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Port Hueneme, California 93043-4370

TECHNICAL MEMORANDUM

TM-2413-OCN

CONCLUSIONS AND RECOMMENDATIONS REGARDING THE DEEP SEA HYBRID POWER SYSTEMS INITIAL STUDY

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14. ABSTRACT

This report summarizes the conclusions made during the Initial Study regarding Deep Sea Hybrid Power Systems, and provides recommendations regarding a path forward. The Initial Study considered numerous power generation/energy conversion and energy storage technologies to support the exploration and production of oil and gas reserves remotely located off shore in the deep ocean. Detailed analyses of the technologies were then conducted. The parameters evaluated at each site included the following: estimated component weight, total weight, and total volume; initial investment, annual cost, and cost of electricity; and the economy of scale.

Based upon the Initial Study, the following conclusions were made:

- The top two candidates for power generation are both based on the small modular pressurized water reactor. One candidate couples the pressurized water reactor with a secondary steam-turbine-generator system, whereas the other candidate couples the pressurized water reactor with a solid-state thermoelectric generator.
- The leading candidates for energy storage are both versions of sodium-beta batteries: sodium/sulfur and sodium/nickel-chloride (also known as ZEBRA batteries).

The recommendation for the initial near-term efforts is to focus on conducting a detailed feasibility and implementation study; including technical approach, cost, and schedule. Additional recommendations regarding specific features that the study should address are provided in the report.

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EXECUTIVE SUMMARY

The Naval Facilities Engineering Service Center (NAVFAC ESC) provides ocean engineering program management and technical services to the Department of Energy (DOE) for matters regarding underwater power systems. As part of this support; NAVFAC ESC in collaboration with Lawrence Livermore National Laboratory (LLNL), Yardney Technical Products, Incorporated (YTP), and the Houston Advanced Research Center (HARC) were tasked to summarize conclusions made during an Initial Study regarding Deep Sea Hybrid Power Systems and provide recommendations regarding a path forward.

As oil and gas reserves on shore or in close proximity to shore are exhausted, it will be necessary to develop fields further from shore and at greater depths. At some point, it may prove to be beneficial to locate both the production equipment, as well as the associated power generation and energy storage equipment on the ocean floor. Locally powered advanced deep ocean drilling operations will provide access to oil and gas reserves otherwise inaccessible. Such technology will therefore enhance the energy security of the United States.

In order to begin the initial study, the need for system requirements was recognized. The system requirements were defined through a series of meetings with the deepwater operators that are members of the research team, followed by further review with service providers. The intent is to locate the power system in remote deepwater production sites. The power system will supply all power needs for the location so that there will be no electrical umbilical from a ‘host’ platform. Water depths of interest range from 8,500 to 12,000 feet. Eight representative deep ocean sites with a wide range of locations, depths, tie-back distances, and power requirements, were identified.

The Initial Study considered numerous power generation/energy conversion and energy storage technologies to support the exploration and production of oil and gas reserves remotely located off shore in the deep ocean. Based upon a preliminary screening of power generation and energy storage technologies, ten conceptual hybrid energy conversion and storage systems were developed for evaluation at each of the eight representative deep ocean sites. Detailed analyses of the technologies were then conducted. The parameters evaluated at each site included the following: estimated component weight, total weight, and total volume; initial investment, annual cost, and cost of electricity; and the economy of scale.

Based upon the Initial Study, the following conclusions can be made:

1. The top two candidates for power generation are both based on the small modularized pressurized water reactor. One candidate couples the pressurized water reactor with a secondary steam-turbine-generator system, whereas the other candidate couples the pressurized water reactor with a solid-state thermoelectric generator.

2. The leading candidates for energy storage are both versions of sodium-beta batteries: sodium/sulfur and sodium/nickel-chloride (also known as ZEBRA batteries), due to the exceptional cycle life possible with this technology (3,000 to 4,500 charge-discharge cycles). Due to a long and successful history with lead acid batteries in maritime application, extending back for decades, it is believed that this technology should also be considered for actual system designs.

Although it has been more than fifty-two years since the world’s first operational nuclear submarine (USS Nautilus) completed the first successful submerged voyage around the North Pole and at present time there are more than 441 light water reactors worldwide, the research team understands that there are extreme differences between a nuclear powered manned submarine operating in relatively shallow water and an unmanned nuclear power plant operating in the remote deep ocean. Systems operating remotely

on the ocean floor require special engineering to optimize reliability, minimize maintenance requirements, and to the extent possible, minimize all failure modes. Furthermore, these remote systems must be specifically designed to facilitate the installation, operation, and required maintenance procedures being conducted through remote operations (e.g., via ROVs).

The research team is also aware of existing barriers regarding nuclear power:

- Public perceptions.
- Domestic and international politics.
- U.S. Nuclear Regulatory Commission (NRC) design, siting, construction, and operation requirements, and approval and licensing timelines.
- National security.
- The Three Mile Island, and Chernobyl events occurring decades ago.
- The current ongoing events with the Deepwater Horizon drilling rig in the Gulf of Mexico (GOMEX).

Taking all these factors into account, the following recommendations are made. The initial near-term efforts should focus on conducting a detailed feasibility and implementation study; including technical approach, cost, and schedule; associated with each of the following:

Detailed Operational Requirements and Interface Specifications. Stakeholder (deepwater operators and service providers) defined baseline operational requirements and interface specifications: notional/representative exploration or production field specifications for all three identified power range requirements, including representative relative geometrical locations and electrical requirements for each power point, thereby incorporating the power distribution requirements.

Design. The design of local area power generation and distribution network systems that are based on a standard submarine power cable system, as well as a small modularized pressurized water reactor. With the pressurized water reactor and for the actual electrical power generation, both the traditional turbine-generator, and the thermoelectric should be investigated. Design considerations should include achieving a modularized approach that can be installed, assembled, and operated remotely in the deep ocean (e.g., 12,000 fsw).

Deployment, Installation/Assembly, and Recovery Plans and Procedures. Notional plans and procedures for deployment, installation/assembly, and recovery that provide a detailed overview of the necessary support vessels and equipment, personnel, logistics, and timelines, and as well as limitations and restraints associated with the subject efforts.

Operation, Maintenance, and Emergency Response Requirements. The operation and maintenance requirements of such a power network, including monitoring protocols and necessary response capability. Issues include maintaining a near continuous system health status, and the capability to appropriately respond (e.g., intervening) in a timely manner.

Approval, Licensing, and Operations Program Plan. A plan that identifies the detailed requirements, organizational roles, and responsibilities associated with obtaining approval and licensing, as well as operating such a power plant. Relevant to note is gas and oil industry’s desire not to operate such a power plant, but merely to purchase the power from the power plant owner/operator. Therefore, the intention is for this plan to address such issues.

Socialization Strategy. A strategic plan purposely developed towards addressing the various non-technical barriers associated with the implementation of a remote deep ocean nuclear power plant.

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1.0 INTRODUCTION

The Naval Facilities Engineering Service Center (NAVFAC ESC) provides ocean engineering program management and technical services to the Department of the Navy (DON) and the Department of Energy (DOE) for matters regarding underwater power systems, including deep submergence batteries. As part of the NAVFAC ESC support to DOE; NAVFAC ESC in collaboration with Lawrence Livermore National Laboratory (LLNL), Yardney Technical Products, Incorporated (YTP), and the Houston Advanced Research Center (HARC) were tasked to summarize conclusions made during an Initial Study regarding Deep Sea Hybrid Power Systems and provide recommendations regarding a path forward. This report is the deliverable for that tasking.

2.0 BACKGROUND

The Energy Policy Act of 2005 established a natural gas supply research and development program associated with Ultra-deepwater and Unconventional Onshore Hydrocarbon Resources to be funded over the next 10 years. The legislation identified the National Energy Technology Laboratory (NETL) as the DOE entity responsible for review and oversight of this program, and the NETL Ultra-deepwater and Unconventional Natural Gas and Other Petroleum Resources Program is the implementation of this legislative direction.

In January 2007, NETL contracted the management of these funds to the Research Partnership to Secure Energy for America (RPSEA). RPSEA is a non-profit corporation established to help meet the nation's growing need for hydrocarbon resources produced from reservoirs in America. The RPSEA corporation is formed by a consortium of U.S. energy research universities, industry, and independent research organizations.

NAVFAC ESC, through tasking received from the DOE National Nuclear Security Administration (NNSA), has been supporting the following RPSEA program: Deep Sea Hybrid Power Systems (Initial Study). The following list summarizes the primary organizations/members of the research team that have been collaborating on this program. Relevant to note is that HARC has been serving as the Program Manager / Prime Contractor, thereby providing direction to the other organizations:

- Houston Advanced Research Center (HARC)
- Lawrence Livermore National laboratory (LLNL)
- Yardney Technical Products, Incorporated (YTP)
- Lithion, Incorporated (Lithion)
- Chevron Energy Technology Company (Chevron)
- Shell Exploration and Production (Shell)[1]
- Total Exploration and Production Research and Technology USA (Total)
- Curtiss-Wright Electro-Mechanical Corporation (Curtiss-Wright)

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[1] Elected not to be included in the Confidential Disclosure Agreement executed December 18, 2009.

3.0 IMPORTANCE OF INVESTIGATION

As oil and gas reserves on shore or in close proximity to shore are exhausted, it will be necessary to develop fields further from shore and at greater depths. At some point, it may prove to be beneficial to locate both the production equipment, as well as the associated power generation and energy storage equipment on the ocean floor. Locally powered advanced deep ocean drilling operations will provide access to oil and gas reserves otherwise inaccessible. Such technology will therefore enhance the energy security of the United States.

4.0 FUNCTIONAL REQUIREMENTS – BASIS OF DESIGN

In order to begin the initial study, the need for system requirements and the establishment of quantitative and qualitative selection criteria was recognized. The system requirements were defined through a series of meetings with the deepwater operators that are members of the research team, followed by further review with service providers.

The intent is to locate the power system in remote deepwater production sites. The power system will supply all power needs for the location so that there will be no electrical umbilical from a ‘host’ platform. The power system would be sized to supply the site specific needs. Three (3) power ranges of interest were identified:

- Mid-power, 1 to 10 MW (AC), for small scale multiphase pumps.
- Large-power, 10 to 30 MW (AC), for gas compression and satellite field installations.
- Mega-power, 30 to 200 MW (AC), for cold-ironing of drilling vessel.

Water depths of interest range from 8,500 to 12,000 feet, with the nominal water temperature at these depths being 39.4 °F. System redundancy and reliability of the subsea power supply is critical. System designs must consider shock loads that may occur during installation. Small equipment must be able to withstand a shock load of up to 3g. Larger equipment must be able to withstand a shock load of 5g.

Eight representative deep ocean sites with a wide range of locations, depths, tie-back distances, and power requirements were selected and are summarized in Table 1. Shtokman (Barents Sea) and Ormen Lange (Norway) have the greatest requirement for electrical power, at approximately 240 and 60 megawatts-electrical, respectively, and also have the greatest tie-back distances, 209 and 193 miles, respectively. The sites at the greatest depths are Chinook and Perdido (Gulf of Mexico), located at approximately 8,800 and 7,999 feet respectively, but have relatively short tie-back distances of approximately 12 miles, and modest power requirements, 7.2 and 5 megawatts-electrical, respectively. The Marimba Field (Campros Basin) has the least power requirement, at only 80 kilowatts-electrical, is located at a depth of only 1,296 feet, and has a tie-back distance of only 1 mile. While the power requirements, tie-back distance, and location for Shtokman and Ormen Lange appear to be sufficiently challenging to warrant extraordinary measures for power, it would be surprising if such measures could be justified at the Marimba Field. All were included in the study to provide a wide range of scenarios. Reference (1) is the Functional Requirements – Basis of Design document developed in December 2008.

TABLE 1

EIGHT (8) REPRESENTATIVE DEEP OCEAN SITES

Field or Project	Owner	Region	Year	Depth	Depth	Tie Back	Tie Back	Total Power
name			calendar	meters	feet	km	miles	MW
Shtokman	Gazprorn	Barents Sea	2020	350	1,148	909.0	565.0	240.0
Chinook	Petrobras	GOM	2009	2,682	8,800	19.3	12.0	0.0
King	BP	GOM	2007	1,700	5,578	29.0	18.0	0.0
Ormen Lange	Hydro	Norway	2011	850	2,789	193.0	120.0	60.0
Perdido	Shell	GOM	2010	2,438	7,999	NA	NA	0.0
Argonauta	Shell	Brazil	2009	1,900	6,234	9.0	5.6	0.0
Marimba Field	Petrobras	Campros Basin	2000	395	1,296	1.1	0.7	0.0
Pazflor	Total	Angola Blk 17	2011	800	2,625	9.0	6.0	0.0
Hypothetical				1,389	4,559	167.1	103.9	37.5

5.0 SUMMARY OF INITIAL STUDY

Energy storage combined with energy conversion/power generation must be integrated, thereby creating a hybrid system capable of providing a constant source of electrical power, as well as enabling either sustained operation or graceful shutdown in the event that the primary power generation systems fails.

As part of the initial study, numerous energy conversion technologies have been considered: (1) proton-exchange membrane fuel cells (PEMFC) powered with hydrogen and oxygen, similar to that used on proven subsurface vessels; (2) fuel-cells capable of using natural gas from deep ocean wells; (3) internal combustion engines (ICE) powered with natural gas from deep ocean wells; (4) turbines powered with natural gas from deep ocean wells; (5) solid-state thermoelectric and thermionic generators (TEG) powered with natural gas from deep ocean wells, geothermal sources, and radioisotopes; (6) renewable energy sources at the surface, including solar, wind and wave powered generators; (7) renewable energy sources on the seafloor, including turbines powered with ocean current; and (8) small pressurized-water reactors (PWR) with low-enrichment fuel, similar to those used on the NS Savannah and NS Otto Hahn commercial ships.

Energy storage technologies that were explored included: mechanical flywheels, compressed-gas storage; regenerative liquid redox batteries; regenerative fuel cells; and both secondary batteries in sealed pressure vessels as well as pressure-tolerant secondary batteries. Battery chemistries included a wide range of other conventional and unconventional batteries such as lead-acid, silver-zinc, sodium-beta, and lithium-ion.

Based upon a preliminary screening of power generation and energy storage technologies, ten conceptual hybrid energy conversion and storage systems were developed for evaluation at each of the eight (8) representative deep ocean sites listed in Table 1. These conceptual hybrid systems are summarized in Table 2.

TABLE 2

SUMMARY OF DEEP OCEAN HYBRID GENERATION AND STORAGE OPTIONS CONSIDERED FOR INITIAL STUDY

NO.	NOMENCLATURE	DESCRIPTION
1	PWR	Nuclear Reactor + Battery
2	FC1	PEMFC + Line for surface O_2 + Wellhead Gas + Reformer + Battery
3	FC2	PEMFC + Stored O_2 + Wellhead Gas + Reformer + Battery
4	SV1	PEMFC + Submersible Vehicle for O_2 Transport + Wellhead Gas + Reformer + Battery
5	SV2	ICE or Turbine + Submersible Vehicle for O_2 + Wellhead Gas + Reformer + Battery
6	SV3	Submersible Vehicle with Large Capacity Batteries + Surface Charging Station
7	PWR TEG	Thermoelectric Generator Powered by Heat from Nuclear Reactor + Battery
8	WELL TEG	Thermoelectric Generator Powered by Heat from Combustion of Wellhead Gas + Battery
9	GRID	Ocean Floor Electrical Grid + Battery
10	DOC	Deep Ocean Current + Battery

The deep ocean current option was abandoned early due to the low ocean floor current velocities (less than 0.5 meters per second), and the very large turbine size required (300-foot span). The submersible vehicle options, subsequent to the detailed analysis described below, were later abandoned due to cost and impracticalities.

Detailed Analysis

Detailed analyses of the technologies were conducted and are formally documented in references (2), (3), and (4). The following provides a summary of the areas of investigation:

Estimated Component Weight, Total Weight, and Total Volume for Each Site

The estimated weights of the energy conversion and storage components for each hybrid system, the estimated total weight for each hybrid system, and the estimated total volume for each hybrid system were evaluated for each of the eight representative sites. The estimated weight of the hybrid energy conversion and storage systems for the three largest sites: Shtokman, Chinook and Ormen Lange, are between 10,000 and 100,000 metric tons. For comparison, the NS Savannah and NS Otto Hahn weighed 25,790 and 22,000 metric tons, respectively. Thus, the largest hybrid systems will have weights comparable to these nuclear powered ships. While the hybrid systems are comparable to the commercial nuclear-powered ships in weight, their density is greater, so they occupy less volume than the ships. Table 3 and Figures 1 through 3 summarize these evaluations.

TABLE 3

SUMMARY OF THE ESTIMATED WEIGHTS AND VOLUMES

Hybrid System Volume (Cubic Meters)									
Site	**PWR**	**FC1**	**FC2**	**SV1**	**SV2**	**SV3**	**PWR TEG**	**WELL TEG**	**GRID**
Shtokman	89,574	185,132	21,126,191	52,815,478	42,795,786	2,433,210	324,766	323,145	92,534
Chinook	3,139	71,237	7,785,692	19,464,230	8,429,285	88,712	12,455	12,397	3,238
King	840	4,642	524,414	1,311,036	921,613	23,442	3,190	3,174	986
Ormen Lange	24,027	69,480	7,953,368	19,883,421	15,506,951	661,517	87,782	87,332	24,551
Perdido	2,112	28,999	3,202,843	8,007,107	4,370,490	59,280	8,313	8,275	2,231
Argonauta	943	6,236	699,846	1,749,614	1,179,736	26,442	3,608	3,590	998
Marimba Field	30	64	7,343	18,358	14,827	817	109	108	38
Pazflor	5,167	15,204	1,760,846	4,402,115	3,447,586	140,892	19,216	19,124	5,108
Hybrid System Weight (Metric Tons)									
Site	**PWR**	**FC1**	**FC2**	**SV1**	**SV2**	**SV3**	**PWR TEG**	**WELL TEG**	**GRID**
Shtokman	56,163	67,923	86,641	216,603	136,060	1,237,266	95,306	94,222	95,938
Chinook	3,476	54,517	45,989	114,973	24,922	85,544	9,018	8,951	4,805
King	736	2,668	2,650	6,625	2,815	17,451	1,654	1,640	2,169
Ormen Lange	16,837	30,173	34,832	87,081	47,791	382,404	32,145	31,818	25,188
Perdido	2,231	20,740	18,208	45,521	13,049	54,117	5,567	5,525	3,584
Argonauta	865	3,810	3,659	9,148	3,597	20,723	2,013	1,996	1,499
Marimba Field	19	24	30	76	47	420	33	32	98
Pazflor	3,732	6,527	7,612	19,030	10,567	83,903	7,001	6,929	3,950
Energy Conversion & Storage Components (Metric Tons)									
Site	**PWR**	**FC1**	**FC2**	**SV1**	**SV2**	**SV3**	**PWR TEG**	**WELL TEG**	**GRID**
Shtokman	49,600	56,866	47,096	117,740	64,762	1,072,340	76,873	75,913	89,499
Chinook	1,488	16,447	8,375	20,937	2,023	32,170	2,306	2,277	2,855
King	413	1,192	732	1,829	546	8,936	641	633	1,852
Ormen Lange	12,400	19,723	14,375	35,937	16,244	268,085	19,218	18,978	20,838
Perdido	1,033	6,879	3,671	9,176	1,388	22,340	1,602	1,582	2,409
Argonauta	455	1,565	924	2,311	602	9,830	705	696	1,097
Marimba Field	17	20	16	40	22	357	26	25	96
Pazflor	2,852	4,396	3,240	8,099	3,735	61,660	4,420	4,365	3,086

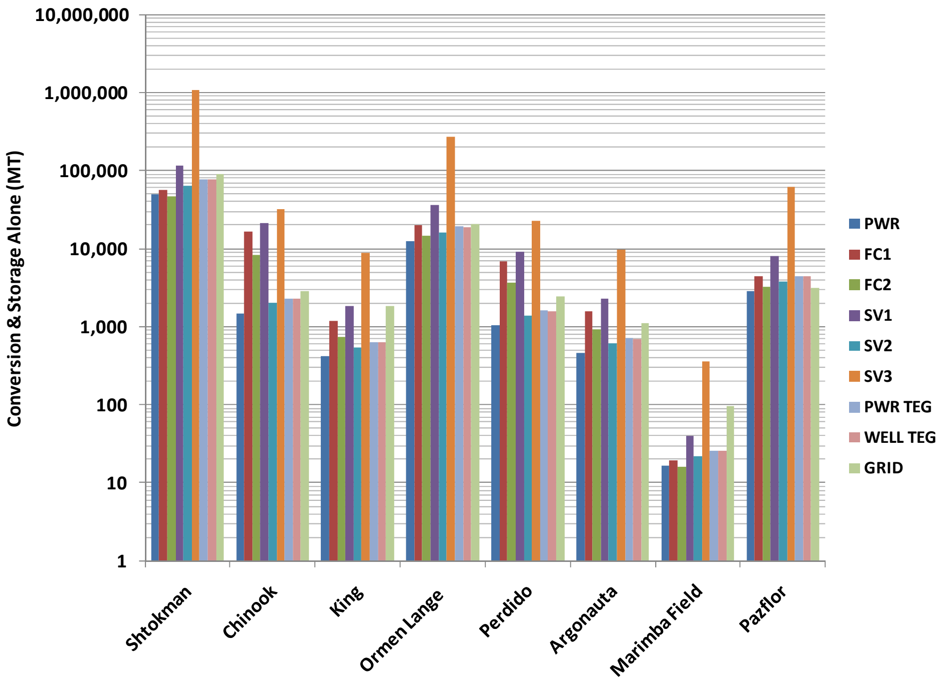


FIGURE 1: Graphical Comparison of Estimated Weights of Power Generation and Energy Storge Components.

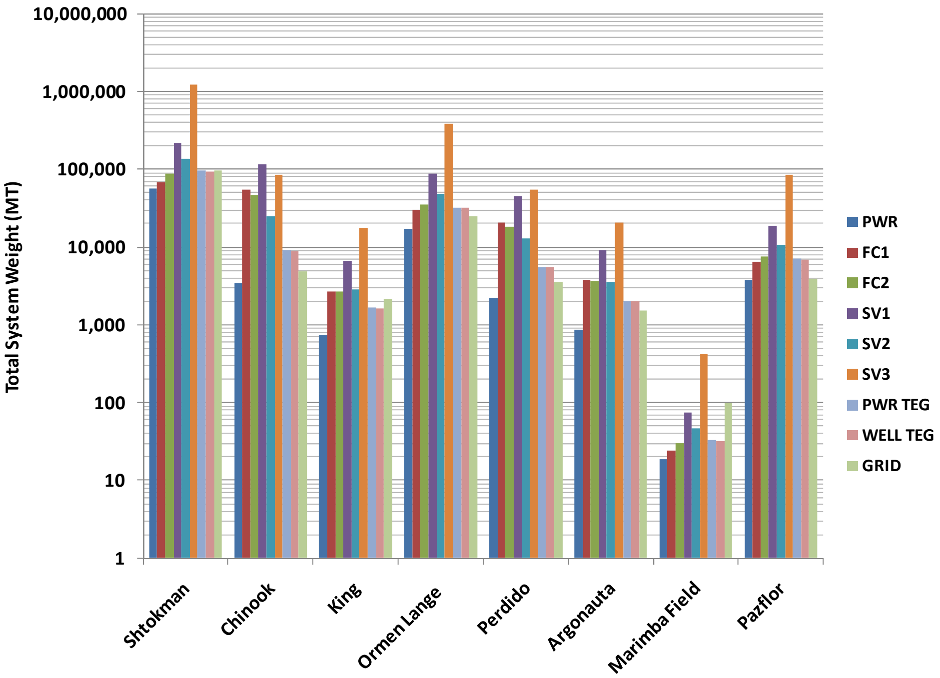


FIGURE 2: Graphical Comparison of Estimated Total Weights of the Hybrid Power Systems.

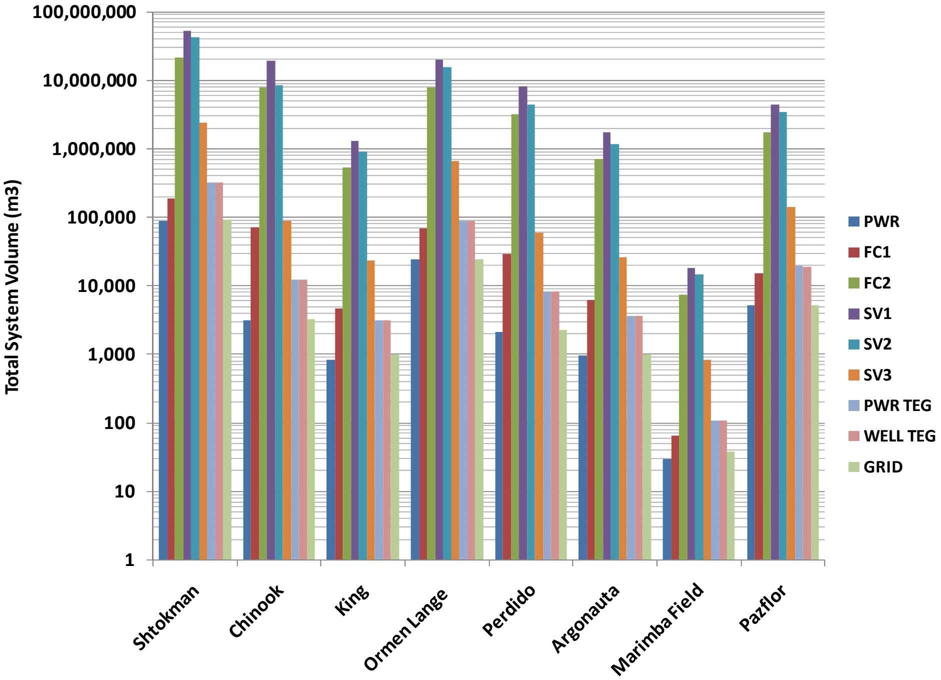


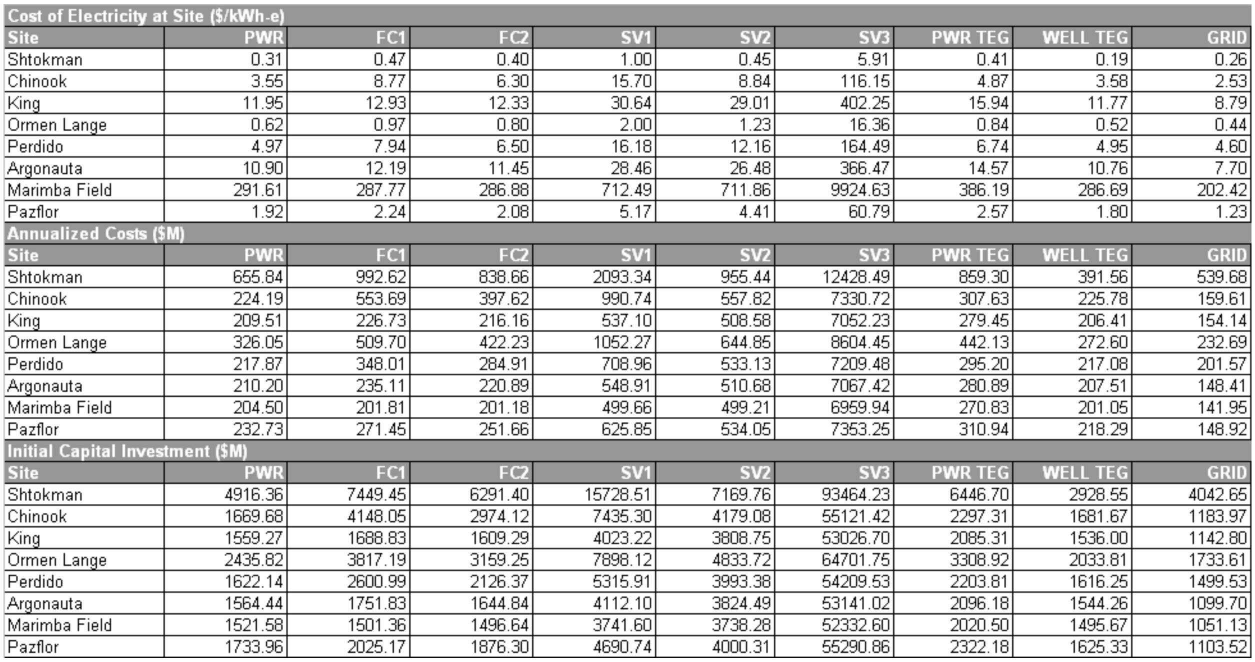
FIGURE 3: Graphical Comparison of Estimated Total Volumes of the Hybrid Power Systems.

Initial Investment, Annual Cost, and Cost of Electricity

The estimated initial capital investment at the commencement of commercial operations, the estimated annualized costs, and the estimated cost of electricity were evaluated for each site, and are summarized in Table 4 and Figures 4 through 6. The capital costs are dominated by parameters that are insensitive to the size of the site, such as those used to account for the assumed protective hull. The subsea vehicular options are the most expensive and least practical. The subsea vehicle that ferries stored energy from the surface to the site via batteries is by far the worst option, and therefore was subsequently not given any serious consideration. Like the initial capital cost, the annualized costs are dominated by parameters that are insensitive to the size of the site. The least expensive option for power at all of the representative sites is the electrical grid, with an assumed cost of approximately $2.5 million per kilometer. In regard to the cost of electricity, hybrid power options that are comparable with the grid option include the pressurized water reactor (PWR), a fuel cell on the ocean floor fueled with wellhead methane and a line to the surface for compressed air (FC1), or a fuel cell on the ocean floor fueled with wellhead methane and oxygen brought to the system in submersible tanks (FC2). That said the research team considers FC2 impractical from an operational point-of-view.

TABLE 4

SUMMARY OF THE INITIAL INVESTMENT, ANNUAL COST, AND COST OF ELECTRICITY



Cost of Electricity at Site ($/kWh-e)									
Site	**PWR**	**FC1**	**FC2**	**SV1**	**SV2**	**SV3**	**PWR TEG**	**WELL TEG**	**GRID**
Shtokman	0.31	0.47	0.40	1.00	0.45	5.91	0.41	0.19	0.26
Chinook	3.55	8.77	6.30	15.70	8.84	116.15	4.87	3.58	2.53
King	11.95	12.93	12.33	30.64	29.01	402.25	15.94	11.77	8.79
Ormen Lange	0.62	0.97	0.80	2.00	1.23	16.36	0.84	0.52	0.44
Perdido	4.97	7.94	6.50	16.18	12.16	164.49	6.74	4.95	4.60
Argonauta	10.90	12.19	11.45	28.46	26.48	366.47	14.57	10.76	7.70
Marimba Field	291.61	287.77	286.88	712.49	711.86	9924.63	386.19	286.69	202.42
Pazflor	1.92	2.24	2.08	5.17	4.41	60.79	2.57	1.80	1.23
Annualized Costs ($M)									
Site	**PWR**	**FC1**	**FC2**	**SV1**	**SV2**	**SV3**	**PWR TEG**	**WELL TEG**	**GRID**
Shtokman	655.84	992.62	838.66	2093.34	955.44	12428.49	859.30	391.56	539.68
Chinook	224.19	553.69	397.62	990.74	557.82	7330.72	307.63	225.78	159.61
King	209.51	226.73	216.16	537.10	508.58	7052.23	279.45	206.41	154.14
Ormen Lange	326.05	509.70	422.23	1052.27	644.85	8604.45	442.13	272.60	232.69
Perdido	217.87	348.01	284.91	708.96	533.13	7209.48	295.20	217.08	201.57
Argonauta	210.20	235.11	220.89	548.91	510.68	7067.42	280.89	207.51	148.41
Marimba Field	204.50	201.81	201.18	499.66	499.21	6959.94	270.83	201.05	141.95
Pazflor	232.73	271.45	251.66	625.85	534.05	7353.25	310.94	218.29	148.92
Initial Capital Investment ($M)									
Site	**PWR**	**FC1**	**FC2**	**SV1**	**SV2**	**SV3**	**PWR TEG**	**WELL TEG**	**GRID**
Shtokman	4916.36	7449.45	6291.40	15728.51	7169.76	93464.23	6446.70	2928.55	4042.65
Chinook	1669.68	4148.05	2974.12	7435.30	4179.08	55121.42	2297.31	1681.67	1183.97
King	1559.27	1688.83	1609.29	4023.22	3808.75	53026.70	2085.31	1536.00	1142.80
Ormen Lange	2435.82	3817.19	3159.25	7898.12	4833.72	64701.75	3308.92	2033.81	1733.61
Perdido	1622.14	2600.99	2126.37	5315.91	3993.38	54209.53	2203.81	1616.25	1499.53
Argonauta	1564.44	1751.83	1644.84	4112.10	3824.49	53141.02	2096.18	1544.26	1099.70
Marimba Field	1521.58	1501.36	1496.64	3741.60	3738.28	52332.60	2020.50	1495.67	1051.13
Pazflor	1733.96	2025.17	1876.30	4690.74	4000.31	55290.86	2322.18	1625.33	1103.52

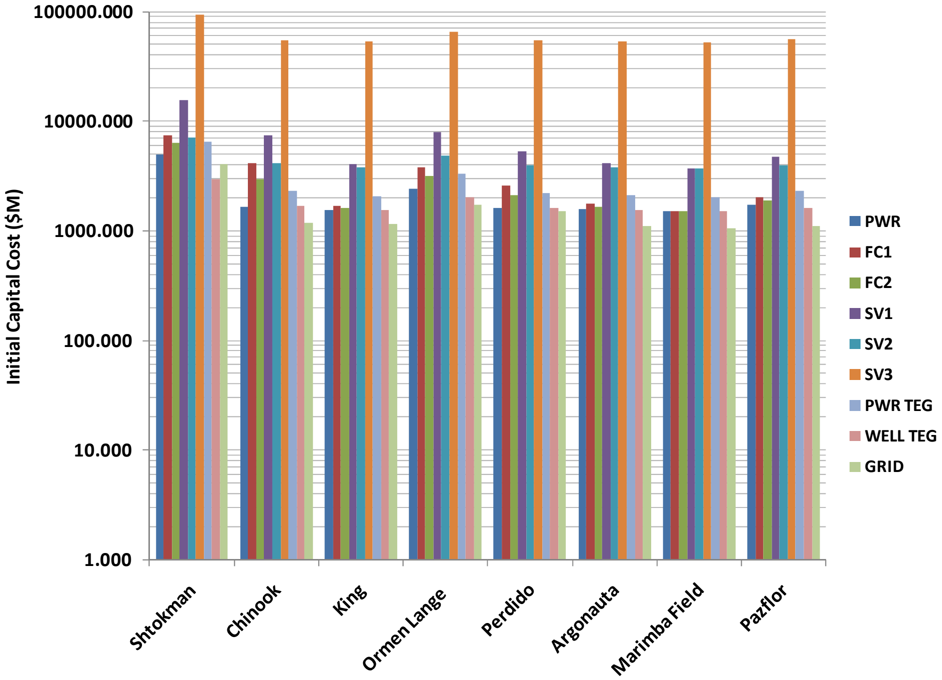


FIGURE 4: Graphical Comparison of the Estimated Initial Capital Investment Required for Each Site.

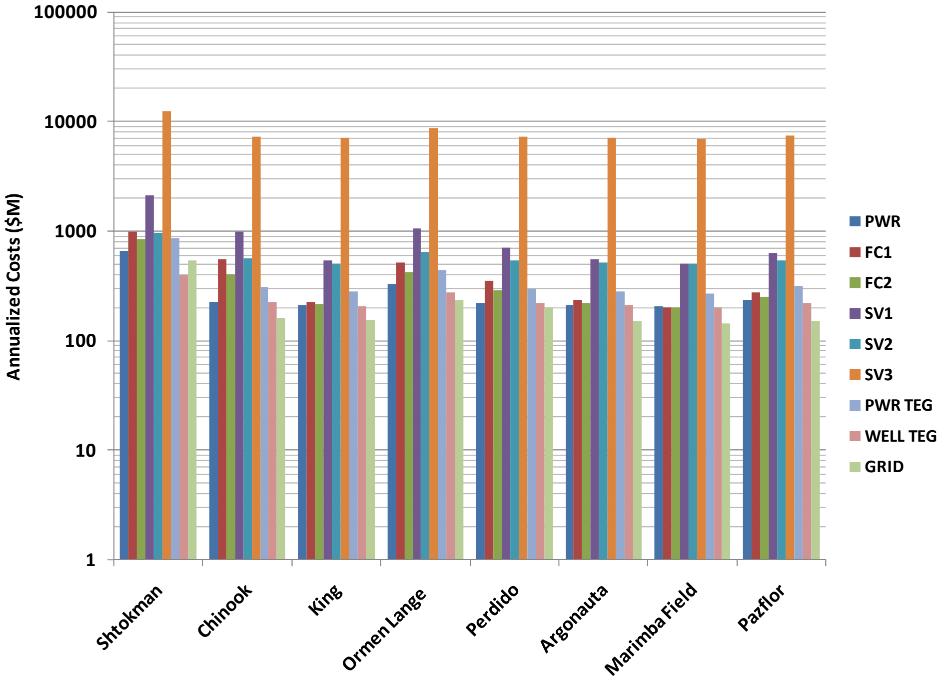


FIGURE 5: Graphical Comparison of the Estimated Annualized Costs for Each Site.

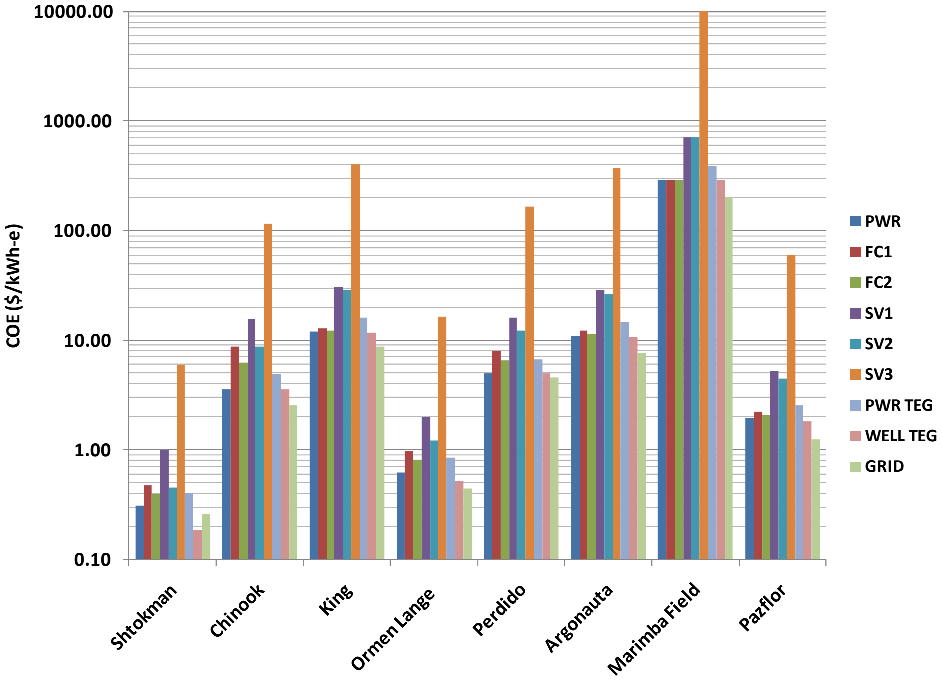


FIGURE 6: Graphical Comparison of the Estimated Cost of Electricity for Each Site.

Economy of Scale

The estimated cost of electricity as a function of power generation capacity is shown in Figure 7, and shows a clear economy of scale. As the systems become larger, the cost of electricity produced by the system becomes less expensive, regardless of the hybrid system assumed. The two largest sites, Shtokman and Ormen Lange are of sufficient size so that power can be supplied for less than $1 per kilowatt-hour, comparable to the cost for grid power.

The power generation systems that have been identified for more detailed evaluation include: small modular pressurized water reactors (PWR); proton-exchange membrane fuel cells (PEMFC), located on the ocean floor and fed with hydrogen produced by reforming natural gas available at subsea wellheads; thermoelectric generators (TEG), powered from heat generated by small pressurized water reactors, or waste heat from subsea wellheads; and subsea electrical grids carrying power from power plants located on shore. From the initial list of energy storage technologies, only rechargeable batteries: lead-acid, sodium-sulfur, ZEBRA, and lithium-ion were identified for more detailed evaluation.

In the case of power generation systems relying on the oxidation of natural gas or hydrogen derived from subsea wells, oxygen from the surface will have to be supplied to the system, either from tanks used to transport it to the site, or via a pipe in communication with the surface. Obviously, the air supply problem is a major impediment for the use of wellhead gas as an energy source.

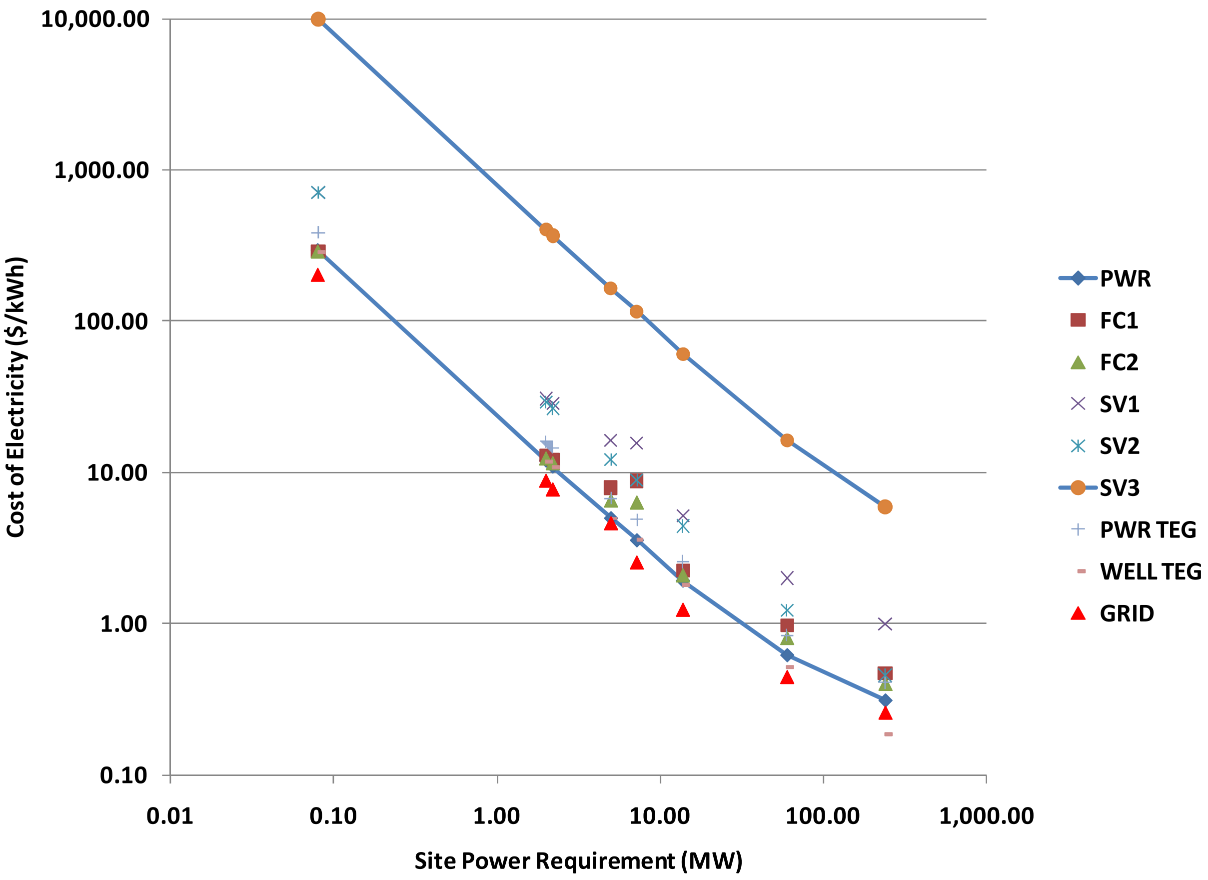


FIGURE 7: Estimated Cost of Electricity as a Function of Power Generation Capacity

Power Generation Technologies

Small Modular Nuclear Reactors

Small modular nuclear reactors are capable of producing immense electrical power, and require relatively little mass or volume. This has led to their application in military ships and boats, including aircraft carriers and submarines. Nuclear powered submarines of several countries have now operated in the oceans of the world for nearly fifty years. While such military systems are both unavailable and inappropriate for the oil and gas industry to consider, other types of nuclear power plants have been successfully deployed onboard commercial ships.

At the present time, there are more than 441 light water reactors (LWRs) worldwide with a total generating capacity of 358.7 GWe. Table 5 summarizes this inventory by global region, and Table 6 provides insight regarding the types and locations of relatively small modular reactors.

TABLE 5

INVENTORY OF NUCLEAR REACTORS WORLD-WIDE BY GLOBAL REGIONS

Worldwide Nuclear Reactors				
	Completed & Operating	Completed & Operating	Under Construction	Under Construction
Regions	Reactors	Total Capacity	Reactors	Total Capacity
	Number	Gwe	Number	Gwe
West Europe	146	125.7	0.0	0.0
East Europe	67	46.1	10.0	8.0
America	124	112.4	1.0	0.7
Asia & Africa	104	74.5	22.0	18.4
World	441	358.7	33.0	27.1

TABLE 6

COUNTRY OF ORIGIN AND ELECTRICAL GENERATING CAPACITY OF SMALL NUCLEAR REACTORS

Reactor	Location	Power
VK-300	Atomenergoproekt, Russia	300 MWe PWR
CAREM	CNEA & INVAP, Argentina	27 MWe PWR
KLT-40	OKBM, Russia	35 MWe PWR
MRX	JAERI, Japan	30-100 MWe PWR
IRIS-100	Westinghouse-led, international	100 MWe PWR
B&W mPower	Babcock & Wilcox, USA	125 MWe PWR
SMART	KAERI, S. Korea	100 MWe PWR
NP-300	Technicatome (Areva), France	100-300 MWe PWR
HTR-PM	INET & Huaneng, China	105 MWe HTR
PBMR	Eskom, South Africa,	165 MWe HTR
GT-MHR	General Atomics (USA), Minatom (Russia) et al	280 MWe HTR
BREST	RDIPE (Russia)	300 MWe LMR
FUJI	ITHMSO, Japan-Russia-USA	100 MWe MSR

The mPower^{TM} reactor being developed by Babcock and Wilcox (B&W) of Lynchburg, Virginia leverages a long history of success with earlier designs. This small PWR has a power of 125 megawatts, a volume of 158 cubic meters and a weight of 500 metric tons. It is fueled with uranium enriched to 7.0 percent U-235. This modular reactor has been designed to have an endurance of 1,825 days (time between refueling operations). The mPower reactor has extremely high specific power, power density, specific energy and energy density: 250 W/kg, 792 W/L, 10,950,000 Wh/kg, and 34,672,967 Wh/L, respectively.

Pressurized water reactors (PWR) were the focus of this study, since much of our experience at sea involves this type of technology. However, as actual designs are developed for deep-ocean systems, other new reactor technologies should also be considered. For example, pebble-bed reactors (PBRs) and very high temperature reactors (VHTRs) are designed to use TRISO (tri-structural isotropic) type fuels, which are capable of being operated at extremely high temperature (up to 1,600°C), with correspondingly high thermal-to-electric efficiency, with relatively high burn-up of the nuclear fuel.

Proton-Exchange Membrane Fuel Cell (PEMFC)

The high reliability of fuel cells, coupled with high energy density, have led to their use in a variety of demanding applications, ranging from space exploration to subsea vessels with long endurance. Proton-exchange membrane fuel cells, with solid-state hydrogen storage and liquid oxygen have been developed and used by HDW in Kiel Germany for providing air-independent propulsion (AIP) for non-nuclear submarines (212 and 214 Classes). These small, relative to the typical U.S. submarines, and efficient submarines have now been produced in relatively large numbers. Thus, the viability of subsea fuel cell systems for demanding large scale applications has been unambiguously demonstrated.

Natural gas from deep ocean wells would be a logical energy source for supplying subsurface fuel cells at deep ocean production sites. Natural gas from the well could be converted to hydrogen via a reformer, and fed to an environmentally benign, ambient temperature PEMFC via gas purification membranes, required to filter out electro-catalytic poisons, including carbon monoxide and sulfur-bearing chemical species. This option could potentially eliminate the need for pipelines to transport natural gas away from subsea well heads. Alternatively, the natural gas could be used directly to fuel a high temperature solid oxide fuel cell (SOFC), though the operation of such a high temperature system on the sea floor poses additional complications.

Thermoelectric Generator Powered by Heat from Wellhead or Nuclear Reactor

Solid-state thermoelectric generators have no moving parts, and can be used for the reliable direct conversion of heat to electrical energy, with exceptional reliability in remote and inaccessible locations, including deep space. Such energy converters could be powered on the seafloor in a variety of ways, including geothermal heat sources, heat from the combustion of natural gas from deep ocean wells, decay heat from radioisotopes, and small deployable nuclear reactors. Radioisotope sources with the necessary power density for the applications of interest to the oil and gas industry are believed to be too limited for serious consideration.

Energy Storage Technologies

Lead-Acid Batteries

The lead-acid battery has a metallic anode made of a lead alloy, a lead-oxide cathode, a porous polyethylene separator, and an electrolyte of concentrated sulfuric acid. This battery can operate from -20 to +60°C. The open-circuit voltage is 2.1 V, with operation between 2.0 and 1.75 V. The specific power, power density, specific energy and energy density are 20 W/kg, 51 W/L, 20-35 Wh/kg, and 50-90 Wh/L, respectively. The cycle life of a typical lead acid battery can be as high as 1100 cycles (to 80% of the original capacity). The cost of energy storage is approximately $150 per kilowatt-hour. In summary, lead-acid batteries are proven technology, with a long history of sub-surface application in submarines. The lead-acid battery is relatively heavy, but is relatively inexpensive, and is therefore considered as a potential candidate for the subject application.

Sodium-Sulfur Batteries

The sodium-sulfur battery is categorized as a sodium-beta battery. It has a molten sodium anode, a $\beta''\text{-}Al_2O_3$ ceramic separator, which also serves as the solid-state, Na^+-conductive electrolyte, and a molten sulfur cathode. This battery is challenged by the need for a relatively high operating temperature of 290 to 390°C. The open-circuit voltage is 2.08 V, with operation between 1.95 and 1.78 V. The specific power, power density, specific energy and energy density are 390-250 W/kg, 604-386 W/L, 117-226 Wh/kg, and 147-370 Wh/L, respectively. The sodium-sulfur battery has exceptional cycle life, with a maximum life of approximately 2,250 cycles (to 80% of the original capacity), making it a reasonable choice for remote deployment where maintenance would be difficult. Despite the use of molten alkali electrodes, which can react with air and water, this battery has a very good safety record. No gaseous reaction products are formed during overcharge, and the separator tends to be self-healing. The cost of energy storage is approximately $300 per kilowatt-hour, which is modest. In summary, sodium-sulfur batteries are proven technology, with a solid history of applications in grid-storage (NGK Corporation of Japan). The sodium-sulfur battery is a reasonable contender for sub-surface applications, but will require insulated battery bottles, and auxiliary heating equivalent to approximately 10% of the batteries stored energy.

ZEBRA Batteries

The ZEBRA battery is also categorized as a sodium-beta battery, like the sodium-sulfur battery. The ZEBRA also has a molten sodium anode and a $\beta''\text{-}Al_2O_3$ ceramic separator, which also serves as the solid-state, Na^+-conductive electrolyte, but has a $Ni/NiCl_2$ cathode with a secondary $NaAlCl_4$ electrolyte, instead of the sulfur-based cathode used in the sodium-sulfur battery. This battery is also challenged by the need for a relatively high operating temperature of 220 to 450°C. The open-circuit voltage is approximately 2.58 V, with operation between 2.25 and 1.72 V, slightly higher than the terminal voltage of the sodium-sulfur battery. The specific power, power density, specific energy and energy density are 171-169 W/kg, 265-261 W/L, 94-119 Wh/kg, and 148-183 Wh/L, respectively, lower than that possible with sodium-sulfur technology. The ZEBRA battery has exceptional cycle life, even better than that achieved with the sodium-sulfur battery, with a maximum life of approximately 3,500 cycles (to 80% of the original capacity), making it a reasonable choice for remote deployment where maintenance would be difficult. The cost of energy storage is only $220 per kilowatt-hour, which is less than that for the sodium-sulfur battery. In summary, ZEBRA batteries are proven technology, with a solid history of applications in transportation, and deep ocean applications. The ZEBRA battery is a reasonable contender for sub-surface applications, but will require insulated battery bottles, and auxiliary heating equivalent to approximately 10% of the batteries stored energy.

Lithium Ion Batteries

The modern lithium-ion battery has an anode that consists of a graphite-based active material (Li-C6) with carbon filler and polyvinylidene fluoride (PVDF) binder coated onto a copper foil current collector; a cathode that consists of a transition metal oxide or iron phosphate (Li-NiO_2, Li-CoO_2, Li-MnO_2, or Li-$FePO_4$) active material with a PVDF binder coated onto an aluminum foil current collector; a microporous porous polyethylene separator, and an electrolyte consisting of a mixed organic carbonate solvent (EC:DMC:DEC) and $LiPF_6$ salt. Of course, more advanced materials are evolving, such as the lithium titanate anode (Li-Ti_2O_4) and solid state electrolytes such as LiPON^{TM}. The liquid cylindrical or prismatic cells are contained in a hermetically sealed metal can, while polymer-gel cells are contained in a soft aluminum-polyethylene laminate package, with thermally laminated seams. In the case of the polymer-gel cell, the polyethylene separator is usually coated on both sides with porous PVDF layers. This battery can operate from -40 to +60°C. The open-circuit voltage is 4.1 V, with operation between 4.0 and 3.0 V (possibly as low as 2.8 V). The specific power, power density, specific energy and energy density are 1100-74 W/kg, 2270-147 W/L, 75-182 Wh/kg, and 139-359 Wh/L, respectively. The cycle life of the best state-of-the-art lithium-ion batteries can be as great as 1500 cycles (to 80% of the original capacity). However, poorly constructed cells can have much shorter lives (300 cycles representing poorer cells). Based upon published data, the cost of energy storage is believed to be approximately $300 per kilowatt-hour (though some quote $1000 per kilowatt-hour). In summary, lithium-ion batteries are proven technology, and are leading candidates for terrestrial electric vehicles. This technology has also enjoyed limited but successful use in autonomous underwater vehicles used for oceanographic research. Unfortunately, lithium-ion batteries have been plagued by a history of significant safety incidents, with some causing serious human injury and property damage (loss of commercial cargo plane, for example). The lithium-ion battery may prove to be relatively expensive, has safety issues that must be dealt with, but has exceptional performance characteristics, that make it a leading candidate for consideration. Designs would have to emphasize safety, thermal management during charge and discharge, and enhanced battery management systems.

Based upon the analyses conducted in references (2) through (4), the conceptual hybrid systems listed in Table 7 have evolved as the leading candidates for powering sub-surface oil and gas production operations. Performance characteristics of these leading candidates are provided in Tables 8 and 9.

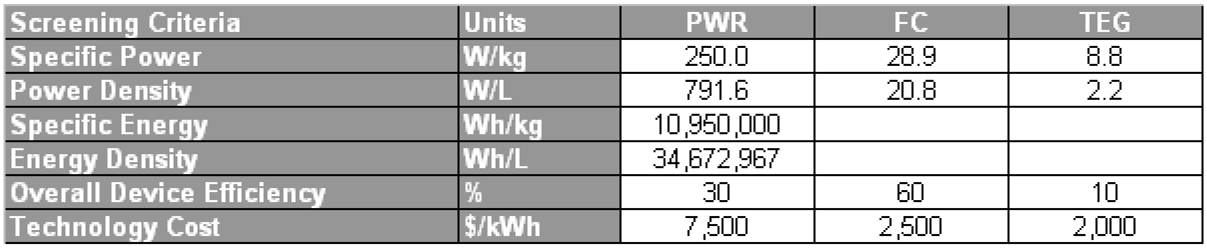
TABLE 7

SUMMARY OF DEEP OCEAN HYBRID POWER GENERATION AND ENERGY STORAGE LEADING CANDIDATES

NO.	NOMENCLATURE	DESCRIPTION
1	PWR	Nuclear Reactor + Battery
2	FC1	PEMFC + Line for surface O_2 + Wellhead Gas + Reformer + Battery
3	PWR TEG	Thermoelectric Generator Powered by Heat from Nuclear Reactor + Battery
4	WELL TEG	Thermoelectric Generator Powered by Heat from Combustion of Wellhead Gas + Battery
5	GRID	Ocean Floor Electrical Grid + Battery

TABLE 8

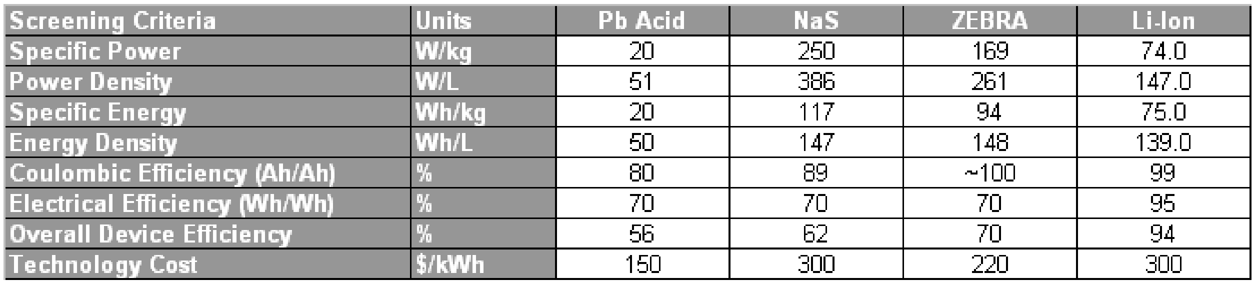
SUMMARY OF KEY ATTRIBUTES OF POWER GENERATION OPTIONS



Screening Criteria	Units	PWR	FC	TEG
Specific Power	W/kg	250.0	28.9	8.8
Power Density	W/L	791.6	20.8	2.2
Specific Energy	Wh/kg	10,950,000		
Energy Density	Wh/L	34,672,967		
Overall Device Efficiency	%	30	60	10
Technology Cost	$/kWh	7,500	2,500	2,000

TABLE 9

SUMMARY OF KEY ATTRIBUTES OF ENERGY STORAGE OPTIONS



Screening Criteria	Units	Pb Acid	NaS	ZEBRA	Li-Ion
Specific Power	W/kg	20	250	169	74.0
Power Density	W/L	51	386	261	147.0
Specific Energy	Wh/kg	20	117	94	75.0
Energy Density	Wh/L	50	147	148	139.0
Coulombic Efficiency (Ah/Ah)	%	80	89	~100	99
Electrical Efficiency (Wh/Wh)	%	70	70	70	95
Overall Device Efficiency	%	56	62	70	94
Technology Cost	$/kWh	150	300	220	300

6.0 RELATIVE RANKING OF THE LEADING CANDIDATES

Based upon the analyses conducted in references (2) through (4), the five conceptual hybrid systems listed in Table 7 have evolved as the leading candidates for powering sub-surface oil and gas exploration and production operations.

Qualitative Ranking

The relative ranking of the candidate hybrid options is clearly dominated by the energy conversion/power generation technology as opposed to the technology for energy storage. This statement by no means is meant to infer that energy storage is not absolutely critical and necessary for enabling sustained operation or graceful shutdown in the event that the primary power generation system fails. The statement is made because the selection of any of the four (4) leading energy storage candidates, all rechargeable/secondary batteries, has little to no impact on the ranking of the energy conversion/power generation technology, and subsequently little to no impact on the ranking of the hybrid system.

With specific regards to the four leading energy storage candidates, the two sodium-beta batteries were identified as the two most promising. Although the two sodium-beta battery technologies share obvious performance advantages over competing systems, the lead acid system also exhibits many advantages based on its significant historical baseline, low cost, and operation at great ocean depths while configured in a pressure tolerant battery design configuration. The primary factors leading to this determination included the following:

- Cycle Life. Lead-acid as high as 1,100; lithium-ion ranging from 300 to 1,500, but being very dependent upon build quality; sodium/sulfur approximately 2,500; and ZEBRA as high as 3,500.
- Safety. Unfortunately, lithium-ion batteries have been plagued by a history of significant safety issues, including relatively recent events.
- Technology/Manufacturing Readiness Level.
  - Sodium/sulfur. Several utilities are putting sodium/sulfur technology to work in the U.S. A variety of large-scale sodium/sulfur load leveling battery systems varying in size between 400 kWh (50 kW) and 64 MWh (8 MW) have been manufactured and placed in operation in Japan by NGK Insulators Ltd (NGK). Manufacturing operations capable of fabricating on the order of 400,000 load leveling sodium sulfur cells per year have been installed by NGK in Japan.
  - ZEBRA (sodium/nickel-chloride). Manufacturing operations of sodium/nickel-chloride cells for electric vehicle applications capable of fabricating a number of cells similar to NGK’s 400,000 per year have been installed by MES-DEA in Switzerland. The sodium/nickel-chloride battery has been developed almost exclusively for electric vehicle applications. The main component of the North Atlantic Treaty Organization (NATO) Submarine Rescue System (NSRS) is the Submarine Rescue Vehicle (SRV), a battery powered manned submersible. The batteries are sodium/nickel-chloride manufactured by MES-DEA in Switzerland. Reportedly, there is also a Chinese SRV that has recently entered service and utilizes the same type of batteries as the NATO SRV.

With regards to energy conversion/power generation, two out of the five options include the utilization of wellhead gas for fuel, and the need for a line to the surface for air/oxidant: #2 FC1 and #4 WELL TEG. As the intent is to avoid an electrical umbilical from a host platform, the need for any above surface infrastructure was identified as undesirable early on in the program. The research team and the deep water operators revisited the system requirements, and concluded that the requirement to avoid any above surface infrastructure is sufficient cause to not consider the WELL TEG or the FC1 any further.

Therefore, the five (5) conceptual hybrid systems listed in Table 7 can initially be reduced to the following three (3): GRID, PWR, and PWR TEG.

With regards to energy conversion/power generation, two out of these three leading candidate approaches include a nuclear reactor, namely PWR and PWR TEG, and the one remaining candidate, GRID, derives power from shore via submarine power cable (e.g., high voltage direct current transmission).

The ranking between either an on-site nuclear reactor or power transmission via submarine cable is likely not an absolute, but rather dependent upon variables that include the following:

- Total targeted power range (e.g., economy of scale).
- Site location/remoteness, including water depth and tie back distance.

In order to further differentiate between the three candidates, cost data from reference (3) can be factored in. Taking into account the initial investment cost, the annual operating cost, and the cost of electricity (see Table 4 and Figures 4, 5, and 6) justifies the following relative ranking from 1 to 3, 1 being most preferred:

#1: GRID
#2: PWR
#3: PWR TEG

Quantitative Ranking

Although the research team is of the opinion that the current resolution level of the information developed so far makes it challenging to develop any significantly more meaningful insights without inducing a level of subjectivity, the team is also of the opinion that at this time it is of significant value to develop a relative quantitative ranking of the three leading candidates.

The approach commenced with the development of selection criteria with assigned weight factors, see Table 10. The weight factors range from 1 to 3, with 3 being high/most desirable.

Relative rankings ranging from 1 to 3, 3 being high/most desirable were then assigned.

TABLE 10

SELECTION CRITERIA AND ASSIGNED WEIGHT FACTORS

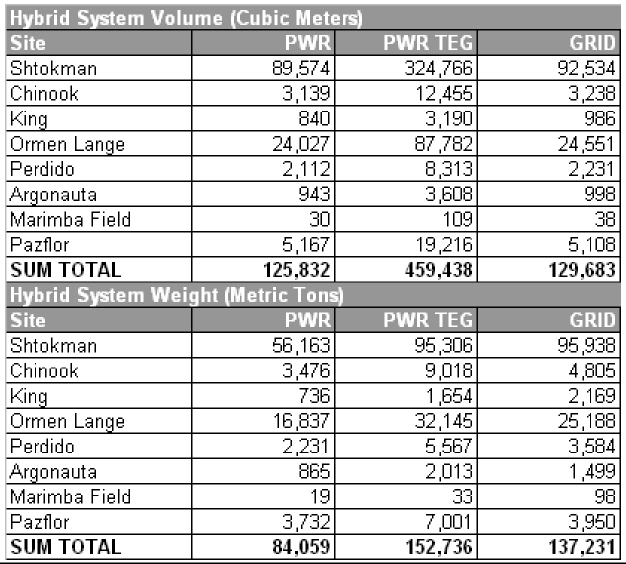
No.	CRITERIA	WEIGHT FACTOR (1-LOW, 3- HIGH)
1	System Volume	2
2	System Weight	2
3	Initial Capital Investment	3
4	Annual Operating Cost	3
5	Cost of Electricity	3
6	Reliability	3
7	Lifetime	3
8	Maintenance	2
9	Complexity	2
10	Regulatory Requirements	2
11	Supply Chain	1
12	Safety	3
13	Technology Readiness Level (TRL)	3
14	Manufacturing Readiness Level (MRL)	2

System Volume, Weight, and Costs

Assigned rankings for each candidate for criterion numbers 1 through 5 were based on the values resulting from the previous detailed analyses. The values shown for each of the eight (8) site locations in Tables 3 and 4 for system volume, system weight, initial capital investment, annual operating cost, and cost of electricity were merely summed; and then a relative comparison among the three candidates was made. These summations are shown in Tables 11 and 12.

TABLE 11

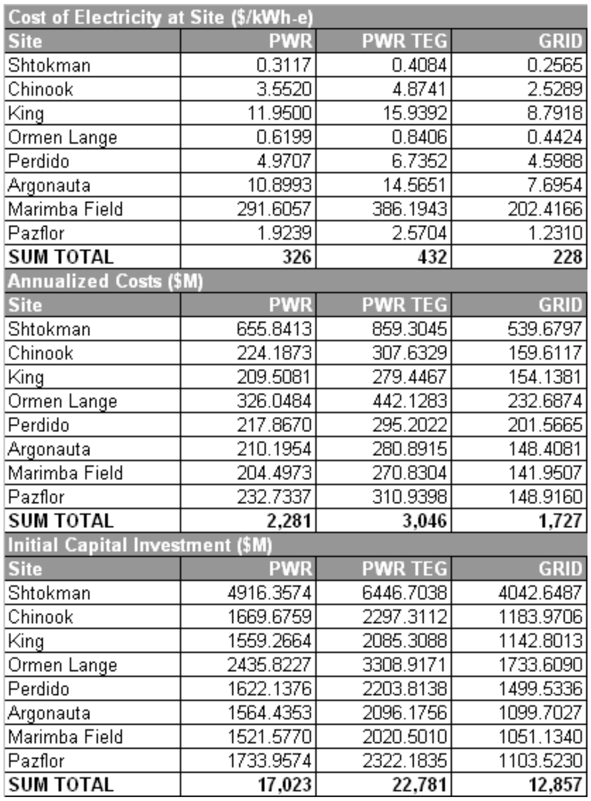
SUMMATIONS OF VOLUME AND WEIGHT VALUES



Hybrid System Volume (Cubic Meters)			
Site	**PWR**	**PWR TEG**	**GRID**
Shtokman	89,574	324,766	92,534
Chinook	3,139	12,455	3,238
King	840	3,190	986
Ormen Lange	24,027	87,782	24,551
Perdido	2,112	8,313	2,231
Argonauta	943	3,608	998
Marimba Field	30	109	38
Pazflor	5,167	19,216	5,108
SUM TOTAL	**125,832**	**459,438**	**129,683**
Hybrid System Weight (Metric Tons)			
Site	**PWR**	**PWR TEG**	**GRID**
Shtokman	56,163	95,306	95,938
Chinook	3,476	9,018	4,805
King	736	1,654	2,169
Ormen Lange	16,837	32,145	25,188
Perdido	2,231	5,567	3,584
Argonauta	865	2,013	1,499
Marimba Field	19	33	98
Pazflor	3,732	7,001	3,950
SUM TOTAL	**84,059**	**152,736**	**137,231**

TABLE 12

SUMMATION OF COST VALUES



Cost of Electricity at Site ($/kWh-e)

Site	PWR	PWR TEG	GRID
Shtokman	0.3117	0.4084	0.2565
Chinook	3.5520	4.8741	2.5289
King	11.9500	15.9392	8.7918
Ormen Lange	0.6199	0.8406	0.4424
Perdido	4.9707	6.7352	4.5988
Argonauta	10.8993	14.5651	7.6954
Marimba Field	291.6057	386.1943	202.4166
Pazflor	1.9239	2.5704	1.2310
SUM TOTAL	**326**	**432**	**228**

Annualized Costs ($M)

Site	PWR	PWR TEG	GRID
Shtokman	655.8413	859.3045	539.6797
Chinook	224.1873	307.6329	159.6117
King	209.5081	279.4467	154.1381
Ormen Lange	326.0484	442.1283	232.6874
Perdido	217.8670	295.2022	201.5665
Argonauta	210.1954	280.8915	148.4081
Marimba Field	204.4973	270.8304	141.9507
Pazflor	232.7337	310.9398	148.9160
SUM TOTAL	**2,281**	**3,046**	**1,727**

Initial Capital Investment ($M)

Site	PWR	PWR TEG	GRID
Shtokman	4916.3574	6446.7038	4042.6487
Chinook	1669.6759	2297.3112	1183.9706
King	1559.2664	2085.3088	1142.8013
Ormen Lange	2435.8227	3308.9171	1733.6090
Perdido	1622.1376	2203.8138	1499.5336
Argonauta	1564.4353	2096.1756	1099.7027
Marimba Field	1521.5770	2020.5010	1051.1340
Pazflor	1733.9574	2322.1835	1103.5230
SUM TOTAL	**17,023**	**22,781**	**12,857**

Reliability

For a truly qualified system-level ranking, detailed designs including the reliability of individual subsystems and components is necessary. The absence of such details provides room for subjectivity, and the rankings of the systems below that are based on to-be-developed technology (i.e., all candidates except GRID), were developed based upon the expectations of the future systems. Assigned reliability rankings were based on the following:

- GRID: Assigned a ranking of 3. The power requirements for the deep sea production equipment are considered to be compatible with standard submarine power and telecommunications cable systems, for which a wide range of industry-approved techniques and equipment exists (e.g., cable burial techniques, standard connection boxes, couplings and penetrators, etc…). All components must survive both the mechanical rigors of installation, and have high reliability and long lifetime under deep ocean conditions (high hydrostatic pressure, corrosive environment, forces and effects of ocean current, etc…). As an industry standard, submarine power or telecommunications cables target a service life of at least 25 years, and must be able to be easily deployed and repaired at sea. Cable ships equipped with remotely operated vehicles (ROVs) provide installation and repair capability. Historically, most reported submarine cable failures occur in shallow water due to fishing/trawling activity and anchors dropped from ships; although natural chaffing, abrasion, and earthquake/volatile seabed related failures occasionally occur in deep water. The most serious limitation with obtaining power at remote deep ocean depths is associated with mechanical and electrical problem areas with underwater electrical connectors and hull/junction box penetrations used to transmit power to submerged loads housed in one atmosphere internal pressure vessels/enclosures. Relative to the other four candidates, the reliability of GRID is considered to be the highest.

- PWR TEG: Assigned a ranking of 2. Thermoelectric generators have a very high level of reliability and proven record of long life space and terrestrial applications. For example, Voyager 1 and Voyager 2 were launched in 1977 and are currently on course to exit the solar system. The solid-state technology is highly scalable and modular, and has no moving parts. It has been more than 52 years since the world's first operational nuclear submarine (USS Nautilus) completed the first successful submerged voyage around the North Pole, and at present time there are more than 441 LWRs worldwide. That said, the reliability of the remote deep ocean PWR TEG is considered second to the GRID.
- PWR: Assigned a ranking of 1. The relative reliability between the PWR TEG and the PWR is based on the relative difference between the solid-state thermoelectric generator and the steam turbine generator system. In future deep-ocean nuclear reactor designs that substitute solid-state thermoelectric generators for conventional Rankine steam-cycle thermal-to-electric converters, a conscious decision will have to be made to trade the higher efficiency of the Rankine cycle for the higher reliability of the thermoelectric generator. By eliminating moving parts and improving reliability, the probability of long-term trouble-free unattended operation should increase.

Lifetime

Assigned rankings for system lifetime were based on the following:

- PWR and PWR TEG: Both assigned a rating of 1. The lifetime of both these systems was based on the reported 5 year capacity (time between refueling) of the B&W mPower^{TM} reactor.
- GRID: Assigned a rating of 3, based on the nominal industry standard 25 years service life for submarine power and telecommunication cable systems.

Maintenance

Effective maintenance is essential for the safe and reliable operation of any power plant. The system must be continuously monitored, and periodically inspected, tested, assessed, and maintained to ensure that the structures, systems, and components (SSCs) function in accordance with the design intents and requirements. The majority of maintenance activities are related to the concept of preventative maintenance, but when the performance or condition of an SSC does not allow it to function per design, corrective maintenance must take place.

Systems operating remotely on the ocean floor require special engineering to optimize reliability, minimize maintenance requirements, and eliminate to the extent possible mechanical parts that can fail. Furthermore, these remote systems must be specifically designed to facilitate the required maintenance operations being carried out via remotely operated vehicles (ROVs).

Assigned rankings for maintenance were based on the following:

- PWR: Assigned a ranking of 1. Extensive preventative maintenance and testing/surveillance programs exist and are necessary for current nuclear power plants to ensure the continued availability, as well that the significant nuclear safety equipment will function when and how it is intended. Due to both the system complexity and the safety issues (both discussed below), the maintenance (both time between and ease of) associated with the PWR relative to the other two candidates is considered to be the most complex, and elaborate.
- PWR TEG: Assigned a ranking of 2. Other than the maintenance associated with the turbine-generator, the PWR TEG maintenance requirements are the same as those for the PWR. Therefore, the PWR TEG maintenance is considered to be the second most complex.
- GRID: Assigned a ranking of 3, considered the least high maintenance item of all the candidates.

System Complexity

Assigned rankings for system complexity were based upon the following:

- PWR: Assigned a ranking of 1. As evident from the following outline of the major systems, the PWR is the most complex of the three options:
  - » Primary System/Reactor Coolant System.
    - Reactor vessel and internals, including fuel rods, and control rods and drive system.
    - Primary cooling system, reactor coolant pump and pressurizer to circulate the reactor coolant heated by the core, transfer heat to the secondary system, and act as a neutron moderator.
    - Chemical and Volume Control System/Makeup and Purification System for coolant makeup to the primary cooling system, removal of corrosion and fission products from the coolant, adjustment of the boric acid concentration, and supply of cooling and lubrication of reactor coolant pump seals.
  - » Secondary system with steam generator and condensate/feedwater system.
  - » Reactor Containment System and Emergency Core Cooling System to provide core cooling following a loss of coolant accident and extra neutron poisons to ensure reactor remains shutdown following the cool down associated with a main steam line rupture.
  - » Turbine-Generator System
- PWR TEG: Assigned a ranking of 2. Other than the lack of a turbine-generator, the PWR TEG requires all of the above systems. Therefore, the PWR TEG is considered to be the second most complex.
- GRID: Assigned a ranking of 3, considered the least complex of all the candidates.

Supply Chain

The Supply Chain was reviewed for each of the options that represent the system of organization, personnel, technology, information, and resources involved in moving a product or service to a customer.

Based on this, the assigned rankings for supply chain were as follows:

- GRID: Assigned a ranking of 3. Relative to the other two candidates, the supply chain is considered the most complete. As indicated earlier, the power requirements for the deep sea production equipment are considered to be compatible with standard submarine power and telecommunications cable systems, for which a wide range of industry-approved techniques and equipment exists (e.g., cable burial techniques, standard connection boxes, couplings and penetrators, etc…).

- PWR: Assigned a ranking of 2. The supply chain is considered less complete than that for the GRID, but more complete than that for the PWR TEG. Specific areas where suppliers are yet to be identified include sources associated with the to-be-determined ocean engineering methods to ensure compatibility with the remote deep ocean environment (e.g., pressure compensation, pressure tolerance, and 1 atmosphere enclosures, as well as methods to enable in-situ maintenance via ROVs).
- PWR TEG: Assigned a ranking of 1. All the deficiencies associated with PWR supply chain apply, as well as those associated with a large scale thermoelectric generator. Although the technology associated with thermoelectric generators is relatively mature, one of this scale designed for the remote deep ocean environment has never been developed.

Safety

When assessing safety, two specific categories are typically considered:

- Hazard Severity. Assessing the worst potential consequence, defined by degree of injury, occupational illness, or an environmental release.
- Mishap Probability. The probability that a hazard will result in a mishap, based on an assessment of such factors as location, exposure limits, and affected population.

Although land-based nuclear power plants and nuclear power submarines and ships have achieved very high standards of safety performance, and the Generation 3+ LWR power plants may claim to have reached the goal of safety assurance, the potential risk to the persons and environment in the vicinity is undeniable:

> Back in MAR 1979, the Three Mile Island heat removal degradation accident became a turning point in history. Caused by equipment failure coupled with faulty operator actions, the accident resulted in at least half of the core melting. The accident caused no injuries, deaths, nor property damage; and it also did not release sufficient fission products to contaminate the soil around, except slightly within the exclusion area..
>
> In APR 1986, the Chernobyl reactivity increase accident occurred resulting in 50 direct deaths, with estimates of another 4,000 additional cancer deaths among the 600,000 of the most highly exposed people near the reactor.

Therefore, both PWR and PWR TEG were assigned a rating of 1. The GRID option was considered the most relatively benign, and therefore assigned a rating of 3.

Technology Readiness Level

Assigned rankings for technology readiness levels (TLR) were based upon the following:

- GRID: Assigned a ranking of 3. Submarine power cables have traditionally been used to link existing land-based power distribution systems whenever the economic advantages have outweighed the cost of the submarine link. Actual subsea power transmission systems have been “flight proven” through successful operations (TRL 9). Relative to the other three candidates, this is clearly the most mature.

- PWR: Assigned a ranking of 2. Nuclear powered submarines of several countries have now operated in the oceans of the world for nearly fifty years. Although such submarines facilitate putting a man in the various operation and maintenance loops, which in comparison differs significantly with the subject application, this technology can be considered "flight qualified" through test and evaluation (TRL 8), and considered second to GRID in maturity.
- PWR TEG: Assigned a ranking of 1. Very similar to the PWR. Both the pressurized water reactor and thermoelectric generator technologies are mature. Estimated to be at a TRL no higher than six: system/subsystem model or prototype demonstration in a relevant environment. The primary areas in need of attention are the engineering related to the deep ocean environment and the system-level integration aspects associated with the targeted application, as well as the scaling up of the thermoelectric generator to meet the subject requirements.

Manufacturing Readiness Level

Assigned rankings for the manufacturing readiness levels (MRL) were based upon the following:

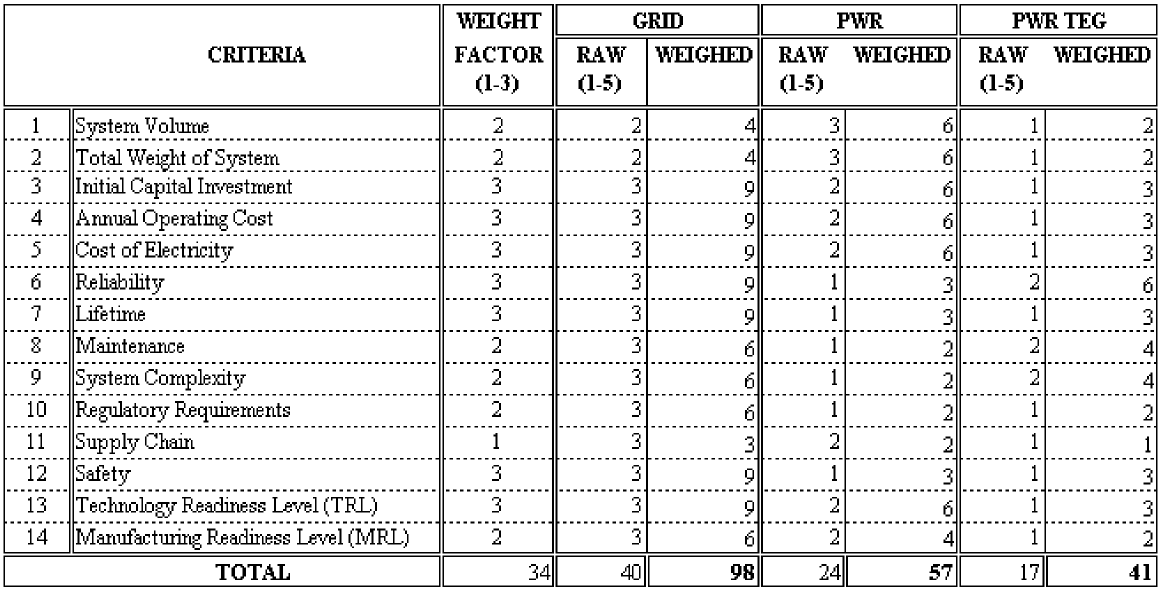
- GRID: Assigned a ranking of 3. Actual subsea power transmission systems have been "flight proven" through successful operations (TRL 9), and an existing manufacturing capability is in place for "full rate production" (MRL 9). Relative to the other two candidates, this is clearly the most mature.
- PWR: Assigned a ranking of 2. This technology can be considered "flight qualified" through test and evaluation (TRL 8), and an existing manufacturing capability to produce actual product in a low rate initial production is in place (MRL 7), and considered second to GRID in maturity.
- PWR TEG: Assigned a ranking of 1. Very similar to the PWR. MRL is estimated to be at or near MRL 7.

Table 13 summarizes the rankings. The admittedly somewhat subjective rating approach described results with the maximum and minimum achievable scores being 102 and 34, respectively. The following summarizes the resulting scores for the three candidate approaches:

- GRID……………98…………... 96%
- PWR…………….57…………... 56%
- PWR TEG……… 41……………40%

TABLE 13

SUMMARY OF RELATIVE RANKINGS



CRITERIA		WEIGHT	GRID		PWR		PWR TEG	
		FACTOR (1-3)	RAW (1-5)	WEIGHED	RAW (1-5)	WEIGHED	RAW (1-5)	WEIGHED
1	System Volume	2	2	4	3	6	1	2
2	Total Weight of System	2	2	4	3	6	1	2
3	Initial Capital Investment	3	3	9	2	6	1	3
4	Annual Operating Cost	3	3	9	2	6	1	3
5	Cost of Electricity	3	3	9	2	6	1	3
6	Reliability	3	3	9	1	3	2	6
7	Lifetime	3	3	9	1	3	1	3
8	Maintenance	2	3	6	1	2	2	4
9	System Complexity	2	3	6	1	2	2	4
10	Regulatory Requirements	2	3	6	1	2	1	2
11	Supply Chain	1	3	3	2	2	1	1
12	Safety	3	3	9	1	3	1	3
13	Technology Readiness Level (TRL)	3	3	9	2	6	1	3
14	Manufacturing Readiness Level (MRL)	2	3	6	2	4	1	2
TOTAL		34	40	**98**	24	**57**	17	**41**

7.0 CARBON EMISSION REPORT

Reference (5) was generated in an effort to document a comparison of the carbon emissions that various alternative power systems may provide if deployed.

The first approach was to investigate various carbon calculators (internet applications that ask various questions about energy use, daily habits, and other important factors and calculates a carbon footprint).

Generally speaking ‘carbon footprint’ is used as a generic synonym for emissions of carbon dioxide or greenhouse gases expressed in CO_2 equivalents, and may be defined as the amount of greenhouse gases, in carbon dioxide equivalent, that an individual, household, or other entity produces in a year. This definition was deemed sufficient because it is the general definition that consumers and the carbon calculators use. This usually means that a carbon calculator will ask for information about electricity usage, household heating, travel by car, and travel by air.

Originally, twelve calculators were examined, chosen from a large list of online calculators. These twelve calculators were then short listed to only include calculators that were from companies or organizations that sold offsets. The carbon calculators considered were: Bonneville Environmental Foundation, Carbon Fund, The Climate Trust, and Native Energy.

The four calculators all required the same input data. For electricity, the calculators asked for the number of kilowatt hours consumed in a year. For a given electricity usage, the calculators varied by as much as 12 percent. This discrepancy is due to the fact that the different carbon calculators rely on different underlying emission factors, largely determined by assumptions made about the mix of energy received in a region. For instance, if most of a company's electricity comes from a coal-fired power plant, there will be significantly more emissions per kWh than if the electricity came from a wind farm or a natural gas fired power plant. This discrepancy can cause large differences because many states have a very different mix of electricity than the national average. As a result, a different method of determining carbon emissions that is directly related to the most realistic solutions was selected.

The realistic options for subsea power generation are nuclear. Cost estimates have been developed and resulted in an estimate between $0.10 and $0.20 per kWh for power delivery. Nuclear energy solutions produce low levels of carbon dioxide emissions from their full life cycle. Nuclear may be comparable with renewables such as wind, solar and hydro in this respect.

In recent years, some utilities generating electricity have undertaken Life Cycle Analysis (LCA) studies as part of their social accountability. The principal focus of LCA for energy systems today is their contribution to climate change. There is an obvious linkage between energy inputs to any life cycle and carbon dioxide emissions, depending on what fuels those inputs. LCA includes mining, fuel preparation, plant construction, transport, decommissioning and managing wastes. In the nuclear fuel cycle energy inputs are low, even with diminishing ore grades. Its very large low carbon advantage over fossil fuels will remain even if very lowgrade ores are used.

LCA data from the following was evaluated:

- Vattenfall's 2002 Environmental Product Declaration for its 3,090 MWe power plant in Forsmark, Sweden.
- The 2005 Environmental Product Declaration for British Energy's Torness 1,250 MWe power station in the United Kingdom (UK).
- The World Nuclear Association's *Energy Analysis* paper.
- Figures published in 2006 for Japan.
- The UK Sustainable Development Commission report in 2006.

All of these suggest a very favorable energy balance for nuclear power, by any criteria, and a very modest carbon dioxide output from the whole fuel cycle, even if moving to very low-grade ores. It is difficult to get simple figures for coal and gas, since so much of the energy input (beyond the fuel itself) is often in transport, which varies from very little to a lot. Energy input figures ranging from 3.5% to 14.0% of lifetime output are published for coal, and 3.8% to 20% or natural gas. Conservatively, the LCA carbon output for nuclear power is about 3% of coal or around 6% of gas. The U.S. Environmental Protection Agency has published annual output emission rates for greenhouse gases (GHG) for the year 2005. The GHG are listed by subregions which are shown in Figure 8. Also listed in this figure are the annual output emission rates for the Electric Reliability Council of Texas (ERCOT) and the Sustainable Energy Research Center (SERC) Mississippi Valley eGRID subregion. These values are listed since they are the subregions that may supply electricity to the western Gulf of Mexico. With nuclear power production generating between 20 and 30 g/kWh of CO2, this would be approximately 3 – 5% of the CO2 generated by ERCOT and approximately 4.3 – 6.5% of the CO2 generated by SERC Mississippi Valley for the same amount of electricity.

Figure 1. US eGRID subregions.

eGRID subregion acronym	eGRID subregion name	Annual output emission rates		
		Carbon dioxide (CO_2) (g/kWh)	Methane (CH_4) (g/MWh)	Nitrous oxide (N_2O) (g/MWh)
ERCT	ERCOT All	600.3	8.5	6.9
SRMV	SERC Mississippi Valley	462.5	11.0	5.3

FIGURE 8: Subregions for which greenhouse gas emission rates are published, and annual output emission rates for the Electric Reliability Council of Texas (ERCOT) and the Sustainable Energy Research Center (SERC) Mississippi Valley eGRID subregion for 2005.

8.0 BUSINESS CASE

As near shore oil and gas reserves are exhausted, it will be necessary to develop fields further from shore and at greater depths. Locally powered advanced deep ocean drilling operations, may provide access to oil and gas reserves otherwise inaccessible. An investment in subsea (deep ocean) hybrid power systems may enable offshore oil and gas exploration and production in such remote, deepwater locations. Such technology will therefore enhance the energy security of the United States.

According to The Economist (September 8th – 14th 2007), there is a "sea change" in offshore drilling technology. They state that "rising costs and clever kits are transforming the oil-platform, and could even do away with it all together." The article discusses the cost and

manpower required to operate a typical oil and gas platform in the middle of the North Sea. There are 435 such platforms in the British waters of the North Sea alone. In regard to costs, the Alwyn North Oil and Gas Platform was built for a cost of £1.5 billion ($2.4 billion) in the mid 1980's, and has spent nearly half that amount upgrading the platform since its construction. Operation of this platform requires that approximately 300 personnel live aboard, with each receiving 3-weeks leave for every 2 weeks on the platform, and an associated cost for flying each to and from the platform being £1,000. According to Oil and Gas United Kingdom, an industry group, oil firms spent over £11 billion last year building and running offshore facilities in British waters alone. Such operating costs place production costs for one barrel of oil at $22 per barrel, which is nearly the highest in the world. These costs are rising rapidly. The Deutsche Bank estimates that inflation in the oil business has run at 30% a year over the past two years, and will continue to rise by at least 15% per year through 2008. The article goes on to state:

> *"No wonder, then, that firms are determined to reduce the expense of producing oil at sea, in the North Sea and elsewhere."*
>
> *"Even more distant fields can be tied back to a platform using pipelines along the sea floor. In a tie-back, the valves that open and close the well are located not on the rig, but on the sea floor; engineers operate them by remote control. Several deposits of oil and gas, including Nuggets, a cluster of gas fields over 40 km away, are linked to Alwyn North in this way. Next, Total plans to connect a new discovery called Jura to the platform. As a result, the lifespan of Alwyn North, estimated at 10 years when it first started production in 1987, has been extended to over 40 years, while its projected output has almost quadrupled."*
>
> *"The next logical step is to put more equipment underwater, in the hope of dispensing with platforms altogether. Statoil, for example, is tapping a gas field called Snøhvit, which lies 143 km offshore, without using a platform. But this is possible only because the pressure of the field is strong enough to keep the gas flowing through the long pipeline back to offshore. Norsk Hydro, another Norwegian energy firm on the verge of merging with Statoil, has developed another gas field, Ormen Lange, in the same way. But in a few years a compressor that can work underwater will be needed to supplement the falling pressure in the field. Last year, Norsk Hydro hired General Electric (GE), an American industrial giant, to build a prototype.*
>
> *"Fifteen years from now, "says Claudi Santiago of GE, "The vision is that offshore platforms will disappear."*
>
> *"Or maybe not … If some way can be found to liquefy gas offshore, Mr. Santiago points out, then deposits that are currently too remote for the construction of pipelines could be developed, and the gas transported in liquid form by ship instead. That would give offshore platforms a whole new life."*

Clearly, there is a strong driving force for the development of capabilities for operations in remote, deepwater locations. Such facilities will require ample supplies of local power to operate machinery, ranging from drilling rigs to pumps and compressors.

9.0 SUMMARY / CONCLUSIONS

The Initial Study regarding Deep Sea Hybrid Power Systems considered numerous power generation/energy conversion and energy storage technologies to support the exploration and production of oil and gas reserves remotely located off shore in the deep ocean. Based upon a preliminary screening of power generation and energy storage technologies, ten conceptual hybrid energy conversion and storage systems were developed for evaluation at each of the eight (8) representative deep ocean sites. Detailed analyses of the technologies were then conducted. The following parameters were evaluated for each site: estimated component weight, total weight, and total volume; initial investment, annual cost, and cost of electricity; and the economy of scale. With regards to energy storage technologies, only rechargeable batteries: lead-acid, sodium-sulfur, ZEBRA, and lithium-ion were identified for more detailed evaluation. Based upon the analyses conducted, the five (5) conceptual hybrid power systems listed in Table 7 were identified as the leading candidates for powering the sub-sea operations.

Obviously, the air supply problem is a major impediment for the use of wellhead gas as an energy source. As the intent is to avoid an electrical umbilical from a host platform, the need for any above surface infrastructure was identified as undesirable early on in the program. Therefore, the research team and the deep water operators concluded that the requirement to avoid any above surface infrastructure, including an air supply line to the surface, was sufficient cause to not consider the WELL TEG or the FC1 any further.

Therefore, the five (5) conceptual hybrid systems was reduced to the following three (3): GRID, PWR, and PWR TEG.

The estimated weights of the hybrid energy conversion and storage systems for the three largest sites, Shtokman, Chinook and Ormen Lange, are between 10,000 and 100,000 metric tons. For comparison, the NS Savannah and NS Otto Hahn weighed 25,790 and 22,000 metric tons, respectively. Thus, the largest hybrid systems will have weights comparable to these nuclear powered ships. While the hybrid systems are comparable to the commercial nuclear-powered ships in weight, their density is greater, so they occupy less volume than the ships.

The capital costs are dominated by parameters that are insensitive to the size of the site, such as those used to account for the assumed protective hull. Like the initial capital cost, the annualized costs are dominated by parameters that are insensitive to the size of the site. The least expensive option for power at all of the concept-of-operations sites is the electrical grid, with an assumed cost of approximately $2.5 million per kilometer. As the systems become larger, the cost of electricity produced by the system becomes less expensive, regardless of the hybrid system assumed. The two largest sites, Shtokman and Ormen Lange are of sufficient size so that power can be supplied for less than $1 per kilowatt-hour, comparable to the cost for grid power.

The research team acknowledged that the current level of resolution of the information developed made it challenging to rank the candidate systems without inducing a level of subjectivity, but was also of the opinion that there was significant value to develop a relative quantitative ranking of the three leading candidates. The approach commenced with the development of selection criteria with assigned weight factors, see Table 8. The weight factors range from 1 to 3, with 3 being high/most desirable. Relative rankings ranging from 1 to 3, 3 being high/most desirable were then assigned.

Table 13 summarizes the rankings. The rating approach described results with the maximum and minimum achievable scores being 102 and 34, respectively. The following summarizes the resulting scores for the three candidate approaches:

- GRID…………….98…………. 96%
- PWR……………..57…………. 56%
- PWR TEG……….41…………. 40%

Relevant to note is that (1) the GRID option is considered as the baseline for which any alternative option must meet or exceed from both a performance and cost perspective, and (2) the primary objective of the Initial Study was to identify the most promising alternative candidates. Therefore, based upon the Initial Study, the following conclusions that can be made:

1. The top two candidates for power generation are both based on the small modularized pressurized water reactor. One candidate couples the pressurized water reactor with a secondary steam-turbine-generator system, whereas the other candidate couples the pressurized water reactor with a solid-state thermoelectric generator.

2. The two leading candidates for energy storage are both versions of sodium-beta batteries: sodium/sulfur and sodium/nickel-chloride (ZEBRA), noting that depending upon the final system requirements (e.g., cycle life) a lead acid system may also provide a suitable solution for energy storage.

10.0 RECOMMENDATIONS

Although it has been more than fifty-two years since the world’s first operational nuclear submarine (USS Nautilus) completed the first successful submerged voyage around the North Pole and at present time there are more than 441 light water reactors worldwide, the research team understands that there are extreme differences between a nuclear powered manned submarine operating in relatively shallow water and an unmanned nuclear power plant operating in the remote deep ocean. Systems operating remotely on the ocean floor require special engineering to optimize reliability, minimize maintenance requirements, and to the extent possible, minimize all failure modes. Furthermore, these remote systems must be specifically designed to facilitate the installation, operation, and required maintenance procedures being conducted through remote operations (e.g., via ROVs).

The research team is also aware of existing barriers regarding nuclear power:

- Public perceptions.
- Domestic and international politics.
- U.S. Nuclear Regulatory Commission (NRC) design, siting, construction, and operation requirements, and approval and licensing timelines.
- National security
- The Three Mile Island, Chernobyl events occurring decades ago.
- The current ongoing events with the Deepwater Horizon drilling rig in the Gulf of Mexico (GOMEX).

Taking all these factor into account, the following recommendations are made. The initial near-term efforts should focus on conducting a detailed feasibility and implementation study addressing the following:

Detailed Operational Requirements and Interface Specifications. Stakeholder (deepwater operators and service providers) defined baseline operational requirements and interface specifications: notional/representative exploration or production field specifications for all three identified power range requirements, including representative relative geometrical locations and electrical requirements for each power point, thereby incorporating the power distribution requirements.

Design. The design of local area power generation and distribution network systems that are based on a standard submarine power cable system, as well as a small modularized pressurized water reactor. With the pressurized water reactor and for the actual electrical power generation, both the traditional turbine-generator, and the TEG should be investigated. Design considerations should include achieving a modularized approach, that can be installed, assembled, and operated remotely in the deep ocean (e.g., 12,000 fsw).

Deployment, Installation/Assembly, and Recovery Plans and Procedures. Notional plans and procedures for deployment, installation/assembly, and recovery that provide a detailed overview of the necessary support vessels and equipment, personnel, logistics, and timelines, as well as limitations and restraints associated with the subject efforts.

Operation, Maintenance, and Emergency Response Requirements. The operation and maintenance requirements of such a power network, including monitoring protocols and necessary response capability. Issues include maintaining a near continuous system health status, and the capability to appropriately respond (e.g., intervening) in a timely manner.

Approval, Licensing, and Operations Program Plan. A plan that identifies the detailed requirements, organizational roles, and responsibilities associated with obtaining approval and licensing, as well as operating such a power plant. Relevant to note is gas and oil industry’s desire not to operate such a power plant, but merely to purchase the power from the power plant owner/operator. Therefore, the intention is for this plan to address such issues.

Socialization Strategy. A strategic plan purposely developed towards addressing the various non-technical barriers associated with the implementation of a remote deep ocean nuclear power plant.

11.0 REFERENCES

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