors - 1
Superconducting Magnets - 1

Chemical → Batteries - 1
Gasoline - 9
Natural Gas - 9
Coal - 9
Hydrogen Fuel Cells - 4
Monopropellants - 14

Minimal Bubble Exhaust & Non Air-Breathing Capabilities: - All 1

Efficiency (based on specific energy content – see Summarizing Table):

Nuclear → Atomic Battery - 13
Plasma-Volt$^{\text{TM}}$ Power Cell - 13
Radioisotope Thermoelectric Generators - 3

Mechanical → Flywheel (fused silica) - 8
Compressed Air - 9
Pumped Hydro - 10
Marine Current Turbines - 13

	Ocean Wave Energy Converter	- 13
Electrical →	Capacitors & Supercapacitors	- 12
	Superconducting Magnets	- 11
Chemical →	Batteries	- 5
	Gasoline	- 1
	Natural Gas	- 4
	Coal	- 2
	Hydrogen Fuel Cells	- 7
	Monopropellants	- 6

G1.3 Summary Table

Energy Source	Specific Energy kJ/kg	Total # Points	**FINAL RANK**
Atomic Battery	Unknown	20	5
Plasma-Volt^{TM} Power Cell	Unknown	21	6
Radioisotope Thermoelectric Generators	19,000	11	2
Flywheel (fused silica)	3,240	30	13
Compressed Air	3,200	29	12
Pumped Hydro	1,080	43	16
Marine Current Turbines	Unknown	37	14
Ocean Wave Energy Converter	Unknown	38	15
Capacitors & Supercapacitors	1.8-->6.7	26	10
Superconducting Magnets	11.5	24	9
Batteries	80-->8,000	**9**	**1**
Gasoline	47,500	19	3
Natural Gas	12,000	23	8
Coal	24,000	22	7
Hydrogen Fuel Cells	3,500	19	3
Monopropellants	2,900-->5,000	26	10

Table 5: Summarizing Table

G2. CONCLUDING REMARKS G

From the brief analysis of energy sources in this project, it seems that ***Batteries*** will still have a major influence in the underwater scene.

It is the recent advances in battery technology (that have been a long time in coming) that have allowed a higher energy content in some batteries, notably the magnesium hydride with nickel catalyst version.

Close behind this are the Radioactive Thermal Generators, which have seen a major boost in research following successful space application missions.

Monopropellants seem to show middling qualities for each constraint bar the noise one. If improvements could be made here though, they could compete in future.

POWER GENERATION

A1. INTRODUCTION

As the beginning of the second part of this power systems project, this report will look at which initial aims have already been achieved, and which ones remain.

A1.1 Title of Project

"A Systems-Level Investigation for Self-Contained Energy Storage System and Power Generation Device"

A1.2 Aims of Project

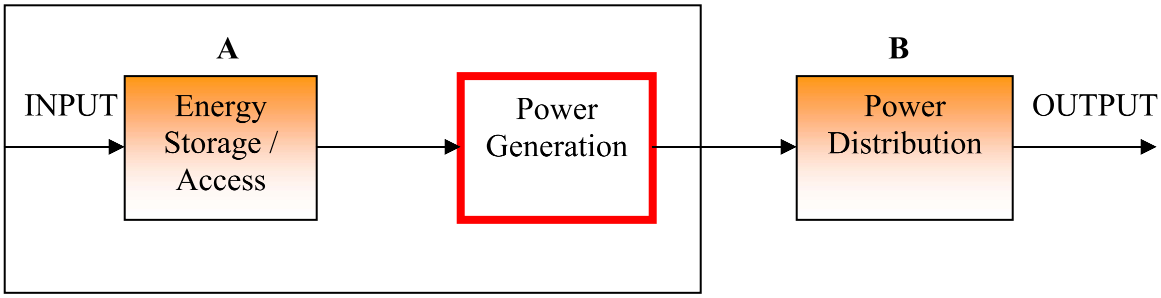


Figure 1: General Block Diagram for this Energy Process [1]

The project now moves its focus on to the Power Generation block, as shown in **Figure 1**.

The overall aims of the project set in Intermediate Report #1 were:

- ~~Deal with the issue under the two headings of Energy Storage & Access and Power Generation.~~
- ~~Look at existing technologies or prototypes for storing energy under the different types (chemical, mechanical etc.) of sources.~~
- ~~Apply a list of constraints to each to determine their suitability for underwater use.~~
- **Repeat the last two points for methods of power generation.**
- **Determine the best combination of these under the final specifics of the problem and/or suggest other paths of possible progress using alternative technologies i.e. technologies that as yet have not been used in the same field.**
- **Produce list(s) in order of ranking for different properties required i.e. depending on the conditions a certain pair may be favored to another.**

A1.3 Constraints

The constraints for the generation of power are similar to the storage of energy – the difference will be that some constraints will be more limiting for storing energy and the others for power generation.

From the first half of the report, the constraints are:

- Non-Air Breathing:

The most obvious constraint that comes to mind when thinking about power generation underwater is the lack of oxygen for combustion. Old submarines used to only run on diesel engines to combat the very fussy petrol engine stoichemetric ratio.

Submarines of late have moved on to having their very own small nuclear reactors in the back end.

Equipment or vehicles underwater outside the submarine, it seems, would have no possibility of working on a combustion cycle due to this lack of air.

But is there really a complete lack of air?

The answer is obviously no, as the people in the submarine need air to breathe, and so do those venturing outside. So equipment could be powered by a combustion cycle that utilizes oxygen from the diver's oxygen tank…

I think that ruling out the possibility of air-breathing equipment at this stage is short-sighted, but recognize the fact that pursuance in this line of thought will probably be to no avail.

- Low Noise:

Stealth is an important part of the military forces' tactics, and nothing is worse than giving away the co-ordinates of your position by sending out a noisy signal.

The water itself will have a large damping affect on the noise of mechanical parts, but not always enough to eliminate all noise. The choice of materials, as well as the actual physical design of the system is important here.

In summary, areas of contention will include
- motors;
- other moving parts;
- chemical reactions;
- noise reduction;
- choice of materials.

- Compactness:

The idea of mobile equipment and instrumentation for human use under water indicates that a certain amount of maneuverability is required. Therefore having a system that is as large as, or larger than, the existing submarine, is pointless.

But just how small can (energy storage and) power generation systems go?

Each existing system will be looked at, and what reasons, if any, they have for their preferred sizes.

- Minimal Bubble Exhaust:

The topic of exhaust is connected to the stealth issue raised for the 'low noise' constraint. If bubbles are released into the water they cause a disturbance, with a detectability that depends on the size of the bubbles.

Bubble release can also increase the noise of the system, and so resistance to this needs to be included in the design from an early stage.

For the examples in this project there will be a variety of waste products including toxic gases from chemical reactions and nothing for electrical systems.

- Efficiency:

Efficiency is a big business. In fact, some businesses make all their money from taking other people's products and making them run smoother, using less fuel or less parts, but always with the intention of saving a few bucks.

Although cost may not seem like much of an object like the US Navy, the lifetime of such a system is. The money will always be there to replace broken equipment, but when you're several thousand feet under the surface of the water, getting new parts to you isn't easy. It can be said that a more efficient system should have a longer life span, and maximizing the efficiency should give more flexibility to underwater operations.

The main efficiency criterion is about how much power you get for your energy input. This, along with expected lifetime, will be examined more closely for each piece of technology.

A2. POWER GENERATION

A2.1 Introduction to Power Generation

The term 'Power Generation' refers to the transference or absorption of energy from an energy source over time in a system **[2]**. However the European Environment

Agency describes it as "the act or process of transforming other forms of energy into electric energy" **[3]**.

A normal car engine runs because power is generated within the combustion chambers, but this is not of the electrical form. The electric energy in a car comes from its battery; the vertical movement of the pistons distributes the power generated by combustion mechanically.

As we will see, most generated power is electrical as this is easiest to distribute, but there are other ways of utilizing a source's energy.

The following section shall take a brief look at the different ways of getting from point **A** in **Figure 1**, a source of stored unconverted energy, to point **B**, a source of converted, readily distributable energy.

A2.2 Types of Power Generation

Just like storing energy, there are two important features for a power generating system:

1) the amount of power to be generated

2) the length of time for maintaining the power level **[4].**

The latter statement wants to be as long as possible (size-limiting), and so is dependent itself on the first statement. But to answer the first statement you need to know **what the power is being generated for**.

As the description suggests, a *mobile* underwater vehicle is going to need to move – a mechanical phenomenon. Also, to sustain life and let that life monitor crucial systems onboard it will also require computers – an electrical phenomenon.

Running computers off of an electrical supply is fairly straightforward once you have it generated, and so more of the focus will be on converting stored energy to mechanical energy – and keeping the noise that this makes to a minimum.

As mentioned earlier, power generation is just an energy conversion process, and so the different 'types' of power generation will come under similar categories to the 'types' of energy storage.

Many of the energy conversion processes are exothermic and some produce direct electrical or mechanical energy.

A2.2.1 Methods of 'Generation'

There are four main areas that will be discussed in this project:

Electrical	→	Direct electrical power
Chemical	→	Heat/mechanical/electrical power
Mechanical	→	Direct mechanical power
Nuclear	→	Heat/mechanical power.

Figure 2 shows a Power Generation Block Diagram.

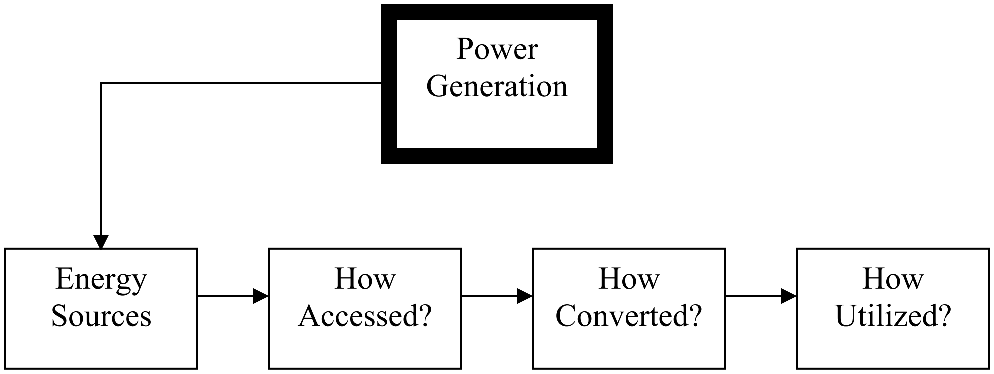


Figure 2: A Power Generation Block Diagram

If electricity is generated, it can be used directly to run computers or an electric motor. If heat is generated it can be driven through a turbine in the form of steam to generate this electricity. Here it is the expansion of the gases that do mechanical work on the turbine blades.

So electricity can be generated in two main ways; from the utilization of heat and the direct product of electrical (or electrochemical, as in the case for batteries) energy sources.

The next two intermediate reports will look at the Generation of Electricity, from both heat and other sources. The latter of these two will include a look at batteries and other electrochemical sources, like fuel cells.

Apart from electricity, combustion is another popular method of producing power. The fourth intermediate report shall look at the different types of engines that work through combustion, what their heat cycles are and which of the constraints limit their performance most.

The noise and exhaust of a system are much more prominent in the power generation stage. Although the exhaust depends heavily on how the power is distributed some of the general characteristics of it can be determined. The fifth report shall focus in on these possible problems and what has already been done to try and reduce their effects.

Finally, the last two reports shall analyze the methods of power generation that have been put forward and come up with a list that ranks them against each of the constraints, similar to that for the energy sources discussed in the first part of the project. The seventh report shall cross-examine both reports to try and determine the best combination of energy source and method of power generation for the mobile underwater vehicle.

A3. CONCLUDING REMARKS A

The second half of the overall project will be more guided by what has already been established. As power generation depends on the existence of an energy source there are only so many methods available for doing so. Therefore the energy sources from the first half of the project will be combined with the turbines, engines and batteries etc. of the second half to come up with the optimum pairing for our mobile underwater vehicle.

Generalizations will be made where no specific information is given and the basic characteristics of the vehicle will be calculated where appropriate in aiding the analysis.

B1. GENERATION OF ELECTRICITY BY HEAT

B1.1 Introduction to Electricity

Electricity is one of the most, if not the, favored forms of energy by mankind to run its machines. It is channeled through cables to power all sorts of devices, doing so silently, and with increased technology, efficiently.

But how is an electrically-induced current produced?

We know from experience that small-scale applications use batteries and large-scale ones use electric generators. So this intermediate report aims to look at the energy conversion processes involved in utilizing the heat from exothermic energy sources, whether mechanically or chemically, to create the most containable source of power that we know of.

B1.2 Generation of Heat

WordNet Dictionary defines the word 'Heat' to mean. "a form of energy that is transferred by a difference in temperature" **[5]**. To scientists though, heat is a phenomena that describes the motion of particles and is described more accurately by Webster's 1913 Dictionary as "not a peculiar kind of matter, but a peculiar motion of the ultimate particles of matter" **[6]**.

Heat itself is not electrcity, but, if put through the right energy conversion processes it can provide useful work in the manufacture of it. For example, the heating of water produces steam which can be driven through a turbine to turn a shaft. So achieving the heat is just one of the stages in the multi-stage process that is generating electricity. Recently, technology has started to move to the direct generation of electricity from heat using thermocouples and these shall be looked at in **A2.3**. First though, this report shall look at some of the methods of generating the heat that is required.

B1.2.1 Nuclear

As seen in **Intermediate Report 2** of the first half of this project, nuclear fuel pellets are a very high-density source of energy. As the control rods are raised and lowered into the reactor core, the temperature rises and lowers respectively, as the neutron-absorbing material of the control rods slows down the self-contained reaction.

The fuel pellets are surrounded by water, which as a nuclear reaction occurs, heats up. This water is actually being pumped around the fuel, carrying heat away from the reactor core, as can be seen in **Figure 3**.

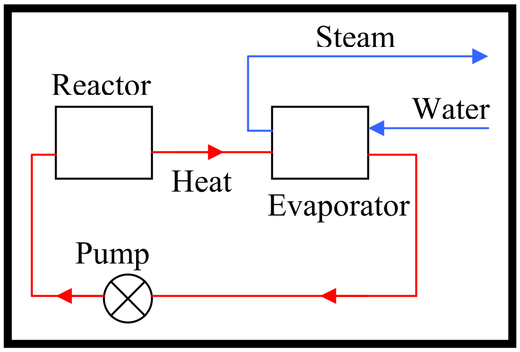


Figure 3: Heat Cycle from a Nuclear Reactor

Figure 3 also shows a second loop involved in the conversion process. The water surrounding the pellets turns to steam from the high temperature of the reaction and passes through a heat exchanger. Here, incoming water is in turn converted to steam to drive the turbine. This way, the water/steam involved in the radioactive reaction never makes contact with the turbine system.

So this highly volatile, but controlled, reaction is very exothermic, but may be limited by our constraints.

Miniaturization:

The miniaturization of the nuclear source has already been dealt with, but not the surrounding pipe work or heat exchangers. The pipe work should obviously be minimized to bring weight and volume down, but is essential in containing the radioactive aspect of our system.

Secondly, there needs to be at least one loop in the system (whether you cut out the second loop shown in **Figure 3** or not) as although the surrounding seawater would be useful carry heat away from the reaction, it should be ensured that this radioactive water does not leak back into the sea.

The heat transfer in the heat exchanger (evaporator) has to be large to be efficient. It is both a function of the surface area and the conductivity of the pipes:

$$\rightarrow Q = -k.A.\frac{dT}{dx}$$

So to maintain the balance of a smaller system the conductivity of the pipes has to be high.

Unfortunately, radioactive shielding is heavy, as it needs to be thick to slow down a radioactive particle. But, this could be where Micro-Electrical Mechanical Systems (MEMs) come into fruition. Technology, as stated before, has had an ever increasing trend towards miniaturization since the early

1900's and the development of entire power systems that fit into the palm of your hand and now not uncommon.

A Radioactive Thermal Generator (RTG) works on the principle of the thermoelectric effect – that is, by using semi-conductor type materials it establishes a current by heating one side while simultaneously cooling the other.

When using plutonium-238, about 1 kW of power can be spontaneously produced for every 2 kg of mass **[7]**. The energy is actually released here by the slowing down of alpha particles, which can only travel short distances.

An advantage of the thermoelectric effect is that it can be used to directly generate electricity using a thermoelectric generator (see **B2.3**). The RTG also has no moving parts leading to greater efficiency.

Of course to the counter-productive side to miniaturization is the decrease in power output, and so designers strive to go small, but keeping the same output (or higher!) as they did before.

Non-Air Breathing:

The utilization of nuclear energy sources is perfect for the non-air breathing environment and has already found numerous applications in recent space programs. The Voyager space probes carried RTGs and because of them were able to send back pictures from Jupiter and Saturn, a feat that would have proved to long for the then conventional batteries. So the lack of air thousands of feet below the ocean surface has no derogatory effects on nuclear energy.

Note:

This report recently discovered that technologies in the area of ***nuclear fusion*** were advancing. At present nuclear power stations utilize energy from the process of nuclear fission – where a colliding neutron splits a nucleus releasing energy. The process of hydrogen fusion "takes place in a small frozen fuel pellet which is heated and compressed by powerful lasers" **[8]**.

The waste products consist of the energetic neutrons and a small amount of helium. As soon as power to the lasers is cut no further heat is generated. One of the disadvantages to this though is that the lasers need a power source of their own to get started.

B1.2.2 Chemical

This section includes all chemical energy sources that produce heat for electricity (bar combustion). Most of the power plants operating today do so by the use of a boiler fueled by one of the fossil fuels e.g. coal. Water is heated in the boiler unit to create superheated steam at very high pressures, which is then driven through a turbine (see **B2.1**).

Miniaturization:

A system that includes a boiler unit is going to be bulky and need its separate energy source just to keep it going. These existing power plants are used for the mass production of electricity for people's homes and are in no way meant to be miniaturized, as scale is what they are all about.

B2. ELECTRIC POWER GENERATORS

B2.1 Turbines

A turbine can be defined as any rotary machine in which a revolving wheel or a cylinder/disk bearing vanes, is driven by a flow of water, steam, gas, wind etc. especially to generate electrical power. Examples include gas turbines, impulse turbines, jet turbines, pump turbines, reaction turbines, shaft turbines and steam turbines.

Steam Turbines:

The modern day steam turbine (also known as a heat-force engine) looks a lot like the reaction turbine invented by J.B. Francis in 1849. This relies on the flow of steam traveling parallel to the axis of rotation (axially).

The steam is at high pressure as it enters the turbine, and cools and expands as it passes through it, leaving eventually at a lower pressure. Therefore a pressure gradient is set up across the turbine. It can be noted that because the gas expands as it cools it requires more volume, hence why the turbine blades increase in size from entrance to exit (conical shape).

This cooling is caused by the steam delivering kinetic energy to angled impellers. In a reaction turbine there are two sets of blades to each stage:

- stator blades → Stationary
- rotor blades → Rotating

The incoming steam hits the stator blades and is optimized in angle to hit the forthcoming rotor blades. The stator blades are required to ensure the steam enters the rotating blades at an angle conducive to the maximum work output. This is due to the fact that the rotating blades give the steam flow a tangential velocity (also known as the gas whirl). Charles Parsons developed the principle of using two blade types in 1833.

Figure 4 shows a cross-section of a multi-stage reaction turbine and **Figure 5** shows the velocity diagrams of the gas flow.

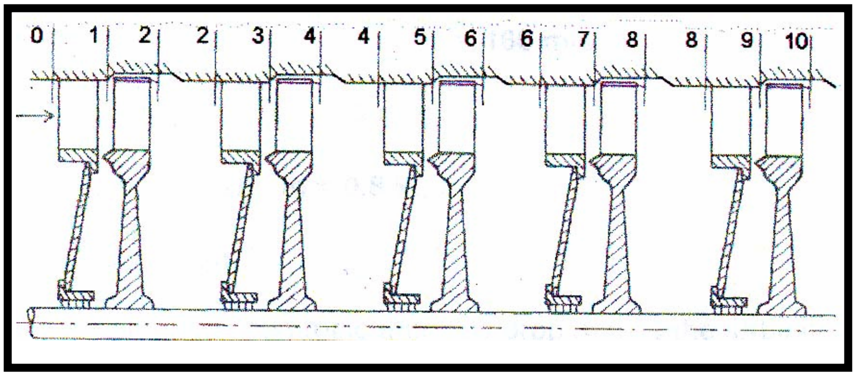


Figure 4: Cross-Section of a Multi-Stage Reaction Turbine

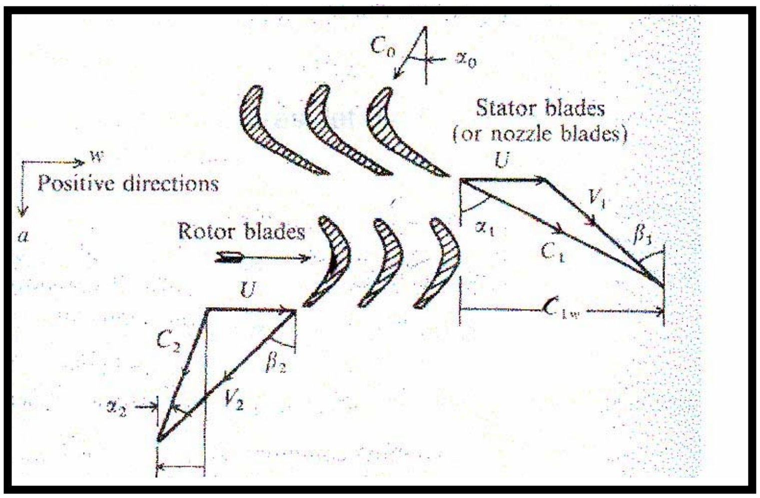


Figure 5: Velocity Diagrams of the Gas Flow [9]

Efficiency with turbines is not terribly good though and so to combat this different pressure-level turbines are coupled together e.g. one high-pressure, two medium-pressure and four-low pressure. This can lead to an efficiency of over 40%, which although sounds low, is better than a diesel engine by comparison. “The strongest steam turbines achieve today performances of more than ***1000 megawatts***” **[10]**.

Figure 6 shows a 2-step steam turbine possessing two impellers and an idler in the centre.

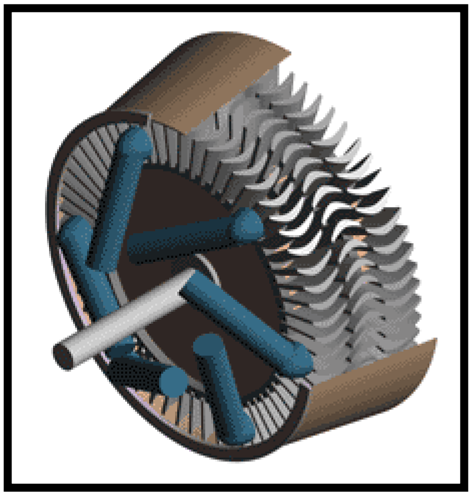


Figure 6: A 2-Step Steam Turbine with two Impellers and an Idler [10]

‘Shirt-Button’ Turbines:

As a battery has always been the biggest constraint as far as miniaturization is concerned, a research team at MIT'S Gas Turbine Laboratory has carried out a project "to develop a turbine engine the size of a shirt button, linked to a tiny electric generator and capable of producing 10 to 20 times as much power as the best chemical batteries" **[11]**.

The concept of miniature turbines has been research since 1994 and much like a jet engine includes three key components:

- Combustion chamber
- Turbine wheel
- Compressor wheel

Exhaust gases from the combustion chamber cause the turbine to rotate by passing through the blades on it. The compressor wheel being connected via a central shaft likewise starts to rotate, and draws air in to feed the burning of more fuel in the chamber.

Figure 7 shows a 4-mm turbine wheel constructed by MIT's Gas Turbine Laboratory. It is made out of silicon.

Figure 7: A 4-mm Turbine Wheel Constructed out of Silicon [11]

To generate a high energy density on such a tiny scale is hard, and relies on the peripheral speed of the vanes. Therefore if the rotor material was not strong enough it would fracture under the high radial stresses imposed upon it.

The viscosity effects of a problem are of much more importance at micro scales and so the researchers had to be able to compensate for any deviations from their expected solution. After a two-year scaling study it was found though that the viscosity problem was not great enough to cause any big design changes, and micro scale materials were less likely to have flaws in them compared to macro scale ones, making them proportionately stronger than conventional turbine blades.

The turbine spins at 2.5 million RPM meaning a peripheral speed of almost twice that in a conventional turbine. Along with the 4-mm turbine wheel, demonstrators have shown how a 2-mm combustion chamber would connect with it and hope to eventually integrate all of the components on to a single silicon chip.

"Ultimately, the researchers hope to produce a prototype turbine power plant weighing less than one gram and capable of producing ***10-100 watts*** of electrical output in a sub-cubic centimeter-sized package" **[12]**.

B2.2 Electric Generators

An electric generator converts mechanical energy to electrical energy using the physics of magnetism to induce an electrical current.

A magnet attached to the end of a rotating shaft is positioned inside a stationary conducting ring that is wrapped with a long, continuous piece of wire. **Figure 8** shows a schematic of this.

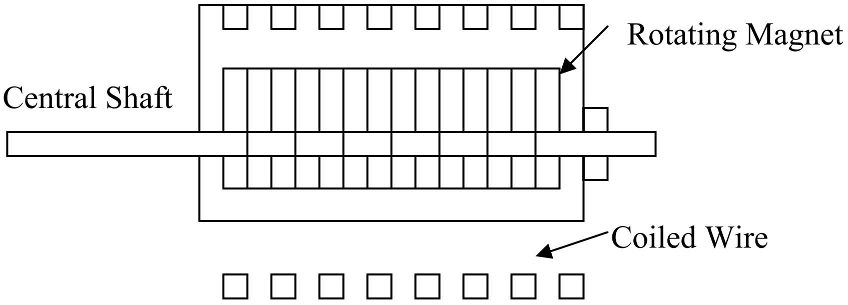


Figure 8: Schematic of an Electric Generator

When an electrically conductive material e.g. a wire, moves through a magnetic field, it cuts through the field's lines of flux, inducing an electrical current in it. The large generators used by the electric utility industry have a stationary conductor. When the magnet rotates, it induces a small electric current in each section of wire as it passes.

Each section of wire constitutes a small, separate electric conductor. All the small currents of individual sections add up to one current of considerable size. This current is used in the form of electric power **[13]**.

B2.3 Thermoelectric Generators

A company called Global Thermoelectric is "the world's largest supplier of thermoelectric generators" **[14]**. **Figure 9** shows a diagram of their generator concept.

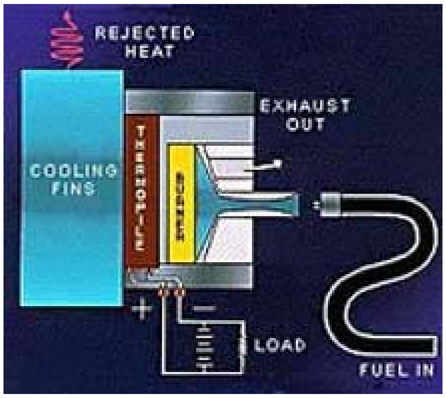


Figure 9: A Diagram of the Global Thermoelectric Generator [14]

The three main parts to the generator are a burner, the thermopile and cooling fins. The concept is all about cutting out the middleman that is the turbine. This eliminates all moving parts by using the thermoelectric effect. Electricity is directly produced from the principles of heating and cooling, reducing space, weight and noise.

More information on this company can be found at: http://www.globalte.com/intro.htm

Like all generators they require a fuel input, and there are many options. But one that has caught the interest of many in the space program recently is the use of nuclear fuels → Radioactive Thermal Generators (RTGs).

The Galileo mission in 1984 had RTGs with a thermal power at the beginning of the mission of ***4,410 W*** per generator **[15]**.

Figure 10 shows a cross-section of a RTG.

Each generator "is about 45 inches long, 16 inches in diameter, and weighs 122 pounds" **[15]**.

This heat is converted to electricity by a thermoelectric converter, which uses the Seebeck effect. An electromotive force is produced from the diffusion of electrons across the junction of two different materials (e.g., metals or semiconductors) that have been joined together to form a circuit when the junctions are at different temperatures – these are known as *thermocouples*.

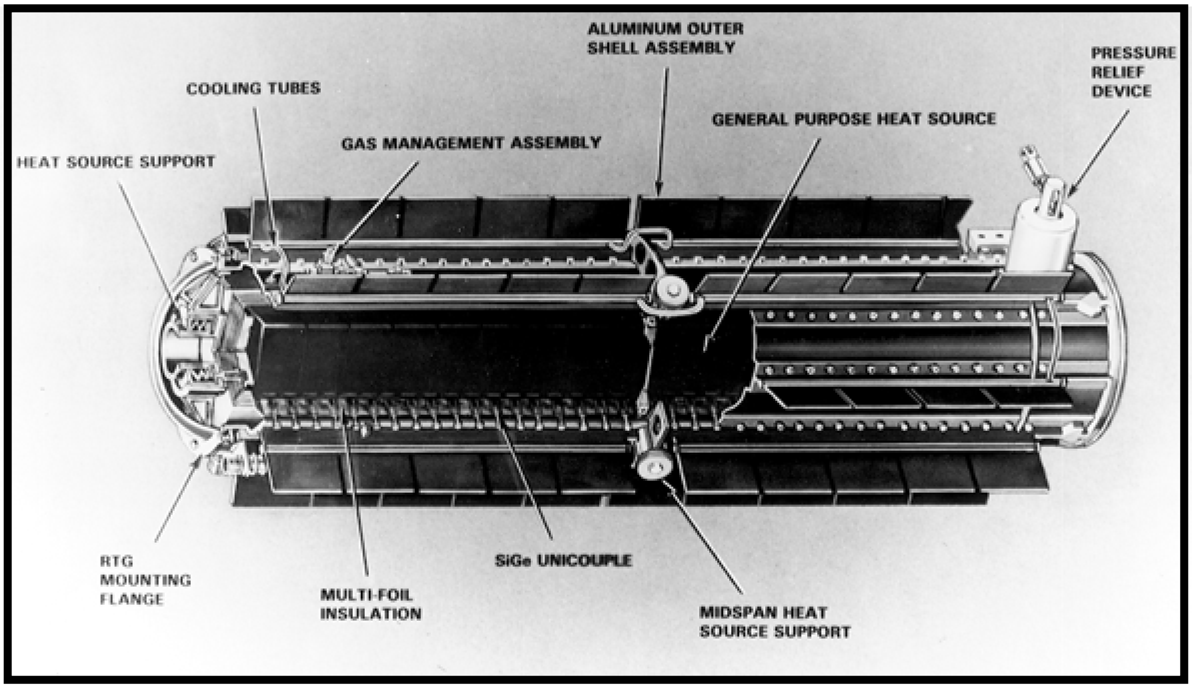


Figure 10: Cross-section of a RTG Used Onboard Galileo 1984 [15]

B3. CONCLUDING REMARKS B

While steam turbines run on fossil fuels produce the largest electrical output, their shear size wipes out the possibility of having a stealthy underwater vehicle with one onboard.

Only if the microturbine sector really takes off can this report see a nuclear powered, steam turbine-driven, electric generated motor.

However, there are distinct possibilities as far as coupling a nuclear reaction with a thermoelectric generator. This would save much space, and leave only exhaust and noise problems to deal with given a good efficiency ratio.

Such progress has been made as demonstrated by the use of RTGs in the space program. Current information on RTGs is limited though as the technology is closely guarded until it is outdated.

C1. GENERATION OF ELECTRICITY BY ELECTROCHEMICAL SOURCES

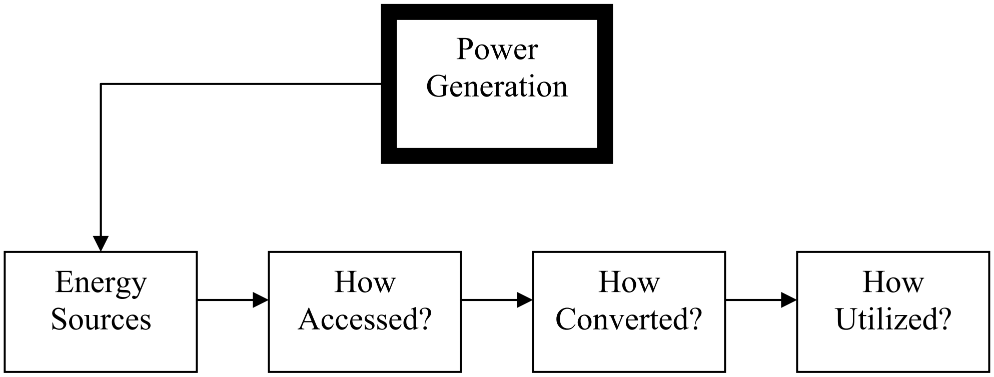


Figure 11: A Power Generation Block Diagram

Figure 11 shows the questions that need to be answered to produce power from an energy source. This report shall look at electrochemical energy sources.

C1.1 Electrochemical Sources

C1.1.1 Batteries

The inability to miniaturize batteries has been the bane of their existence. Sure, they are a lot more compact than your car engine or your flywheel, but in the electronics world in which they live they are usually many times bulkier than the rest of the components put together.

Here we shall look at some of the different types of batteries at present available and their respective power density.

Super Power Accumulators:

A company called Venture Scientific International has developed what they call Super Power Accumulators (SPAs). They consist of a sealed accumulator with water alkaline electrolyte and new electrodes.

Results of experimental study apparently show that they have a specific power "*ten times higher than any existing batteries*" **[16]**.

They have a high density of discharging current (up to 1A/cm^2) and in fact, a 50kg SPA can accelerate a car from 0 to 100 km/h in 10 seconds at an average power of 75kW.

Table 1 compares the general characteristics of one cell to electrochemical capacitors and flywheels.

Parameter	**Units**	**Super Power Accumulators**	**Electrochemical Capacitors**	**Flywheels**
Energy Density	Wh/kg	10 - 20	2 - 4	1.5 –5
	Wh/liter	25 - 50	3 - 6	(50 theoretical)
Power Density	kW/kg	**1.5 - 5**	4 - 6	~1
Cell voltage	v	1.2	-	-
Cycles life	Thousands	**15 - 25**	100 - 500	--
Charging time	Seconds	**10-100**	100-2000	--
Discharge time	Seconds	**5-50**	~2	--
Fire hazard	Yes/no	**no**	yes	yes
Explosion hazard	Yes/no	**no**	yes	yes

Table 1: Comparison of SPA to Electrochemical Capacitors & Flywheels [16]

While much more energy dense than electrochemical capacitors, SPAs are not as power dense and have a shorter life cycle. On a positive note though, the charging and discharging times are much more favorable and they present no fire or explosion hazard.

Lithium-Ion:

Lithium-ion batteries are high-energy dense batteries incompatible with normal batteries. The positive electrode uses lithium metallic oxide and the anode uses standard carbon material.

The high energy density means that the size and weight of each battery is drastically reduced. Its advantage over Nickel Cadmium and Nickel Metal Hydride batteries is that is doesn't suffer from memory accumulation (when a battery remembers how much it is discharged, resulting in a temporarily voltage drop **[17]**) giving a full charge each time **[18]**.

Table 2 shows a previously released comparison of the above batteries' chemistries.

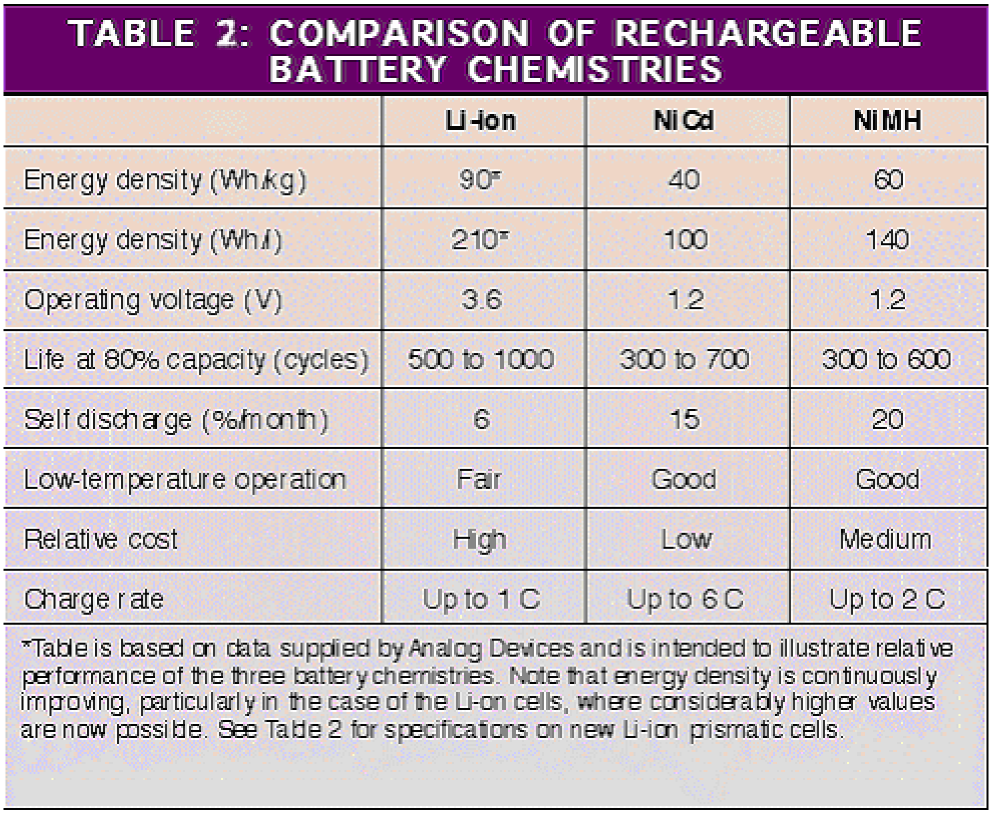


TABLE 2: COMPARISON OF RECHARGEABLE BATTERY CHEMISTRIES

	Li-ion	NiCd	NiMH
Energy density (Wh/kg)	90*	40	60
Energy density (Wh/l)	210*	100	140
Operating voltage (V)	3.6	1.2	1.2
Life at 80% capacity (cycles)	500 to 1000	300 to 700	300 to 600
Self discharge (%/month)	6	15	20
Low-temperature operation	Fair	Good	Good
Relative cost	High	Low	Medium
Charge rate	Up to 1 C	Up to 6 C	Up to 2 C

*Table is based on data supplied by Analog Devices and is intended to illustrate relative performance of the three battery chemistries. Note that energy density is continuously improving, particularly in the case of the Li-on cells, where considerably higher values are now possible. See Table 2 for specifications on new Li-ion prismatic cells.

Table 2: Comparison of Rechargeable Battery Chemistries [19]

Prismatic Li-ion cells are flat, rectangular shaped batteries that were developed in response to the need for thinner batteries to better fit cell phones, notebook computers, and other portable consumer items. "Cells that are 8 to 10 mm thick have become widely available, and it has been possible to obtain over 1000 mAh of capacity in a prismatic measuring 34 by 48 by 8 mm. More recently, 6-mm cells have arrived—albeit with battery capacity closer to 700 mAh—to satisfy the requirements of thinner products" **[19]**.

A ***36Wh lithium-ion battery weighs only 350g*** including protective cases and connectors. Its dimensions are 40mm by 65mm by 70mm.

Hydrino Hydride Battery:

Not quite fully developed, the Hydrino Hydride Batteries (HHBs) show a lot of promise from preliminary studies. Thus far, lithium-ion batteries have deservedly been the number one choice when considering weight (lithium is the lightest metal) and energy density, but as far as their use in electric cars goes, these factors are still too much of a hindrance.

Blacklight Power Inc. (BLP) is currently developing the Hydrino Hydride Battery "in which the hydrino hydride-ion shuttles between the anode and cathode **[20]**."

The cathode is a hydride and the anode is either a hydride or a metal with a hydride ion conductor as the electrolyte. Hydrogen is the active element, and combined with lithium (or other such light cation) gives much lighter electrode materials than in a lithium-ion battery.

The HHB should have a higher voltage and energy density than a lithium-ion battery when fully developed, and should also be cheaper eventually, as it is the byproduct of an energy process using hydrogen.

Table 3 shows a comparison between a lithium-ion battery and the projected specifications of a HHB.

	Hydrino Hydride	Lithium-Ion
Energy Density (Volumetric)	Up to **182,000 Wh/l**	Up to **300 Wh/l**
Energy Density (Gravimetric)	Up to **222 Wh/g**	**0.12 Wh/g**
Capacity	Up to 4000 Ah/kg	32 Ah/kg
Voltage Range	Up to 75V	2.5 to 4.2 V
Average Voltage (C/5)	Unknown	3.7 V
Cycle Life	Unknown	500 cycles to 80% capacity
Charge Acceptance	Unknown	>80% in 10 hours

Table 3: Comparison of the Lithium-Ion and Hydrino Hydride Batteries

A company document states that:

"BLP's battery compound may release about **100 times the energy** and **1,000 plus times the power** of any other conventional chemical used in batteries. This, in turn, means that proportionally less chemical will be required to manufacture BLP's battery. The overall weight should not exceed **1/10th that of a conventional electric vehicle battery**. This implies that the cost of manufacturing BLP's battery will be correspondingly low **[20]**"

Other batteries in use include an aluminum-oxygen battery that has been tested in an Autonomous Underwater Vehicle (AUV) in Canada, and a low-voltage magnesium battery, with a potential range of 1,100 to 1,200 nautical miles in a similar vehicle. This battery has one of the highest specific energy specifications to date **[21]**.

C1.1.2 Fuel Cells

The fuel cell not only doesn't require combustion (producing therefore no pollutants such as nitrogen oxide) but also is more efficient than a combustion engine.

The Proton Exchange Membrane Fuel Cell (PEMFC) is at present the most promising type of fuel cell. The hydrogen-oxygen version of this is hoped to eventually power buses and other such vehicles.

Hydrogen gas is pressurized at the anode and forced through the catalyst. When the H_2 molecules come into contact with the catalyst (platinum here) it splits, sending two electrons through the anode and an external circuit (to do work on our load). The H^+ ions go through the proton exchange membrane, combining with the pressurized oxygen ions and electrons that make their way back to the cathode.

At present a single cell can only produce about 0.7 V, which is why fuel-stacks are manufactured to capitalize on this. The current power density levels achievable sum up into the fact that "a device about the size of a small piece of luggage can power a car **[22]**."

Efficiency:

To determine a rough efficiency of fuel cells when used for a modern-day application we shall look at the fuel cell powered electric car. Both Toyota and Ford are bringing out such vehicles this year, with the latter opting for a hybrid engine.

The efficiency of a fuel cell run on pure hydrogen is high (can be up to 80%) because hydrogen has a high *specific energy* (see **box** below).

Specific Energy:

The amount of energy a battery stores **per unit mass** at a specified discharge rate; also called gravimetric energy density; usually measured in watt-hours per kilogram.

Energy density:

The amount of energy a battery stores **per unit volume** at a specified discharge rate; also called volumetric energy density; usually measured in watt-hours per liter **[23]**.

For most power sources, a high-energy density source has a low power-density. Hydrogen falls into this category and has a low energy density because it is the lightest element in the periodic table. Therefore, "high-power applications cannot take advantage of the long operational life high-energy density sources offer, unless the size of the source is significantly and prohibitively increased" **[24]**.

PEMFC's are high energy-density, low power-density components, allowing for a long life time when used in a stack. If an instantaneous power demand that exceeds its rating occurs though, it doesn't respond well, causing the stack to overheat and individual cells to become polarized.

Thus far, increasing power for fuel-cells has meant increasing the number of cells or stacks, which for miniaturization purposes serves no good at all (see Hybrid section below).

Because hydrogen presents such a difficult obstacle as regards storage, two options are left to progress with:

→ *Need better way to store hydrogen (do away with extra parts)*

or

→ *Need a reformer to produce hydrogen from alcohols etc. onboard.*

A reformer can be used to convert methanol or other such alcohols/hydrocarbons to hydrogen, but then the efficiency drops to about 30-40% for producing the resultant electricity. This is because the reformer produces other gases and heat in its primary reaction. When combined with the efficiency of the electric motor (and inverter) to produce mechanical power (about 80%), the overall efficiency for a **fuel-cell powered car** falls to **24-32%**. **[22]**

Cell-stack outputs currently range from **50 to 250 kW**.

Compared to a **gasoline-powered car**, this efficiency is slightly better as most of the energy is wasted through the exhaust or radiator. There are also many other subsystems that need powering and tap off the engine main-circuit to do so. An approximate efficiency of a car engine is then about **20%**.

Neither the fuel-cell nor gas powered car efficiencies match that of the battery powered electric car. Car batteries can be about 90% and combined with the same motor/inverter efficiency of the fuel-cell powered car, the overall efficiency becomes about **72%**.

This last efficiency is drastically reduced if you consider the processes involved to produce the charged battery (in fact lowering it to nearer *26%* when including the efficiency of a power plant).

Solid Oxide Fuel Cells:

Another type of fuel cell is the solid oxide fuel cell, which at present is best suited for large-scale generators. Solid-oxide fuel cells (SOFCs) are made from solid-state materials, namely ceramic oxides and operate at high temperatures. Consequently they can be unreliable, but if utilized underwater this problem could be avoided with sufficient cooling.

About a year and a half ago Lawrence Livermore National Laboratory conducted experiments to try and increase the power density of single cells. They succeeded by achieving "1.4 watts per square centimeter, one of the highest values reported for power density at 800°C. **[25]**"

"A three-cell stack prototype generated **61 watts** and the power density of the stack was 1.05 watts per square centimeter (at 800°C using hydrogen fuel), a value at least 50 percent higher than any stack power density previously reported. **[25]**"

Zinc/Air Fuel Cells (ZAFCs):

The electrochemical process in a zinc/air fuel cell is similar to that of a PEMFC apart from the refueling process, for which the former is more like a battery's (they are sometimes referred to as zinc/air batteries). A company called MetallicPower is now working on a Zinc/Air fuel cell that would contain a zinc "fuel tank" and a zinc refrigerator that would automatically and silently regenerate the fuel" **[26]**.

The main advantage that ZAFCs have over other fuel cells is that it has a high specific energy "which is a key factor that determines the running duration of a battery relative to its weight. **[27]**"

Hybrid Engines:

The Navy is just one of many organizations looking at hybrid engines to power future ships and submersibles. Part of their research has included looking at a ***diesel reformer*** for producing hydrogen.

The Navy already favors Diesel and taking advantage of its low cost to power fuel cells would be a step in the right direction. As today's ships only travel at low to medium speeds they don't require the peak use of the power plant, thus lowering further an already low efficiency.

The fuel cell being designed is hoping to achieve a **37-52%** efficiency. More information about ONRs (Office of Naval Research) testing on a 500kW diesel reformer can be found at: http://www.onr.navy.mil/media/tipoff_display.asp?ID=49#1

The U.S. Army is currently looking at power sources combining high-energy density, low-power density sources (zinc-air 'battery', PEMFC) with high-power density, low-energy density sources (lithium-ion batteries) to deal with high current pulses and extended life of a source.

The idea is to cancel out, or at least offer a compromise of each ones characteristics. **Figure 12** shows the potential output from such a hybrid compared to each source on their own.

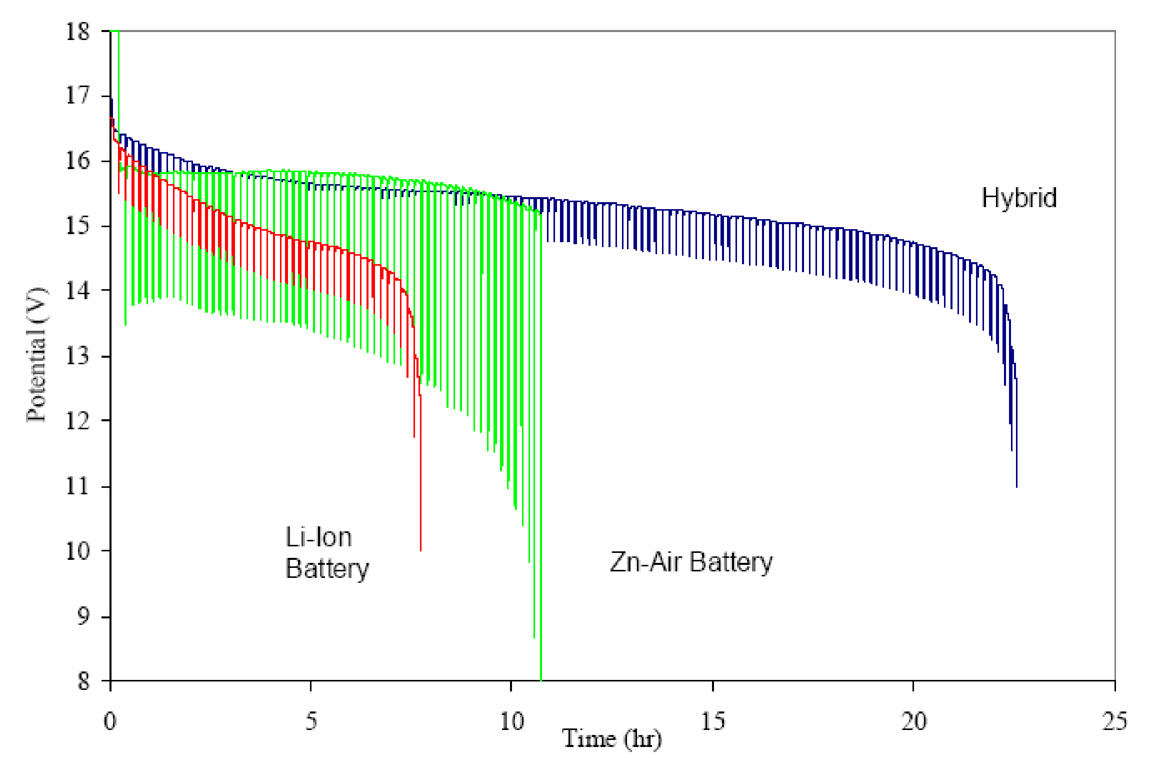


Figure 12: Zinc-air/Li-Ion Hybrid Discharged Under 12W 9 min: 40W 1 min Cyclic Load [24]

The graph shows that the hybrid system operates for longer than the lithium-ion and zinc/air batteries lifetimes put together. The hybrid system is also lighter and smaller than the two separate systems.

C2. CONCLUDING REMARKS C

Electrochemical sources are clearly some of the most progressive technologies in the market at present. Batteries, although hindered for many years by their high energy-density, low power-density relationship, are now making advances in miniaturization with Lithium-Ion and Hydrino-Hydride (up to **222 Wh/g**) types.

Fuel cells are part of an exciting field to be in these days, and already there are fuel-cell powered buses and bicycles in selected towns and cities. The efficiency of fuel cells is good, varying slightly with each type, but is hampered by the ever-difficult problem of storing hydrogen.

A recent suggestion to try and get the best out of both technologies is a hybrid of a high-energy density component with a high-power density one to balance each other’s benefits and problems. This has been suggested by the U.S. Army and is currently undergoing testing.

D1. GENERATION OF POWER BY COMBUSTION

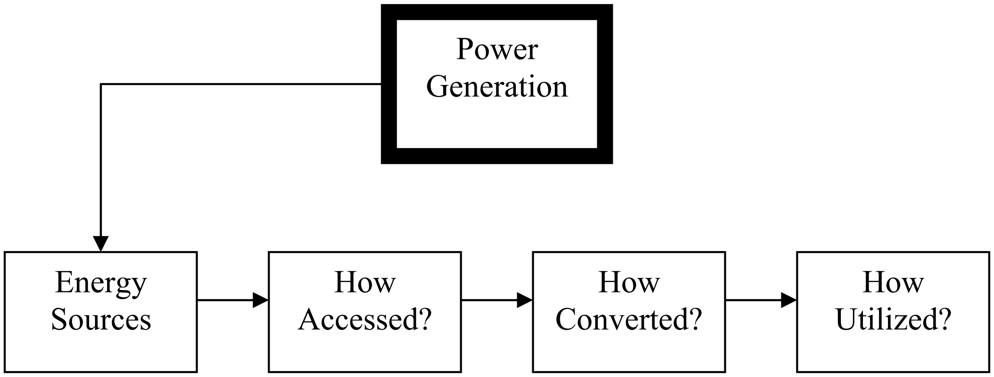


Figure 13: A Power Generation Block Diagram

Figure 13 shows the questions that need to be answered to produce power from an energy source. This report shall look at combustion and heat engines.

D1.1 Engine Cycles

Engine cycles are processes used by heat engines to function. They combine processes that use constant pressure or volume, and are isothermal or adiabatic, and are often represented by P-V diagrams. The most efficient (ideal) engine cycle is the Carnot cycle.

D1.1.1 The Carnot Cycle

This is the most efficient cycle allowed by physical laws and utilizes two isothermal and two adiabatic processes. It sets a limiting value on the heat fraction that can be converted to do useful work, and so engines that use cycles that approach these characteristics are much sought after. Due to physical practicalities though, no real engine cycle can avoid an increase in entropy (governed by the second law of thermodynamics) which is what the Carnot cycle requires.

As Schroeder puts it "So don't bother installing a Carnot engine in your car; while it would increase your gas mileage, you would be passed on the highway by pedestrians." **[28]**

D1.1.2 The Otto Cycle

The Otto cycle is the best known engine cycle due to its huge presence in the car industry. This simple four-stroke cycle is illustrated in **Figure 14** and explained beneath it.

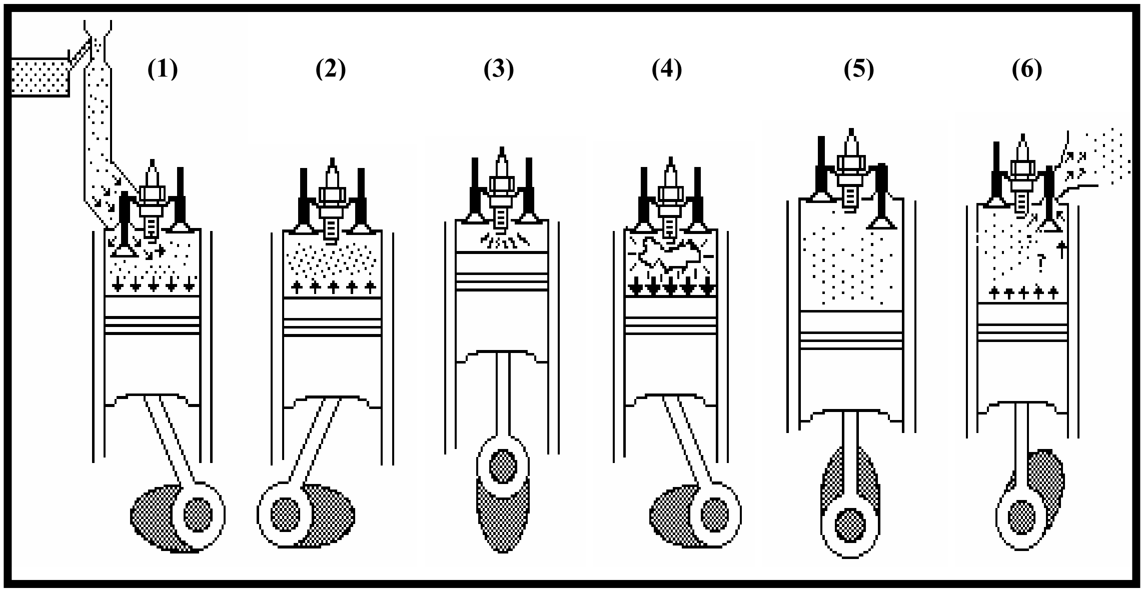


Figure 14: Diagrams Illustrating the Otto Cycle [29]

Cycle:

- Air/fuel mixture is drawn in by drop of piston (1).
- Piston rises up again and compresses gas mixture adiabatically (2).
- Spark ignites mixture causing huge rise in temperature and pressure (3).
- The expanding gas does work on the piston (adiabatically) – this is known as the power stroke (4).
- The exhaust valve opens, allowing pressure to drop and as the piston returns it forces the waste gases out of the combustion chamber (5) and (6).

This cycle is used extensively today, in many variations (see **Engines**).

D1.1.3 The Rankine Cycle

The rankine cycle is the cycle used for turbines in power plants by converting water to steam using a heat source. **Figure 15** shows this cycle.

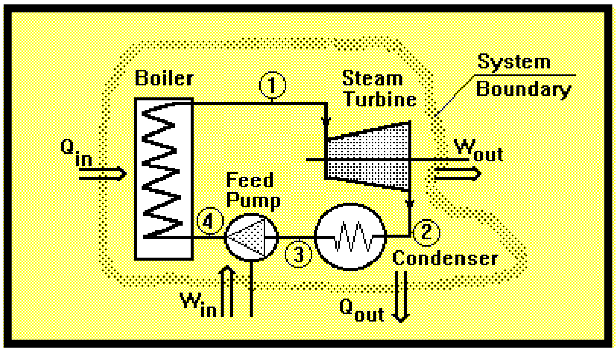


Figure 15: The Rankine Cycle [30]

More about this engine cycle can be found in **Power Report #2**.

D2. HEAT & OTHER ENGINES

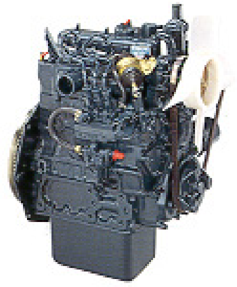
The heat cycles are useful to know, to give us an understanding of what possible engine power they can produce. But they don't tell us any specific figures, which is where existing technologies can help. This section will look at some of the engines out there, how small they can get, and what sort of power output they give.

D2.1 Heat Engines

A heat engine utilizes the energy that it can be converted to by using the expansion of gases to in a combustion cycle to do useful work. Examples include the diesel engine, gasoline engine, wankel engine

D2.1.1 The Diesel Engine

The diesel engine is already favored by many of the world's Navies due to the transportation frame for diesel that is already in existence. Diesel engines for ships and aircraft carriers though are huge in comparison to what we require.A company called Kubota Engine America has a 'mini' series of engines, that includes the smallest available engine, the Z602-E. **Figure 16** shows the Z602-E model from this Kubota Super Mini Series.



- Specifications – Z602-E
- Configuration: In-line 2, IDI diesel, water cooled
- Displacement: 0.6-litre (599cc)
- Bore x Stroke: 72.0mm x 73.mm
- **Power: 10.3kW @ 3200rev/min**
- Torque: 35N.m @ 2600rev/min
- **Dimensions: Length- 375mm, Width- 404mm, Height- 544mm**
- **Weight: 60kg (dry)**

Figure 16: Z482-E Kubota Super Mini Series Specification [31]

A weight of 60kg is a lot for a person to carry if above ground, but with the water's buoyancy effects and the power produced, it might be suitably light for the desired application.

Unfortunately, it is bulky and not streamlined, with geometry characteristics that represent a heavy backpack. Space would still be required for fuel storage and air supply, as there would be no environmentally available oxygen.

D2.1.2 The Wankel Engine

Figure 17 shows a cross-section of the Wankel engine, devised in the 1950s by Felix Wankel. It utilizes all four elements of the Otto cycle but in a clever rearrangement that saves space and time.

Cycle:

- The air/fuel mixture is drawn in at (1) by the rotating triangular piston.
- As the rotor turns it compresses the mixture around point (2).
- At point (3) the spark ignites the mixture forcing the piston around further.
- The exhaust from the reaction then exits at (4).

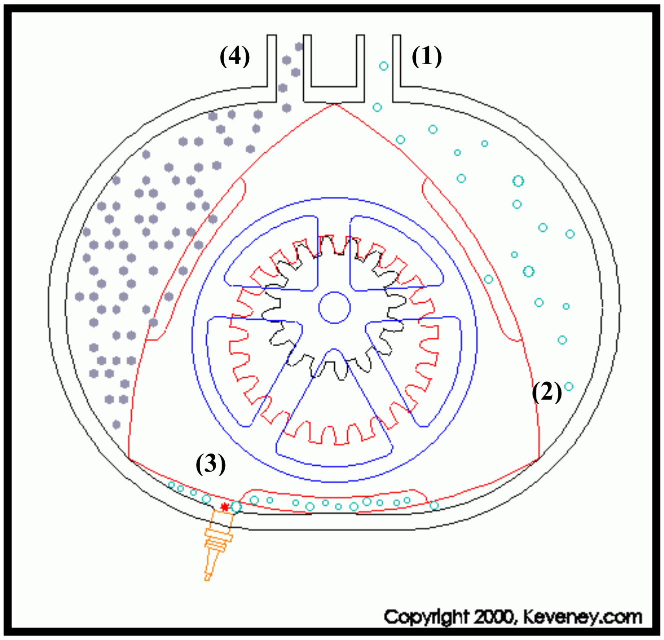


Figure 17: A Schematic Diagram of the Wankel Engine Operation [32]

The Wankel engine is a type of rotary engine, and some progress has been made in the miniaturization of these engines.

Micro Electrical Mechanical Systems (MEMS) technology has been used to fabricate tiny components using techniques from the integrated circuit industry.

Compared to batteries, gasoline has a much higher energy density, but this is not utilized because of normal gasoline engines' poor efficiencies.

Figure 18 shows the comparison of a battery to the possible miniature rotary engine package.

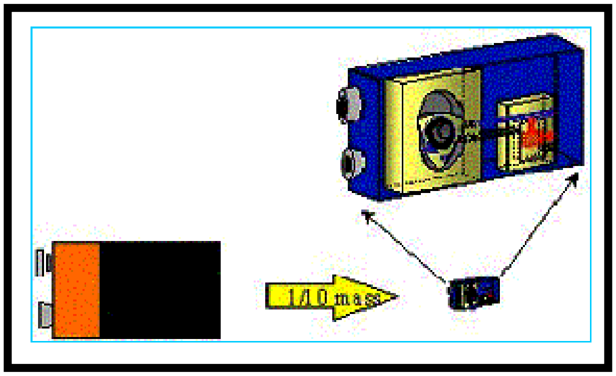


Figure 18: Micro Rotary Engine Scheme [33]

The micro-engine illustrated would only need to be 20% efficienct to have at least 10 times the energy density of the equivalent weight in batteries.

The current goals of a program at the University of California, Berkeley, are to produce a rotry engine with the following specifications:

- Rotor – **1mm**
- Max. RPM (est.) – 40,000
- Power Output (est) – **26mW**
- Displacement – 0.064 mm^3 **[34]**

Eventually, like fuel cells, these could be stacked up to produce a similar effect in terms of generation.

There is a hydrogen fueled rotary engine out at the moment, with not only the high power-to-weight ratio characteristic of rotary engines (less mechanical parts etc.) but also extremely low emissions as hydrogen burns to form water (**2.2kW** engine).

Present rotary engines with sufficient power are far too bulky and consume more fuel than a normal Otto cycle engine.

D2.2 Heat Engines

D2.2.1 The $C0_2$ Motor

Figure 19 shows a cross-section of the $C0_2$ engine, used mainly these days in model aeroplanes. It utilizes the basic principle of using direct thrust from a pressurized container to move the piston downward turning the crankshaft.

<u>Cycle:</u>

- The $C0_2$ gas is drawn in at (1) when the piston pushes the ball upwards .
- This pressurized gas forces the piston downwards turning the shaft at point (2).

- At point (3) the 'exhaust' gas exits through a hole when the piston passes below it.
- The momentum from the intial downward force carries the piston back upward with enough force to push the ball up again, releasing more gas into the chamber.

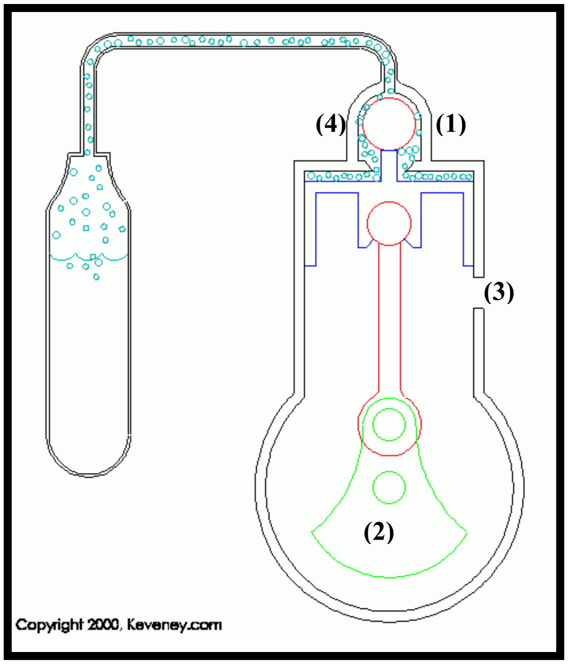


Figure 19: A Schematic Diagram of the $C0_2$ Engine Operation [35]

This motor at present is generally only used for model aeroplanes etc., but could find use if the principle was expanded to meet the exoskeleton's needs.

D3. CONCLUDING REMARKS D

In conclusion, combustion is always going to be tricky underwater. Whether it be for the lack of oxygen to combust with, or the lack of suitable environment to expel exhaust gases into, practicalities arise in the process.

Miniaturization of engines is not easy either, as there are many moving parts that need to be scaled down to microscopic levels. Obviously the rotary engine benefits over the four-stroke piston engine in this area as it has fewer moving parts and takes less time to complete one cycle.

An idea for rotary engines is to fit them into similar packaging as batteries with their own fuel and oxygen supply. If successful, the lifetime of these componenets should be much longer due to a higher power to weight ratio (batteries have always suffered from their weight problem).

Lastly, the CO_2 motor is probably not feasible as a power source for an exoskeleton, based on the weight of the gas tanks required and the amount of energy each would produce.

E1. SYSTEM NOISE

E1.1 Introduction to Noise Problems

Intermediate report 5 dealt with issues of noise for energy sources, and concluded that most noise, and all exhaust problems would be to do with the methods of power generation and distribution.

From the standpoint that noise is just all *'unwanted sound signals'*, then all signals (e.g. vibrations) emitted by the system are 'noisy'.

Noise is like a label, in that it pinpoints your position if detected by other equipment. As highlighted in report 5, noise cannot be avoided but it can be controlled i.e. there will always be some noise about.

Thankfully though, these signals do not maintain their acoustic power as they travel, in fact it diminishes. The rate at which is does so varies depending on the frequency of the signals. High-frequency signals die out quicker underwater than low-frequency ones – in fact it is generally low-frequency signals that are picked up by sonar.

Noise also is an indicator of how or if a system is working. For example, when the system is not operating, there should be no noise (system noise – unless a spontaneous nuclear reaction accounts for some). When operating, the sequence of events that occur to produce power should create some noise, whether it is from moving parts, chemical reactions, or the hum of an electrical device.

One would expect that the louder the noise produced, the more violent the event happening. Noise can tell you about when the event will fatigue (whether it be actual parts, or chemical processes using up their reactants), and so a violent event would be expected to fatigue earlier.

So limiting noise is two-fold, in that it shall enable the system to move undetected through the water, but also lengthen its lifetime. This section shall look at where and how noise might emanate from the system and what possible solutions there are currently available for the different types of power generation that we have.

E1.2 Noise Problem Areas

Moving parts and vibrating surfaces are the two biggest sources of noise in any mechanical system. As highlighted in an earlier part of this project, the three main steps for noise are:

- the generation of vibratory motion
- the transmission of this vibration to a radiating surface
- the radiation of sound into the medium.

The acoustic energy of a sound wave can be measured by a hydrophone on a sonar set up. It measures the oscillations in pressure, the size of which is the amplitude.

The power of a sound wave is proportional to the square of the amplitude, so the larger the amplitude the higher the power.

This energy is gradually lost by attenuation – where the transfer of pressure differences is not 100% efficient in water (some is lost as heat) **[36]**. As highlighted earlier, the high-frequency waves are attenuated much more rapidly than the low-frequency waves, which can travel much further in water.

Now nothing can really be done about active sonars that are going to send out their own signals, looking for echoes to pinpoint a foreign object, but the passive sonars which just listen for radiated noise should be made to work harder, by making our system as quiet as possible.

Mechanical - Moving Parts

When turbines and propellers rotate it causes pressure fluctuations in the surrounding air. Depending on the number of impacts the blades have in a certain time determines the frequency of the sound wave produced.

For example, a turbine or propeller with a few blades will produce lower-frequency sounding waves, which although are easier on the ears of the operator, will travel much further in the water, for a passive sonar to pick up on. The more blades used the quicker the acoustic energy is lost, and the smaller the attenuation 'bubble' (see **Figure 20**).

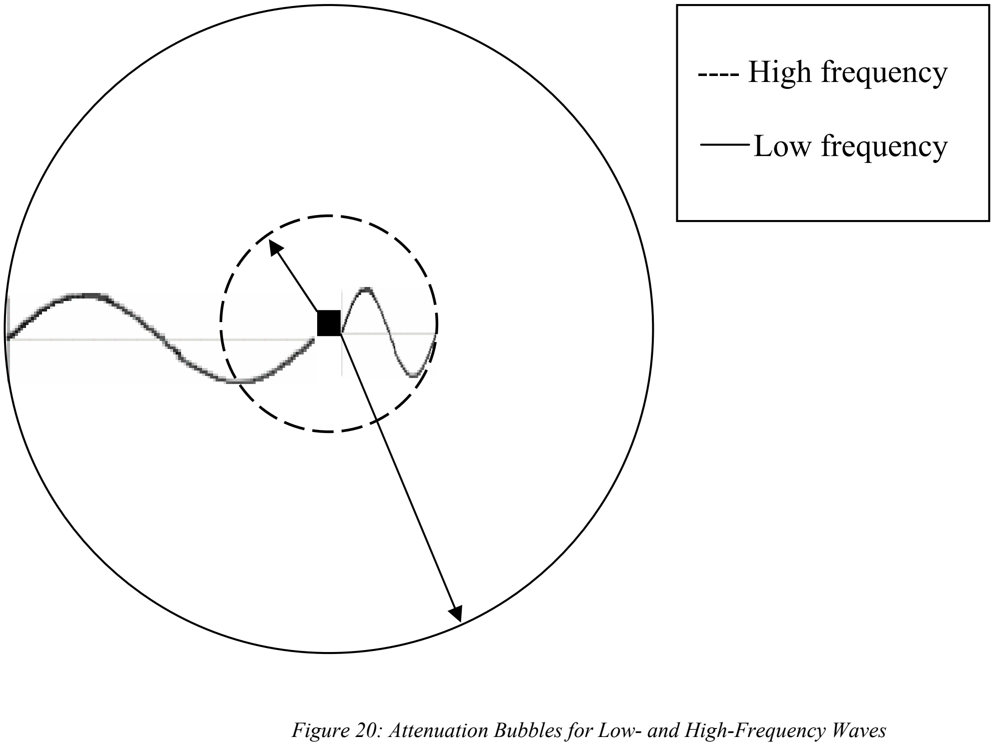


Figure 20: Attenuation Bubbles for Low- and High-Frequency Waves

So any noise that arises from the system should be either reduced to such a level that a passive sonar cannot detect it (given that a passive sonar can pick up 1W of acoustic power over a long distance), or increased to such a frequency that it attenuates within a sufficiently small radius.

Mechanical – Vibrating Surfaces

The buzz of a car engine is a familiar sound, one that results from the overall vibratory effect of the moving parts. A vibration is not the same motion as that which results from a moving part, but rather one that results from this motion.

A vibration tends to be symmetrical and even about one of the material's axes resulting from a back and forth motion, whereas a moving part may take a reciprocal or asymmetrical path.

Vibrations can cause: ***radiated*** sound (by inducing pressure pulses in the surrounding medium) and ***conducted*** sound (through the material itself).

Section **E1.3** deals with how to reduce radiated and conducted sound.

Mechanical - Flowing Fluids

Energy report #5 covered areas such as ducts (including obstructions and exit noise) and cavitation, highlighting where a fluid's mechanical properties can cause problems.

The most obvious restriction is the trade-off between long pipes for laminar flow, and lack of space for miniaturization.

A look at how exhaust gases can be treated for noise is addressed in section **E1.3**.

Chemical & Nuclear – Reaction Noise

We are all familiar with the roar of an intense flame and the buzz of a car engine. Chemical and nuclear reactions, especially exothermic ones, can be very noisy. There is direct and indirect combustion noise arising from the unsteady combustion process and entropy noise respectively **[37]**.

The noise from nuclear reactions is continuous (due to the spontaneity of the reaction) and so hard to deal with.

Limiting this noise is hard, and so methods of containing it are focused on instead.

Electrical –Electromagnetic Interference

As stated in intermediate report #5, the electrical noise induced by circuitry is unavoidable, but largely unnoticeable. State-of-the-art circuitry design should minimize this though, and so compared to the other sources of noise it can be considered silent.

E1.3 Current Noise Solutions

Geometry Optimization

Section **E2.2** of **report #5** covers certain aspects of how the geometry should be configured to minimize noise. This includes removal of sharp bends and tapered nozzles into mixing areas **[38]**.

Absorbing Materials

If you want a good absorptive material you want it to reflect as little as possible. Good absorptive materials include fiberglass, due to the porous nature that traps the sound, like insulation traps heat. The sound waves get stuck reflecting around inside the mesh of strands that eventually they cancel each other out (see Mufflers).

This material can be used within the system, or just for the system itself, as long as the material properties are not weakened by its use. Damped materials reduce sound, but sometimes do not maintain the strength of the undamped material.

An example is with ***conducted*** noise, where these materials can be used as absorbing pads underneath the vibrating surface. This way the sound is isolated as it is lost in the foundation material. The smaller the surface as well, the smaller the sound radiated.

Enclosures

Enclosures are used to try and contain ***radiated*** noise, although some sound still gets through by conduction through the walls.

By enclosing the vibratory source, the sound waves reflect back in on themselves, and similarly to how they act in fiberglass, cancel parts of each other out.

Enclosures add weight and are sometimes not convenient for the geometry of the problem though, so are used sparingly.

Mufflers

There are many types of mufflers available, but all have a common goal in mind – to reduce noise by canceling sound waves with other (out-of-phase) sound waves. This is known as *destructive interference*.

There are two parts to sound that are of interest:

- The frequency of the sound wave – The higher the frequency, the higher the pitch.
- The level of air pressure – The higher the wave amplitude, the higher the volume.

For example, when the exhaust valves on a car engine open, a high-pressure gas enters the exhaust system. These molecules collide with lower pressure ones and stack up down the pipe leaving a low-pressure area behind. If the engine is running faster, the valves will open more frequently, increasing the frequency of the sound traveling down the pipe, thus increasing the pitch that we hear **[39]**.

Standard Muffler:

Figure 21 shows a diagram of a standard muffler, as found on all modern cars.

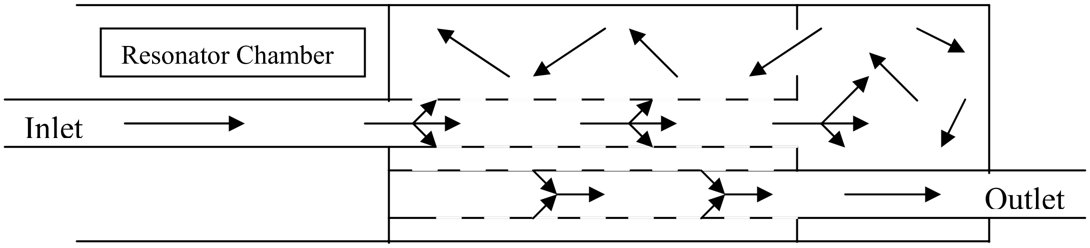


Figure 21: Diagram of a Common Muffler

This is a type of passive noise-canceling muffler that is designed to reflect the sound waves of the exhaust in such a way so that they at least partially cancel each other out. It is done by sending the exhaust through a resonator chamber and on to the back wall of the muffler. Here the sound waves reflect back into the center chamber through a hole, bouncing off the walls as they do so. All of the tiny holes in the pipes emit lots of little sound waves that do cumulatively cause sound wave destruction.

A problem with standard mufflers is the backpressure they cause, reducing the flow, and thus the engine power.

Glass-pack Muffler:

A glass-pack muffler, also known as a cherry bomb, reduces sound by absorption only. Their main advantage over standard mufflers is that they cause less of a backpressure.

Active Noise-Canceling Mufflers:

Under experimentation recently have been active noise-canceling mufflers that use microphones and a speaker to adjust to the sound of the system. A speaker is located in a pipe that encases the exhaust pipes, and microphones are located upstream and downstream from this point.

The upstream microphone detects the sounds from the engine, processes them through a computer and tells the speaker what it should produce in order to cancel out the incoming sound waves. The downstream microphone is there to tell the computer how well the speaker-microphone system is doing in canceling the sound so that it can adjust if needs be.

E2. SYSTEM EXHAUST

E2.1 Introduction to Exhaust Problems

Exhaust is an issue similar to noise, in that it can be detected and followed, to lead straight to where the system is currently operating. Exhaust is the combination of waste products that are unnecessary for the system to continue operating, and depending on the type of power source, will vary from nothing to a mixture of combustion gases.

The aim here is for any exhaust expelled from the system to be minimized and to die away

- quickly,
- and discretely.

How the exhaust reacts with the surrounding seawater (e.g. creating bubbles and/or heat differentials) is an issue that relates to the above objectives.

We have already seen how the noise of an exhaust can is treated and so this section of the report shall look at minimizing the bubble exhaust of the system and other current exhaust solutions around for the different types of power generation that we have.

E2.2 Minimizing Bubble Exhaust

To know how to minimize the bubble exhaust of our system we first need to understand what a bubble is and how it is formed.

A bubble forms and grows when a cavitation nucleus is subjected to sufficient tension. The cavitation nucleus is formed from a pressure drop within the volume of the liquid or at the liquid-solid interface.

The contents of the bubble are a mixture of vapor and gas. Mainly vaporous bubbles are responsible for noise and erosion as opposed to mainly gaseous bubbles that limit transducer outputs.

Pure liquids can actually sustain very high tensile strengths without rupturing, but it is the *impurities* in them that lower the rupture pressure. So system fluids can be purified to reduce bubble inception, but the seawater unfortunately cannot.

Why do bubbles grow and collapse?

- The cavitation nucleus is subjected to sufficient tension
- This causes the inside pressure to drop to the vapor pressure
- It then expands as a vapor bubble until it experiences a positive pressure
- Then it ceases growing, reverses and collapses.

Factors that affect the rates of growth and collapse include:

- Surface tension – As described above.
- Heat conduction – Need to reduce heat conduction in exhaust.
- Evaporation – Need to prevent evaporation.
- Viscosity – Fewer bubbles for high-viscosity liquids, but louder collapse noises.
- Compressibility – The compressibility of seawater cannot be changed noticeably.
- Pressure & Velocity fields of a moving boundary – Dominant factor for most part.

The impact of bubbles collapsing is what causes propeller erosion on ships. At first it was thought to be a chemical event, but it turns out to be the cumulative effect of many, many bubbles collapsing so fast as to cause shockwave blows to the propeller.

There is noise associated with this, which can be reduced however by the existence of *permanent gases* in the bubbles. They control the cavitation inception process as well as helping to ‘cushion’ the collapse of the bubble i.e. the bubble radius doesn’t reach zero but rebounds repeatedly until its energy dissipates into the surroundings.

So, to minimize bubble existence in the exhaust, control of the pressure drops is most important. Mixing areas should be tapered into, and exit nozzles likewise **[40]**.

Cavitation, and how to help avoid it is mentioned in **E2.2** of **Energy report #5**.

E2.3 Current Exhaust Solutions

Steam Exhaust

The ‘exhaust’ from the nuclear process into the water would at worst be steam, and likewise so for the hydrogen fuel cell.

Water is obviously non-toxic, so could be pumped out into the ocean as long as it was done slowly enough to minimize on bubble inception, and at a low enough temperature so as not to burn the operator (see **E2.2**).

Combustion Exhaust

This is harder to deal with underwater, as first of all the primary exhaust gases are toxic, and may need a catalytic converter to convert them to less harmful gases. The speed of exit from the system is again a factor here.

E3. CONCLUDING REMARKS

The system noise needs to be controlled for two reasons:

- The safety of the operator
- To reduce the chance for foreign sonars to pick up on any radiated noise.

There is a slight trade-off here because although low frequency sounds are easier on the human ear, they travel much further in water than high frequency sound waves.

However, high frequency waves are attenuated much quicker and so reduce the possibility of being detected at long range.

The system needs to operate at the most feasibly low sound level. After this any noise that cannot be avoided must be tuned to as high a frequency as is safe for the operator, so that low-frequency sound waves that escape into the water are at a minimum.

The exhaust should also be controlled for the above reasons.

Minimizing bubble exhaust is key because of how long it takes to dissipate. A lingering exhaust gives a foreign sonar time as well as accuracy to your position.

Some of the methods of power generation have exhausts that are easier to deal with than others, while some have no exhaust at all.

The methods of power generation shall be graded in a subsequent intermediate report according to:

- the amount of noise the method generates;
- the amount of exhaust the method generates;
- the toxicity of the exhaust;
- the level of sound generated by the exhaust.

F1. CONCLUSIONS

F1.1 Description of Summarizing Techniques

In this concluding section, I again aim to arrive with one recommended method of power generation for the mobile underwater units. Again though, they will not be weighted recommendations that take into account the type of energy source that they use.

I shall rank the methods of power generation for each constraint, with a ‘1’ indicating the ‘best’. This number shall equate to a point score, and the method with the lowest total score will emerge as the best solution for these unweighted constraints.

The final section to this report is the Overall Summary that will take into account both source and method to produce the optimum combination.

So here below is the ranking for each method, and following that a summarizing table for the ‘technically best’ solution.

F1.2 Ranking of Power Generation Methods for Each Constraint

Miniaturization:

Electricity – Heat →	Thermoelectric Generators	- 12
	RTG’s (nuclear)	- 13
	Reaction Turbines + Generator	- 17
	Shirt-button^{TM} turbines	- 1
Electricity – Electrochemical Sources →	Super Power Accumulators	- 9
	Lithium Ion Batteries	- 2
	Nickel Cadmium Batteries	- 2
	Nickel Metal Hydride Batteries	- 2
	Hydrino Hydride Batteries	- 2
	PEM Fuel Cells (without reformer)	- 6
	(with reformer)	- 10
	Solid Oxide Fuel Cells	- 6
	Zinc/Air Fuel Cells	- 6
	Hybrid – Fuel Cell + Battery	- 10
Mechanical Power →	Diesel Engine	- 14
	Wankel Engine	- 14
	$C0_2$ Motor	- 16

Noise:

Electricity – Heat →	Thermoelectric Generators	- 14
	RTG’s (nuclear)	- 13
	Reaction Turbines + Generator	- 17
	Shirt-button^{TM} turbines	- 10
Electricity – Electrochemical Sources →	Super Power Accumulators	- 9
	Lithium Ion Batteries	- 1

	Nickel Cadmium Batteries	- 1
	Nickel Metal Hydride Batteries	- 1
	Hydrino Hydride Batteries	- 1
	PEM Fuel Cells (without reformer)	- 5
	(with reformer)	- 11
	Solid Oxide Fuel Cells	- 5
	Zinc/Air Fuel Cells	- 5
	Hybrid – Fuel Cell + Battery	- 8
Mechanical Power →	Diesel Engine	- 15
	Wankel Engine	- 15
	$C0_2$ Motor	- 12

Minimal Bubble Exhaust:

Electricity – Heat →	Thermoelectric Generators	- 13
	RTG's (nuclear)	- 6
	Reaction Turbines + Generator	- 14
	Shirt-button^{TM} turbines	- 12
Electricity – Electrochemical Sources →	Super Power Accumulators	- 1
	Lithium Ion Batteries	- 1
	Nickel Cadmium Batteries	- 1
	Nickel Metal Hydride Batteries	- 1
	Hydrino Hydride Batteries	- 1
	PEM Fuel Cells (without reformer)	- 7
	(with reformer)	- 11
	Solid Oxide Fuel Cells	- 7
	Zinc/Air Fuel Cells	- 7
	Hybrid – Fuel Cell + Battery	- 10
Mechanical Power →	Diesel Engine	- 16
	Wankel Engine	- 16
	$C0_2$ Motor	- 15

Non-Air Breathing Capabilities:

Electricity – Heat →	Thermoelectric Generators	- 14
	RTG's (nuclear)	- 1
	Reaction Turbines + Generator	- 1
	Shirt-button^{TM} turbines	- 14
Electricity – Electrochemical Sources →	Super Power Accumulators	- 1
	Lithium Ion Batteries	- 1
	Nickel Cadmium Batteries	- 1

Nickel Metal Hydride Batteries - 1
Hydrino Hydride Batteries - 1
PEM Fuel Cells (without reformer) - 1
(with reformer) - 1
Solid Oxide Fuel Cells - 1
Zinc/Air Fuel Cells - 1
Hybrid – Fuel Cell + Battery - 1

Mechanical Power → Diesel Engine - 14
Wankel Engine - 14
$C0_2$ Motor - 1

<u>Efficiency (based on specific power):</u>

Electricity – Heat → Thermoelectric Generators - 13
RTG's (nuclear) - 8
Reaction Turbines + Generator - 16
Shirt-button^{TM} turbines - 16

Electricity – Electrochemical Sources → Super Power Accumulators - 4
Lithium Ion Batteries - 5
Nickel Cadmium Batteries - 9
Nickel Metal Hydride Batteries - 5
Hydrino Hydride Batteries - 1
PEM Fuel Cells (without reformer) - 9
(with reformer) - 9
Solid Oxide Fuel Cells - 4
Zinc/Air Fuel Cells - 12
Hybrid – Fuel Cell + Battery - 5

Mechanical Power → Diesel Engine - 2
Wankel Engine - 3
$C0_2$ Motor - 15

F1.3 Summary Table

Power Source	Specific Power W/kg	Total # Points	**FINAL RANK**
Thermoelectric Generators	14 **[41]**	66	17
RTG's (nuclear)	25-170 **[42]**	41	10
Reaction Turbines + Generator	Unknown	65	16
Shirt-button^{TM} turbines	Under development	53	12

Super Power Accumulators	1500-5000 **[43]**	24	5
Lithium Ion Batteries	200-300 **[44]**	10	=2
Nickel Cadmium Batteries	80-150 **[44]**	14	4
Nickel Metal Hydride Batteries	200-300 **[44]**	10	=2
Hydrino Hydride Batteries	Aim : (222,000)**[45]**	**(6)**	**(1)**
PEM Fuel Cells (without reformer)	150	28	6
(with reformer)	150	42	11
Solid Oxide Fuel Cells	low	33	8
Zinc/Air Fuel Cells	140 **[46]**	31	7
Hybrid – Fuel Cell + Battery	> separate systems	34	9
Diesel Engine (Kubota)	up to 83,300	61	14
Wankel Engine	~ 60,000	62	15
$C0_2$ Motor	low	59	13

Table 4: Summarizing Table

F2. CONCLUDING REMARKS

Several points come to mind on first look at **Table 4**.

Because of the unweighted analysis performed, the specific ranking that each power source comes in at will probably fluctuate slightly, but it is important to note that where they fall is roughly expected.

For example the batteries occupy the first five places, followed by the fuel cells, then RTGs and then combustion engines. This general theme of placement has been

noted throughout the report, as batteries are the all in one energy and power source, whereas combustion engines, although high in specific power, are bulky and create lots of waste products.

A power source that maybe maybe we expected to rank higher than last place was the Thermoelectric generator, which gained points for size, specific power and the need for air.

Although hydrino hydride batteries ranked in at number 1, their characteristics are as yet unproved, and so first place is not justified at this time.

By default this sends Lithium Ion batteries back into the top spot, along with, Nickel Metal Hydride batteries. Noise, bubble exhaust and non-air breathing all scored the minimum, with miniaturization being the main problem.

Fuel cells are good, and in fact weigh less than batteries, but take up more room with their external energy source. Solid oxide fuel cells however are only suited to stationary applications as their specific power is low.

In the Overall Summary I hope to look at the energy and power sources and decide which of them might be possible pairing solutions, focusing closer on which constraints are more important (than the others) – this should leave us with an optimum solution for the generation of power for a mobile underwater unit.

A1. CONCLUSIONS

A1.1 INITIAL CONCLUSIONS

An advantage of systems design is that when you deal with the specifics of a problem you can break it up in to its own sub-systems. Tackling the inner problems of a sub-system are often overcome by applying existing methods and technologies, but it is then the integration of this new solution with the other sub-systems that causes most complications. The approach to integrating the sub-systems then often requires design by innovation.

This project was investigated by dealing with the problem of a power source for a mobile underwater unit as two separate sub-systems – an energy source and a method of power generation from this source. Each analysis yielded its own conclusions, based solely as if the sub-system was the only problem to solve – i.e. a list of constraints was applied to each existing technology for both energy sources and methods of power generation, but no integration of the two sub-systems was made.

From the brief analysis of energy sources in this project, it seems that ***Batteries*** will still have a major influence in the underwater scene. It is the recent advances in battery technology (that have taken their time to arrive) that have allowed a higher energy content in some batteries, notably the magnesium hydride with nickel catalyst version.

Close behind this are the Radioactive Thermal Generators, which have seen a major boost in research following successful space application missions.

Monopropellants seem to show middling qualities for each constraint except the noise one. If improvements could be made here though, they could compete in future.

The conclusions for the best method of power generation though were harder; as it all depended on what energy source you were generating power from.

Because of the unweighted analysis performed, the specific ranking that each power source comes in at will probably fluctuate slightly, but it is important to note that where they fall is roughly expected.

For example the batteries occupy the first five places, followed by the fuel cells, then RTGs and then combustion engines. This general theme of placement has been noted throughout the report, as batteries are the all in one energy and power source, whereas combustion engines, although high in specific power, are bulky and create lots of waste products.

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Fuel cells are good, and in fact weigh less than batteries, but take up more room with their external energy source. Solid oxide fuel cells however are only suited to stationary applications as their specific power is low.

Below, I hope to look at the energy and power sources and decide which of them might be possible pairing solutions, focusing closer on which constraints are more important (than the others) – this should leave us with an optimum solution for the generation of power for a mobile underwater unit.

A1.2 POSSIBLE COMBINATIONS

1) Just Batteries

If it weren't for their bulky structure, batteries would surely be first choice for this mobile underwater system. They are exhaust free, require no oxygen from the atmosphere to function and provide negligible noise by electromagnetic interference.

To provide the same power as a top performance combustion engine, batteries would have to be pretty much larger than the car itself – if it weren't for batteries, cell phones could be designed as small as a pinhead.

Batteries are heavy too, but augmented power for the system would hopefully support this extra weight. With recent advances in Lithium Ion battery technology and the development of new types of batteries (hydrino-hydride by Blacklight Power and Super Power Accumulators by Venture Scientific International) the efficiencies of them has increased while maintaining a certain size.

If this system does not need the high power that a combustion engine can provide then perhaps batteries are the way forward.

2) Fuel cells w/ onboard hydrogen

Fuel cells are seen as not the answer to the impending fossil fuel shortage, but rather a way to halt its arrival.

The most promising fuel cell at present is the Proton Exchange Membrane Fuel Cell, which uses hydrogen as its fuel and releases water as its exhaust.

PEMFC's are high energy-density, low power-density components, allowing for a long life time when used in a stack. They don't respond well to instantaneous power loads though.

The main problem with a fuel cell of this nature though is the storage of hydrogen. Hydrogen has a very high specific energy (per kg), but a disastrous energy density (per liter). As the first element in the periodic table it takes up the most room, and so tanks of hydrogen gas would limit the amount of fuel you could take at any one time due to their required size.

Their exhaust though is simply water thanks to the reaction produced at the membrane. Pressurized oxygen is required for this reaction, again limited by space available.

Compared to batteries their weight is marginally better, but if you considered a reformer to combat the hydrogen tank problem, not only would this swing back in favor of batteries, but also the overall efficiency would drop to about 30-40%.

A fuel cell approach might best be considered if combined with another technology.

3) Zinc/Air fuel cell and Lithium Ion Battery hybrid

This combination was considered in section ***C1.1.2*** of the **Power report** and proved advantageous in a couple of ways.

The U.S. Army is currently looking at power sources combining high-energy density, low-power density sources (zinc-air 'battery', PEMFC) with high-power density, low-energy density sources (lithium-ion batteries) to deal with high current pulses and extended life of a source.

Figure 12 of the **Power report** shows that the hybrid system operates for longer than the lithium-ion and zinc/air batteries lifetimes put together. The hybrid system is also lighter and smaller than the two separate systems.

There is no need for hydrogen tanks here, but the lack of air would mean you would need air tanks instead. A possibility therefore would be to increase the size of the air tank for the operator so that the system could tap air off for use in the fuel cell.

4) Radioactive Thermoelectric Generators (RTGs)

Concerns with RTGs normally revolve around the radioactivity aspect of them, and how human life would suffer if around them too long. In the space programs they were separate from the crew (as part of the power system) and so adequate shielding was already in place. Therefore if adequate shielding could be provided for the operator in our

case then an RTG is a feasible option.

The whole process takes place within the shell (usually aluminum) and uses the Seebeck effect to directly create electricity. They are a low noise and exhaust problem with a better specific power than batteries, but suffer similar weight and volume problems.

Unfortunately though, current information on RTGs is limited as the technology is closely guarded until it is outdated.

5) Thermoelectric generator w/ external heat exchanger

A possible solution that didn't achieve as high a ranking as maybe expected is the thermoelectric generator.

Small enough generators are available (see ***Appendix B***) from GlobalTe, but there is an exhaust to deal with. A possible solution to minimizing this gaseous bubble exhaust is the use of an external heat generator to cool down (using the sea water) and hot exiting gases before they hit the ocean.

The efficiency and power output is not bad due to their use of fuel, so noise may be the only real problem. This could be dealt with using techniques highlighted in this report.

A2. CONCLUDING REMARKS & SUGGESTED SOLUTION

One of the biggest obstacles for tackling this problem was which property was more important:

Specific Energy or Energy Density?
and
Specific Power or Power Density?

The specific quantity is the amount of that quantity a source stores or provides **per unit mass** at a specified discharge rate; also called the gravimetric density; usually measured in per kilogram.

The density is the amount of that quantity a source stores or provides **per unit volume** at a specified discharge rate; also called the volumetric density; usually measured in per liter **[23]**.

Unfortunately, sources on the internet vary in their understanding of this concept, and so consequently values are often quoted with either the wrong units or the wrong conversion.

I think this problem, although requiring a high efficiency for weight requires more of a focus on the volume aspect of energy and power. This mobile underwater unit will be supplementing the movements of a human being, and so it should be able (up to a point) to support some extra weight.

Therefore I recommend that batteries are researched first, and that if they can provide enough power to satisfy the units other systems then they should be seriously considered as a solution. They are a safe, well-researched technology that excels in most of the areas of constraint.

If batteries are looking like they will not be feasible due to weight I suggest research into the fuel cell/battery combination that can have useful hybrid effects.

As a third suggestion, I wouldn't rule out RTGs because nuclear fuel is the most energetically dense and will keep on powering your system at 80% for many thousands of operations.

I hope the work in this report has been a useful starting point for those who wish to continue this research in the future,

Joseph Macklin May 7th, 2004

REFERENCES

[1] – http://www.chinfo.navy.mil/navpalib/news/.www/status.html
[2] – http://www.chinfo.navy.mil/navpalib/cno/n87/themes/forcestr.html
[3] – Jensen, J. – ENERGY STORAGE, Butterworth & Co Ltd. 1980, 1st Edition.
[4] – http://science.howstuffworks.com/nuclear-power.htm
[5] – Gilbert, Horace – MINIATURIZATION, Reinhold Publishing Corp, 1961, 1st Edition.
[6] – Carter, Raymond H. – PROBLEMS IN DESIGN, Miniature Precision Bearings, Inc.
[7] – Nesterenko, G. N. – APPLICATION OF ATOMIC ENGINES IN AVIATION, United States Department of Commerce, 1957.
[8] – http://www.usdpi.org/nuclear_fundamentals.htm#1.17.2
[9] – http://www.howstuffworks.com
[10] – http://www.spacedaily.com/news/energy-tech-02r.html
[11] – http://www.plasmavolt.com/
[12] – http://mems.sandia.gov/scripts/index.asp
[13] – http://www.nae.edu/NAE/naehome.nsf/weblinks/MKEZ-5HUQ7J?OpenDocument
[14] – http://www.doc.ic.ac.uk/~mpj01/ise2grp/energystorage_report/
[15] – http://www.ozonelab.com/products/OLO/regulators.htm
[16] – http://www.marineturbines.com/home.htm
[17] – http://www.owec.com/
[18] – http://hypertextbook.com/facts/2002/MichaelNg.shtml
[19] – http://lookwayup.com/free/dictionary.htm
[20] – http://science.howstuffworks.com/battery.htm
[21] -http://www.arofe.army.mil/Conferences/Recent_Abstract?200th_Meeting/symposia/b1c/0293.pdf
[22] – http://www.energyadvocate.com/batts.htm
[23] – http://www.mmc.or.jp/no.29/MM29f.pdf
[24] – http://www.nesea.org/greencarclub/factsheets_naturalgas.pdf
[25] – http://hypertextbook.com/facts/2003/JuliyaFisher.shtml
[26] – http://zebu.uoregon.edu/1996/ph162/l10.html
[27] – http://zebu.uoregon.edu/1996/ph162/l11.html
[28] – http://science.howstuffworks.com/fuel-cell.htm
[29] – http://www.hfcletter.com/
[30] – http://www.powerball.net/
[31] – Ross, Donald – MECHANICS OF UNDERWATER NOISE, Pergamon Press, 1976, 1st Edition
[32] – http://imagine.gsfc.nasa.gov/docs/features/movies/gamma_rays.html

[33] – http://www.nohsc.gov.au/OHSInformation/OHSSolutions/noise/contents.htm
[34] – http://www.niagaramohawk.com/house/pwrqual/emi.html
[35] – http://www.psaudio.com/articles/hum.asp
[36] – http://omp.gso.uri.edu/dosits/people/comm/2.htm
[37] – http://education.yahoo.com/reference/dictionary/entries/81/m0398100.html
[38] – http://www.qrg.northwestern.edu/projects/vss/docs/Propulsion/

[39] – http://www.patentec.com/data/class/defs/60/205.html
[40] – http://quest.nasa.gov/aero/planetary/MarsAir.html
[41] – http://fourier.vuse.vanderbilt.edu/cim/projects/presentations/exo/11-01%20Exo%20PI%20meeting.pdf
[42] – http://www.yet2.com/app/list/techpak?id=28238&sid=80&page=novelty
[43] – http://www.purdue.edu/UNS/html4ever/9912.Rusek.peroxide.html
[44] – http://www.ott.doe.gov/otu/field_ops/pdfs/fcm01r0.pdf
[45] – Macklin, Joseph – INTERMEDIATE REPORT #1, POWER SYSTEMS, 2003.
[46] – http://www.its.bldrdoc.gov/fs-1037/dir-028/_4082.htm
[47] – http://glossary.eea.eu.int/EEAGlossary/P/power_generation
[4(8)] – J. Jensen – ENERGY STORAGE, 1980, Butterworth & Co Ltd., 1st Edition.
[48] – http://dict.die.net/heat/
[49] – http://www.hyperdictionary.com/dictionary/heat
[50] – http://science.howstuffworks.com/framed.htm?parent=question136.htm&url=http://ans.neep.wisc.edu/~ans/point_source/AEI/apr95/batteries.html
[51] – http://www.joebuff.com/essay04.htm
[52] – Rogers & Mayhew, ENGINEERING THERMODYNAMICS – WORK & HEAT TRANSFER, 4th Edition, 1992, Longman
[53] – http://library.thinkquest.org/C006011/english/sites/dampfturbine.php3%3fv=2?tqskip1=1
[54] – www.techreview.com/articles/print_version/reporter10198.asp+%22Shirt+button+turbines%22&hl=en&ie=UTF-8
[55] – http://www.eecs.mit.edu/AY96-97/events/19.html
[56] – http://www.eia.doe.gov/kids/electricity.html
[57] – http://www.globalte.com/intro.htm
[58] – http://www.jpl.nasa.gov/galileo/messenger/oldmess/RTGs.html
[59] – http://www.hydridetech.com/Science___Research/High_Power_Density_Batteries_f/high_power_density_batteries_f.html
[60] – http://www.sanyo.co.jp/energy/english/faq1.htm
[61] – http://www.sanyo.co.jp/energy/english/f10.htm
[62] – http://www.elecdesign.com/Articles/Index.cfm?ArticleID=1151
[63] – http://www.blacklightpower.com/battery.shtml
[64] – http://books.nap.edu/books/0309053846/html/92.html
[65] – http://science.howstuffworks.com/fuel-cell.htm
[66] – http://www.ott.doe.gov/pdfs/energyhev_factsheet.pdf
[67] – http://www.asc2002.com/summaries/f/FP-01.pdf
[68] – http://www-cms.llnl.gov/s-t/solid_oxide.html
[69] – http://metallicpower.com/

[70] – http://www.fuelcells.org/
[71] – http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/c1
[72] – http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/otto.html#c1

[73] – http://www.taftan.com/thermodynamics/RANKINE.HTM
[74] – http://www.kubotaengine.com/kubotaperformance.htm
[75] – http://www.keveney.com/Wankel.html
[76] – http://www.me.berkeley.edu/mrcl/why.html
[77] – http://www.me.berkeley.edu/mrcl/micro.html
[78] – http://www.keveney.com/co2.html
[79] – http://www.mbari.org/data/mbsystem/formatdoc/L3TheoryOperation/thop_02.pdf
[80] – http://www.combustion-noise.de/subproject.php?project=5
[81] – http://www.nohsc.gov.au/OHSInformation/OHSSolutions/noise/contents.htm
[82] – http://auto.howstuffworks.com/muffler.htm
[83] – Macklin, Joseph – BUBBLE NUCLEATION & CAVITATION, 2003.
[84] – www.globalte.com
[85] – http://dutlsisa.lr.tudelft.nl/Propulsion/Data/Powerplants.htm
[86] – http://www.hydridetech.com/Science___Research/High_Power_Density_Batteries_f/high_power_density_batteries_f.html
[87] – http://books.nap.edu/books/NI000488/html/25.html#p200061ea9960025001
[88] – http://www.blacklightpower.com/battery.shtml
[89] – http://www.electric-fuel.com/defense/UVS02.pdf