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TECHNICAL REPORT NO. LWL-CR-06-RAB

A REPORT ON THE PERFORMANCE CHARACTERISTICS OF
POWER SOURCES FOR REMOTE AREAS

Final Report
Contract No. DAAD05-68-C-0178

By
Booz - Allen Applied Research, Inc.
4733 Bethesda Avenue
Bethesda, Maryland

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Aberdeen Proving Ground, Maryland 21005

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ABSTRACT

This report summarizes performance characteristics of candidate power sources planned particularly for use by indigenous forces of friendly, underdeveloped nations. Older types of power sources, such as heat engines, hydroelectric and magnetohydrodynamic, are suggested for continued research and development. Newer concepts, such as fuel cells, thermoelectric, thermionic and solar, are investigated for special applications. A table which summarizes in detail the status of technologic development of power sources is included.

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FOREWORD

This report was prepared in compliance with Work Assignment No. 4, Contract No. DAAD05-68-C-0178. The objective of the work assignment was to determine what power levels and other performance characteristics can be achieved for remote areas with various power sources currently in state-of-the-art, development, and planning stages. The power sources of interest range from a few watts to two or three kilowatts of power output.

I. INTRODUCTION

Special and counterinsurgency forces of the U. S. Army are employed primarily to assist indigenous forces of friendly underdeveloped nations in self-development. A basic requirement for national development is electrical power. Initial electrical power requirements need not be for large quantities but, rather, may be only for vital services such as communications and medical care. Since the term "underdeveloped" connotes a restricted transportation system and the absence of a national electrical distribution system, emphasis must be placed upon localized sources, use of indigenous fuels, simple maintenance, and a minimal requirement for repair parts. Efficiency becomes a minor criterion; what is far more important is the impact of fuel and spare parts requirements upon the national economy. Inefficient use of cheap, locally available fuel — for example, alcohol — may be of greater benefit than efficient use of imported fuel which adds to a strained balance of trade.

As the economy of a nation grows, the transportation system must also grow. Power requirements for transportation then must be added to those of vital services. The foregoing criteria remain important, nevertheless. That is, those power sources which offer the greatest benefit and are least expensive should be sought. In fact, in view of the growing shortage of copper,¹ one might predict that the massive electrical distribution systems of the United States and Western Europe will not be duplicated. Austere systems will be developed which will minimize the use of copper, of course. However, these systems will be costly and development and installation will be time-consuming.

It is well to note that even in the United States, with its extensive electrical distribution system, the commercial market for local electrical power sources in remote areas **continues** to expand. Examples of such use are power for remote automatic weather stations, remote microwave relay stations, and, perhaps more surprising, radio and lighting for the caboose of freight trains.

1 / National Resources - A Summary Report, NAC-NRC Publication, 1000, November 1962, F. Seitz.

Electrical power requirements in the lower range of power outputs can conveniently be grouped in three categories: outputs from less than one watt to a few, say 50 or 60, watts; outputs from a few watts to about one kilowatt; and outputs from about one kilowatt upwards to about two or three kilowatts. These categories are considered somewhat arbitrary and have not constrained the present survey except as they establish the order of magnitude of the output range of interest.

Power of a few watts is adequate for small communication receivers and transmitters. Power up to about one kilowatt is adequate for larger communication apparatus, for microwave relay stations, and for related applications, including small refrigeration units. Power of more than one kilowatt is, of course, needed for heavier service applications.

In the range of power outputs of interest, there are several power system options available, some with several energy sources. Table 1² provides a broad overview of the state-of-the-art of several candidate types of devices. This table attempts to portray the status of energy systems as of the 1964 time frame. One should note the cost of power generation indicated in Table 1 with some caution. Costs indicated are at the source; distribution costs in the United States normally range from 3 to 20 times the cost at source. A similar report³ prepared by the National Aeronautics and Space Administration in 1967 indicates that NASA has reduced some 30-50 candidate types of systems to 15 of greatest interest. These 15 are illustrated in Figure 1. The NASA report concludes that development of 15 candidates would require excessive financial support and further reduces them to a total of eight as illustrated in Figure 2. These eight candidate system types will receive primary development support from NASA over the next several years.

2 / Energy R&D and National Progress, prepared for the Interdepartmental Energy Study by the Energy Study Group, Office of Science and Technology, 1964.

3 / Transcript of the Briefing for Industry on NASA Space Power and Electric Propulsion Programs, National Aeronautics and Space Administration, April 1967.

TABLE 1- —Status of technologic development of energy devices

Name	Description of device				State of technology			Performance				
	Primary application	Resources input (form of energy)	Type output (form of energy)	Scaling range	State of R&D or technology	Current engineering efficiency	Possible engineering efficiency	Limiting phenomena and required research	Specific power of device (watt/ft ²) (except as noted)	Watt/ft ² (except as noted)	Reliability	Present life
HEAT ENGINES												
Diesel	Transportation	Chemical fossil fuels (except as noted)	Mechanical (except as noted)	5-25,000 hp	Noted below	38-38 percent (600 hp)	Only minor improvements in efficiency are expected	Research to understand combustion, ignition, and pre-ignition phenomena for non-diesel fuels.	41-187 (600 hp)	Unlimited		Has been increasing
Otto	Transportation	Fossil fuel		1/2-3,000 hp	Stage 6	38-38 percent (600 hp)		Study how to control wear and to improve air-fuel mixture. Limitations are the formality of fuel-air mixture.	62-187 (600 hp)		40,000 hours (automotive)	
Two stroke	Transportation	Fossil fuel		Fractional to 100 hp	do	28 percent (300 hp)			200-746		20,000 hours (automotive)	
Gas turbine	Power generation	Fossil fuel		100-47,000 hp (38,000-hp turbine plants)	do	15-20 percent		Reduce cost, find inexpensive fuels with long life at high temperatures, highly reliable regenerative heat exchangers, thermal turbo compressors.	370 (example)		7,000 hours (automotive)	
Stirling	Auxiliary power source application	Heat sources (external combustion engine)		Unknown	Stage 3	40 percent (100 hp/cylinder)		Develop ways to reduce boiler maintenance costs.	67-86		10 years (stationary)	
Free-piston gas engine	Power generation	Fossil fuel		do	do	38 percent (1,000 hp)		Find cheaper ways to control maintenance costs.	62 (example)		Depends on economic considerations	
Wankel	Transportation	Fossil fuel		10-50 hp	Stage 4	18-25 percent (150 hp)		Improve sealing in combustion chamber.	370 (example)			
Steam plant (conventional, natural gas-fired)	Power generation	Natural gas	Electrical A.C.	Within limits	Stage 5	32 percent average (48.8 percent maximum estimated for 1,000 M w)	38.3 percent average (48.8 percent maximum estimated for 1,000 M w)	Develop ways to reduce boiler maintenance costs. Improvement of methods of fabrication of good quality turbine parts for steam turbines.	Not applicable			
Steam plant (conventional, coal-fired)	do	Coal	do	17. M w-213 M w	do	4- to 6-percent increase over steam	do	Improvements of materials so that to increase boiler pressure, initial superheat, and condenser vacuum.	do			
Steam plant (conventional, gas and steam turbine)	do	Natural gas	do	do	do	25 percent increase over steam	do	Not necessarily feasible at present time. High plant construction and high fuel performance—Accumulate statistical data on which process specifications for both materials and manufacturing processes can be based. Work to lower fuel fabrication cost.	do			
Mercury steam	do	Coal, natural gas, oil	do	1,500 kw-40 M w	do	do	do	Work to lower fuel fabrication cost. Demonstration of ability to recycle plutonium in present system.	do			
Steam plant (nuclear reactor)	do	Uranium, thorium	do	do	Stage 4	do	Presently 32 percent for lightwater reactors (estimated maximum for 1960)	System dynamics—Interaction between reactor power level, fuel exposure, coolant flow, and control system characteristics. Improve instrumentation. Plant construction and simplification. Cooling and problems of heat transfer and fluid flow.	do			
HYDROELECTRIC												
Reversible or pumped storage type electric generator	Power generation, flood control, irrigation, recreation	Mechanical	Electrical, A.C or D.C.	240 M w, largest existing plant. 1,974 M w, largest existing plant.	Stage 5	Hydraulic turbine approximately 90 percent	Only minor improvements in efficiency are expected.	Need to develop economical long-life electrodes.	do	Excellent	Unlimited	Not applicable
MAGNETOHYDRODYNAMICS												
Open cycle	Direct generation of electrical energy	The MHD generator extracts electrical energy from the moving conducting fluid. The generator output is delivered to the load by a transformer, inductor and a rectifier. The system concept is to use the flow and the liquid in the generator as the energy source or reactor (fuel).	Electrical DC (except as noted). Voltages in the kilovolt range.	Efficiency increases with limit to how small a unit can provide enough power for starting plant.	Noted below (where available)	Noted below (where available)	Need to develop superconducting magnets including superconductivity in gases. A search for superior seed materials for refinements of present values for voltages, cross sections in	Not applicable in general to laboratory models.	Not applicable in general to laboratory models.	Not established. Potentially good.	Short.	Not established. Potentially good.

TABLE 1- Status of technologic development of energy devices

Primary application	Description of device			State of technology			Performance			Economics						
	Resource input (form of energy)	Type output (form of energy)	Scaling range	State of R&D or technology	Current engineering efficiency	Possible engineering efficiency	Limiting phenomena and required research	Specific power of device		Reliability	Present life	Future life	Capital costs		Power costs	
								Wattage (except as noted)	Wattage (lb except as noted)				Present	Future		Present	Future
NES	Chemical fossil fuels (except as noted)	Mechanical (except as noted)	Noted below	Noted below	At point of maximum efficiency	Only minor improvements in efficiency are expected	Research to understand combustion, ignition, and pre-ignition phenomena for non-nuclear fuels.	Not applicable	Not applicable	Unlimited	Has been increasing				Should not change too much because technology is well advanced and is being balanced by increasing fuel costs.	
e	Fossil fuel		5-25,000 hp	Stage 1	35-38 percent (600 hp)		Study how to control wear and tear on high speed parts. Develop highly reliable regenerative form of fuel-air mixture.	41-187 (600 hp)			46,000 hours (20 years stationary)				7 mills/kwh	
e	Fossil fuel		1/2-3,000 hp	do	20 percent (300 hp)		Learn how to control wear and tear on high speed parts for steam turbine.	62-187 (600 hp)			20 years (stationary)				30 mills/kwh	
e	Fossil fuel		Fractional to 100 hp	do	15-20 percent		Develop use for thermal turbo compressors.	370 (example)			7,000 hours (automotive)				20 percent larger than Otto	
e	Fossil fuel		100-57,000 hp (150,000-hp turbine planned)	do	24-30 percent (350 hp)		Reduce cost, find inexpensive ways to control wear and tear on high speed parts for steam turbine. Develop use for thermal turbo compressors.	300-620			20 percent larger than Otto for marine mobile turbine.				\$30/kwh (forecast for marine mobile turbine)	
gas	Heat source (external)		Unknown	Stage 3	40 percent (100 hp)		Reduce weight.	750 kw ft (airplane jet engine)			10 years (stationary)				\$300/kwh (500 kw stationary)	
gas	Fossil fuel		do	do	30 percent (1,000 hp)		Improve sealing in combustion chamber.	83 (example)			Compatible with Otto				Do	
gas	Fossil fuel		10-50 hp	Stage 4	18-25 percent (150 hp)		Develop ways to reduce boiler maintenance costs.	370 (example)			10 percent larger than Otto				Do	
gas	Natural gas	Electrical A.C.	Within limits, efficiency in excess with 600 kw-1,000 M w	Stage 5	30 percent average (48.3 percent maximum estimated for 1960)	38.3 percent average (48.3 percent maximum estimated for 1960)	Find cheaper ways to control wear and tear on high speed parts for steam turbine. Improve methods of lubrication of good quality turbine oil. Improve methods of materials so that they can stand higher temperatures, and control chamber wear.	Not applicable			Depends on components				Do	
gas	Coal	do	do	do	4-6 percent increase over steam		Not necessarily feasible at present time. High cost of plant construction and high fuel performance—Accumulate statistical data on which to base design. Develop process specifications for both material and manufacturing. Work to lower fuel fabrication cost.	do			do				Do	
gas	Natural gas	do	17 M w-213 M w	do	25 percent increase over steam		Develop ways to reduce boiler maintenance costs.	do			do				Do	
gas	Coal, natural gas, oil	do	1,500 kw-40 M w	do	do		Improve methods of lubrication of good quality turbine oil. Improve methods of materials so that they can stand higher temperatures, and control chamber wear.	do			do				Do	
gas	Uranium, thorium	do	do	Stage 4		Presently 32 percent for lightwater reactors (estimated maximum efficiency in 1960)	Demonstration of ability to recycle plutonium in present system. System dynamics—Interaction between reactor power level, fuel exposure, coolant flow, and control system characteristics. Improve instrumentation.	do			do				Do	
TRIC or storage generator	Mechanical	Electrical, A.C. or D.C.	240 M w, largest existing plant. 1,874 M w, largest existing plant.	Stage 5	Hydraulic turbine approximately 98 percent	Only minor improvements in efficiency are expected	Improve instrumentation. Improve combustion and air pollution control. Improve flow characteristics of reactor design.	do		Excellent	Unlimited	Not applicable			Not applicable	Not applicable
YDRO	The MHD generator extracts mechanical energy from a fluid and delivers electrical energy to the fluid by a magnetic field and a nozzle. The system concept is to use the flow and the fluid in the generator and reactor fuel.	Electrical D.C. (except as noted) Voltages in the kilovolt range.	Efficiency in excess with small unit can provide enough power for magnetic field, generator and reactor.	Noted below (where available)	Noted below (where available)	Noted below (where available)	Need to develop economical long-life electrodes. Need to develop superconducting magnets. Study electrical conductivity in gases. A search for superior seed materials.	Not applicable in general to laboratory models.			Not established	Potentially good.			Not established	Not applicable

J

<p>vide enough er for mag- ic field.¹³</p>				<p>Need to develop economical long-life dectrodes.</p>			
	Stage 2			<p>Need to levelop supercon- ducting magnets. Study electrical conductivity in gases. A search for superior seed material. Refinement of present values for collison cross sections in gases of interest. Problem of chemical inter- actions between seed ma- terials and uncooled wall insulation. Engineering and economic studies of overall-plant or propulsion-system design.</p>			
w unit g studied.	Design		53 percent (esti- mated) 40 percent steam plant, 70 per- cent MHD power.				
(net)	do.	Estimated 2.5 percent. ¹⁴					
w (gross)	Tested	Approximately 5 percent. ¹⁴					20 seconds
r	Design	Estimated 5.5 percent. ¹⁴			0.1 ^{13 15}		3 minutes
r	Tested						10 minutes
w	do.	2 percent					30 minutes
x, 0.05-1 lb st of lab- ory devices.	Stage 2	10-70 percent es- timated maxi- mum effect of laboratory de- vices.					
	Preliminary cal- culations. ¹⁷	Approximately 70 percent (esti- mated overall efficiency).				Thrust-to-weight ratio of 10.	

Table I - Continued - Status of technologic development of energy devices¹

Name	Description of device				State of technology			Performance			Economics						
	Primary application	Resource input (form of energy)	Type output (form of energy)	Scaling range	State of R&D or technology ¹	Current engineering efficiency	Possible engineering efficiency	Limiting phenomena and required research	Specific power of device	Reliability	Present life	Future life	Capital costs				
													Present	Future			
						Watts/lb (except as noted)	Watts/lb (except as noted)										
Closed cycle	Bulk or space power with nuclear reactor	Nuclear fission fuels	Electrical D.C. high current, low voltage	Laboratory size being constructed	Stage 2	40 percent (estimated) (no turbine) (MHD-steam closed cycle power plants)	Must find low-temperature liquid fuel (1,200° F) conducting liquid (e.g., sodium) with low recombination rates. Reconnection between ion and electron beams, with aluminum cathodes. Impurity problems. Pumping problems.	0.5-5 kw/lb	Not established	Thousands of units, some of which are being tested for other devices.	1 year (estimated)	5-10 years (estimated)	\$47,000/kw (estimated)	Present	Future	7 ²	
Vortex type	Bulk power	Fossil fuels	Electrical A.C.	Not established	Stage 1	Not established for complete energy conversion system.	Need for qualified electro-chemical mechanisms and/or suitable electrolytes. Development of stable electrolytes for use at low and intermediate temperatures. Research on novel materials and novel fuels characterized by low potential loss, low overpotential, and high energy density. Development of research in microbiology and space catalysis. Development of corrosion-resistant materials for high temperature electrolysis. Research to study: Membrane transport. Catalyst recovery and regeneration. Fuel purification.	5-40	Not established	4,000 hours (laboratory tests)							
AC type	Space power	Nuclear fission fuels	Electrical D.C. high current	Efficiency is independent of size. Six to 20w-3kw.	Several units have been tested in laboratory. Several prototypes ready in from 2 to 5 years.	40-80 percent (estimated)	Basic research on catalysis and electro-chemical mechanisms and/or suitable electrolytes. Development of stable electrolytes for use at low and intermediate temperatures. Research on novel materials and novel fuels characterized by low potential loss, low overpotential, and high energy density. Development of research in microbiology and space catalysis. Development of corrosion-resistant materials for high temperature electrolysis. Research to study: Membrane transport. Catalyst recovery and regeneration. Fuel purification.	7-18 (including auxiliary systems)	Not established	4,000 hours (laboratory tests)							
RED	Power generation	Nuclear fission fuels	Electrical A.C.	Not established	Stage 1	Not established for complete energy conversion system.	Need for qualified electro-chemical mechanisms and/or suitable electrolytes. Development of stable electrolytes for use at low and intermediate temperatures. Research on novel materials and novel fuels characterized by low potential loss, low overpotential, and high energy density. Development of research in microbiology and space catalysis. Development of corrosion-resistant materials for high temperature electrolysis. Research to study: Membrane transport. Catalyst recovery and regeneration. Fuel purification.	0.5-5 kw/lb	Not established	4,000 hours (laboratory tests)							
FUEL CELLS	Direct generation of power requirements. Moderate size. Operation of fuel cells auxiliary power supplies for military and underdeveloped countries. Motive power for special applications.	Chemical - Gas or liquid	Electrical D.C. high current	Efficiency is independent of size. Six to 20w-3kw.	Several units have been tested in laboratory. Several prototypes ready in from 2 to 5 years.	40-80 percent (estimated)	Need for qualified electro-chemical mechanisms and/or suitable electrolytes. Development of stable electrolytes for use at low and intermediate temperatures. Research on novel materials and novel fuels characterized by low potential loss, low overpotential, and high energy density. Development of research in microbiology and space catalysis. Development of corrosion-resistant materials for high temperature electrolysis. Research to study: Membrane transport. Catalyst recovery and regeneration. Fuel purification.	0.5-5 kw/lb	Not established	4,000 hours (laboratory tests)							
Primary: Low temperature (<150° F)		H ₂ -O ₂ H ₂ -H ₂ O Alcohol-air Hydrocarbon-air	Electrical D.C. high current	Efficiency is independent of size. Six to 20w-3kw.	Several units have been tested in laboratory. Several prototypes ready in from 2 to 5 years.	40-80 percent (estimated)	Need for qualified electro-chemical mechanisms and/or suitable electrolytes. Development of stable electrolytes for use at low and intermediate temperatures. Research on novel materials and novel fuels characterized by low potential loss, low overpotential, and high energy density. Development of research in microbiology and space catalysis. Development of corrosion-resistant materials for high temperature electrolysis. Research to study: Membrane transport. Catalyst recovery and regeneration. Fuel purification.	0.5-5 kw/lb	Not established	4,000 hours (laboratory tests)							
Intermediate temperature (<800° F)		H ₂ -O ₂ Alcohol-air, ammoniacal Hydrocarbon-air	Electrical D.C. high current	Efficiency is independent of size. Six to 20w-3kw.	Several units have been tested in laboratory. Several prototypes ready in from 2 to 5 years.	40-80 percent (estimated)	Need for qualified electro-chemical mechanisms and/or suitable electrolytes. Development of stable electrolytes for use at low and intermediate temperatures. Research on novel materials and novel fuels characterized by low potential loss, low overpotential, and high energy density. Development of research in microbiology and space catalysis. Development of corrosion-resistant materials for high temperature electrolysis. Research to study: Membrane transport. Catalyst recovery and regeneration. Fuel purification.	0.5-5 kw/lb	Not established	4,000 hours (laboratory tests)							
High temperature (>800° F)		H ₂ -O ₂ C ₂ H ₆ -O ₂ Hydrocarbon-air	Electrical D.C. high current	Efficiency is independent of size. Six to 20w-3kw.	Several units have been tested in laboratory. Several prototypes ready in from 2 to 5 years.	40-80 percent (estimated)	Need for qualified electro-chemical mechanisms and/or suitable electrolytes. Development of stable electrolytes for use at low and intermediate temperatures. Research on novel materials and novel fuels characterized by low potential loss, low overpotential, and high energy density. Development of research in microbiology and space catalysis. Development of corrosion-resistant materials for high temperature electrolysis. Research to study: Membrane transport. Catalyst recovery and regeneration. Fuel purification.	0.5-5 kw/lb	Not established	4,000 hours (laboratory tests)							
Very high temperature (>800° F)		C-O ₂	Electrical D.C. high current	Efficiency is independent of size. Six to 20w-3kw.	Several units have been tested in laboratory. Several prototypes ready in from 2 to 5 years.	40-80 percent (estimated)	Need for qualified electro-chemical mechanisms and/or suitable electrolytes. Development of stable electrolytes for use at low and intermediate temperatures. Research on novel materials and novel fuels characterized by low potential loss, low overpotential, and high energy density. Development of research in microbiology and space catalysis. Development of corrosion-resistant materials for high temperature electrolysis. Research to study: Membrane transport. Catalyst recovery and regeneration. Fuel purification.	0.5-5 kw/lb	Not established	4,000 hours (laboratory tests)							
Secondary		Fuel cell reactions can be regenerated by electricity, heat, and radioactivity.	Electrical D.C. high current	Efficiency is independent of size. Six to 20w-3kw.	Several units have been tested in laboratory. Several prototypes ready in from 2 to 5 years.	40-80 percent (estimated)	Need for qualified electro-chemical mechanisms and/or suitable electrolytes. Development of stable electrolytes for use at low and intermediate temperatures. Research on novel materials and novel fuels characterized by low potential loss, low overpotential, and high energy density. Development of research in microbiology and space catalysis. Development of corrosion-resistant materials for high temperature electrolysis. Research to study: Membrane transport. Catalyst recovery and regeneration. Fuel purification.	0.5-5 kw/lb	Not established	4,000 hours (laboratory tests)							
Low temperature		H ₂ -O ₂ Thermo-regenerative Alcohol-air Hydrocarbon-air	Electrical D.C. high current, low voltage	Efficiency is independent of size.	Stage 1	65 percent maximum (estimate)	Need for qualified electro-chemical mechanisms and/or suitable electrolytes. Development of stable electrolytes for use at low and intermediate temperatures. Research on novel materials and novel fuels characterized by low potential loss, low overpotential, and high energy density. Development of research in microbiology and space catalysis. Development of corrosion-resistant materials for high temperature electrolysis. Research to study: Membrane transport. Catalyst recovery and regeneration. Fuel purification.	7-18 (including auxiliary systems)	Not established	4,000 hours (laboratory tests)							
Intermediate temperature		K-Hg	Electrical D.C. high current, low voltage	Efficiency is independent of size.	Stage 1	65 percent maximum (estimate)	Need for qualified electro-chemical mechanisms and/or suitable electrolytes. Development of stable electrolytes for use at low and intermediate temperatures. Research on novel materials and novel fuels characterized by low potential loss, low overpotential, and high energy density. Development of research in microbiology and space catalysis. Development of corrosion-resistant materials for high temperature electrolysis. Research to study: Membrane transport. Catalyst recovery and regeneration. Fuel purification.	7-18 (including auxiliary systems)	Not established	4,000 hours (laboratory tests)							
High temperature		See below	Electrical D.C. high current, low voltage	Efficiency is independent of size.	Stage 1	65 percent maximum (estimate)	Need for qualified electro-chemical mechanisms and/or suitable electrolytes. Development of stable electrolytes for use at low and intermediate temperatures. Research on novel materials and novel fuels characterized by low potential loss, low overpotential, and high energy density. Development of research in microbiology and space catalysis. Development of corrosion-resistant materials for high temperature electrolysis. Research to study: Membrane transport. Catalyst recovery and regeneration. Fuel purification.	7-18 (including auxiliary systems)	Not established	4,000 hours (laboratory tests)							
Bioelectric		See below	Electrical D.C. high current, low voltage	Efficiency is independent of size.	Stage 1	65 percent maximum (estimate)	Need for qualified electro-chemical mechanisms and/or suitable electrolytes. Development of stable electrolytes for use at low and intermediate temperatures. Research on novel materials and novel fuels characterized by low potential loss, low overpotential, and high energy density. Development of research in microbiology and space catalysis. Development of corrosion-resistant materials for high temperature electrolysis. Research to study: Membrane transport. Catalyst recovery and regeneration. Fuel purification.	7-18 (including auxiliary systems)	Not established	4,000 hours (laboratory tests)							
Thermoelectric		See below	Electrical D.C. high current, low voltage	Efficiency is independent of size.	Stage 1	65 percent maximum (estimate)	Need for qualified electro-chemical mechanisms and/or suitable electrolytes. Development of stable electrolytes for use at low and intermediate temperatures. Research on novel materials and novel fuels characterized by low potential loss, low overpotential, and high energy density. Development of research in microbiology and space catalysis. Development of corrosion-resistant materials for high temperature electrolysis. Research to study: Membrane transport. Catalyst recovery and regeneration. Fuel purification.	7-18 (including auxiliary systems)	Not established	4,000 hours (laboratory tests)							
Seebeck devices		See below	Electrical D.C. high current, low voltage	Efficiency is independent of size.	Stage 1	65 percent maximum (estimate)	Need for qualified electro-chemical mechanisms and/or suitable electrolytes. Development of stable electrolytes for use at low and intermediate temperatures. Research on novel materials and novel fuels characterized by low potential loss, low overpotential, and high energy density. Development of research in microbiology and space catalysis. Development of corrosion-resistant materials for high temperature electrolysis. Research to study: Membrane transport. Catalyst recovery and regeneration. Fuel purification.	7-18 (including auxiliary systems)	Not established	4,000 hours (laboratory tests)							

1

Technology	Development	Research	Design	Construction	Operation	Cost	Reliability	Weight	Power	Efficiency	Life	Notes
C-O ₂	Fuel cell reactants can be regenerated by electrolysis, light, and radioactivity.	Stage 1	65 percent maximum (estimate)	10 kw/ft ³	200-800 hours (laboratory tests)	Microbiology research to study potential of biochemical fuel cells. Develop process resistant to low temperature acid electrolyte cells. Develop materials for high temperature cells. Research on heat transfer. Mass transfer. Catalyst recovery and regeneration. Fuel purification.						
H ₂ -O ₂	Thermo regenerative (PbO ₂ /PbSO ₄)	Stage 1	15-30 percent		600 hours (laboratory tests)							
K-Hg	See below	Stage 1	Unknown		500 hours (laboratory tests)							
For supplying power in the human body	Direct generation of electric power for implantable devices. Example: Replace batteries for danger signals, radios, furance fans, or vehicle radar.	Stage 1	Maximum 10 percent (estimated)		5-10 years (estimated)	Potentially better than other conversion methods involving parts.						
Marine and terrestrial	Natural gas	Stages 2,3,4,5	1-6 percent		4-15 watt commercial device (ma led)							
Propane	Example design (28 volts and about 10 amp)	Stage 2	1.4-3 percent		Greater than 5 years							
Gasoline		Stages 2,3,4	4-5 percent		Greater than 5 years (1975)							
Diesel		Stages 2,3,4	8-11 percent (estimated for 1975)		Greater than 5 years (1975)							
Radioisotope		Stages 2,3,4	5-8 percent (estimated for 1975)		Greater than 5 years (1975)							
Nuclear reactor		Stages 2,3	1.7 percent (estimated)		Greater than 5 years (1975)							
Space	Solar radiation	Stages 2,3,4	1.5 percent		Greater than 5 years (1975)							
Space	Concentrator radiation	Stages 2,3,4,5	2 percent		Greater than 5 years (1975)							
Cooling	Heat pumps (submarine air conditioning)	Stages 1,2	Not established		Not established							
Direct generation of electrical power for special applications	Heat and magnetic field	Stages 1,2	Not established		Not established							
Heat pump for temperatures below room temperature	Heat pumps (submarine air conditioning)	Stages 1,2	Not established		Not established							

65 percent maximum estimate.	200-800 hours (laboratory tests).	Estimate based on \$2-\$3/kwh. \$30/watt device amortized over 5-year period.	Not established.
Unknown.	600 hours (laboratory tests).	4-15 watt commercial device estimate.	Not established.
Maximum 10 percent estimate.	550 hours (laboratory tests).	5-10 years (estimated).	Not established.
Unknown.	30	Potentially better than other conversion methods involving parts.	Not established.
8-11 percent estimate for 1975.	150	5 (Typ) (w/5 lb fuel).	Estimate based on \$11.5/kwh (10 watt device) estimate for 1975. Estimate for 1975, does not include isotopes.
5-8 percent estimate for 1975.		8 (Typ) (includes fuel for 8 hours).	\$25/kw. Estimate for 1975.
5-8 percent estimate for 1975.		10 Laboratory generator w/o isotopes.	\$22/kw. Estimate for 1975.
6-8 percent estimate for 1975.		15.5-50 " Combined generator, does not include shielding."	\$25/kw. Estimate for 1975.
7-10 percent estimate for 1975.		15-20 w/o system deploy and support structure.	\$25/kw. Estimate for 1975.
7-10 percent estimate for 1975.		1w/lb with thermal storage.	Not applicable.
5 percent (projected estimate) for 1975. (Theoretical estimate (B = 10 kilogauss 300° K. 2-4 percent theoretical estimate).		Estimated 200 lb/ton air conditioning.	Not applicable.
Not established.		5w/lb (projected estimate). 1.45-10w/lb " (Theoretical estimate). Assumes superconducting magnet and neglects weight of heat source.	Not established.

4

Table I - Continued - Status of technologic development of energy devices

Name	Description of device				State of technology			Performance				
	Primary application	Resources input (form of energy)	Type output (form of energy)	Scaling range	State of R&D or technology	Current engineering efficiency	Possible engineering efficiency	Limiting phenomena and required research	Specific power of device (Watts/lb (except as noted))	Reliability	Present life	Future life
THERMIONICS												
Chemical	Direct generation of electric energy	Noted below	Electrical DC, low voltage and high current	Efficiency relatively independent of size. ^a	Stages 2 and 3	do		Develop technology of coupling converter with different sources available then the present. Study physics of the plasma tube. Research into optimization of collector surfaces and collector surfaces and their effect on the work function. Studies on the effect of contaminants on the work function. Studies on the effect of contaminants on the work function. Studies on the effect of contaminants on the work function.	1-200 w (estimated)	Depends on mechanism. Potentially better than thermionic tubes with moving element materials.	1,000 hours (estimated to be less than present material)	1-5 years (estimated)
Nuclear	Terrestrial	Fossil fuel, such as gasoline, kerosene, fuel oil, or natural gas.	Electrical DC	0.01-5 kw (estimated)	Estimated that Stage 2 unit may be tested in 1 year.	10-15 percent (estimated), ^a	Develop technology of coupling converter with different sources available then the present. Study physics of the plasma tube. Research into optimization of collector surfaces and collector surfaces and their effect on the work function. Studies on the effect of contaminants on the work function. Studies on the effect of contaminants on the work function.	1-200 w (estimated)			1-5 years (estimated)	1-5 years (estimated)
	Space	Radioisotopes	Electrical DC	0.01-5 kw (estimated) (SNAP-10-25 watts)	Stage 2 unit may be available in 2 years.	10-15 percent (estimated), ^a	Develop technology of coupling converter with different sources available then the present. Study physics of the plasma tube. Research into optimization of collector surfaces and collector surfaces and their effect on the work function. Studies on the effect of contaminants on the work function. Studies on the effect of contaminants on the work function.	1-200 w (estimated)			1-5 years (estimated)	1-5 years (estimated)
	Next (submarine) powerplant	Nuclear reactor	Electrical DC	1 kw-10 Mw (design objective) (estimated)	Flight test in 2 to 3 years.	10-15 percent (estimated), ^a	Develop technology of coupling converter with different sources available then the present. Study physics of the plasma tube. Research into optimization of collector surfaces and collector surfaces and their effect on the work function. Studies on the effect of contaminants on the work function. Studies on the effect of contaminants on the work function.	1-200 w (estimated)			1-5 years (estimated)	1-5 years (estimated)
	Underdeveloped countries	Solar radiation	Electrical DC	0.01-5 kw (estimated)		10-15 percent (estimated), ^a	Develop technology of coupling converter with different sources available then the present. Study physics of the plasma tube. Research into optimization of collector surfaces and collector surfaces and their effect on the work function. Studies on the effect of contaminants on the work function. Studies on the effect of contaminants on the work function.	1-200 w (estimated)			1-5 years (estimated)	1-5 years (estimated)
Electrical simulating test source		Electrically heated in laboratory	Electrical DC	1 kw-10 Mw (design objective) (estimated)		10-15 percent (estimated), ^a	Develop technology of coupling converter with different sources available then the present. Study physics of the plasma tube. Research into optimization of collector surfaces and collector surfaces and their effect on the work function. Studies on the effect of contaminants on the work function. Studies on the effect of contaminants on the work function.	1-200 w (estimated)			1-5 years (estimated)	1-5 years (estimated)
		Nuclear heated in laboratory	Electrical DC	0.01-5 kw (estimated)		10-15 percent (estimated), ^a	Develop technology of coupling converter with different sources available then the present. Study physics of the plasma tube. Research into optimization of collector surfaces and collector surfaces and their effect on the work function. Studies on the effect of contaminants on the work function. Studies on the effect of contaminants on the work function.	1-200 w (estimated)			1-5 years (estimated)	1-5 years (estimated)
		Solar unit electrically heated in laboratory	Electrical DC	0.01-5 kw (estimated)		10-15 percent (estimated), ^a	Develop technology of coupling converter with different sources available then the present. Study physics of the plasma tube. Research into optimization of collector surfaces and collector surfaces and their effect on the work function. Studies on the effect of contaminants on the work function. Studies on the effect of contaminants on the work function.	1-200 w (estimated)			1-5 years (estimated)	1-5 years (estimated)
SOLAR												
Domestic	Heating (air conditioning)	Radiation	Electrical DC	0.01-10 kw ^b	Stage 1	Approximately 15 percent	Research and development in low-temperature vacuum seal.	0.1 g/lb ^c		Potentially good		
Industrial	Cooling (air conditioning)	do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	13.36				
Direct Photovoltaic Silicon	Desalting	do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	45 w (typical)				
	Auxiliary power	do	do	do	Stage 5	do	Research and development in low-temperature vacuum seal.	14.3 w (typical)				
	power levels for industrial zone, munitions, (use) poor countries.	do	do	do		do	Research and development in low-temperature vacuum seal.	10				
Thin film		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	9-16.5 w ^d				
Photochemical		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	17				
Thermionic	Space	do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	2				
Thermoelectric Flat Plate		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	2.5				
Concentrator Turbo-erator		do	do	do	Flight tested	do	Research and development in low-temperature vacuum seal.	10				
High Temperature Oxide		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	9-16.5 w ^d				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	17				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	2				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	2.5				
		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	4-5.5				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	10				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	17				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	2				
		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	2.5				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	4-5.5				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	10				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	17				
		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	2				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	2.5				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	4-5.5				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	10				
		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	17				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	2				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	2.5				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	4-5.5				
		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	10				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	17				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	2				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	2.5				
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		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	17				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	2				
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		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	4-5.5				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	10				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	17				
		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	2				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	2.5				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	4-5.5				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	10				
		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	17				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	2				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	2.5				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	4-5.5				
		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	10				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	17				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	2				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	2.5				
		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	4-5.5				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	10				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	17				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	2				
		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	2.5				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	4-5.5				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	10				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	17				
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		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	4-5.5				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	10				
		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	17				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	2				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	2.5				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	4-5.5				
		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	10				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	17				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	2				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	2.5				
		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	4-5.5				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	10				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	17				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	2				
		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	2.5				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	4-5.5				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	10				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	17				
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		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	2.5				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	4-5.5				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	10				
		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	17				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	2				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	2.5				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	4-5.5				
		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	10				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	17				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	2				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	2.5				
		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	4-5.5				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	10				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	17				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	2				
		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	2.5				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	4-5.5				
		do	do	do	Stage 3	do	Research and development in low-temperature vacuum seal.	10				
		do	do	do	Stage 4	do	Research and development in low-temperature vacuum seal.	17				
		do	do	do	Stage 1	do	Research and development in low-temperature vacuum seal.	2				
		do	do	do	Stage 2	do	Research and development in low-temperature vacuum seal.	2.5				
		do										

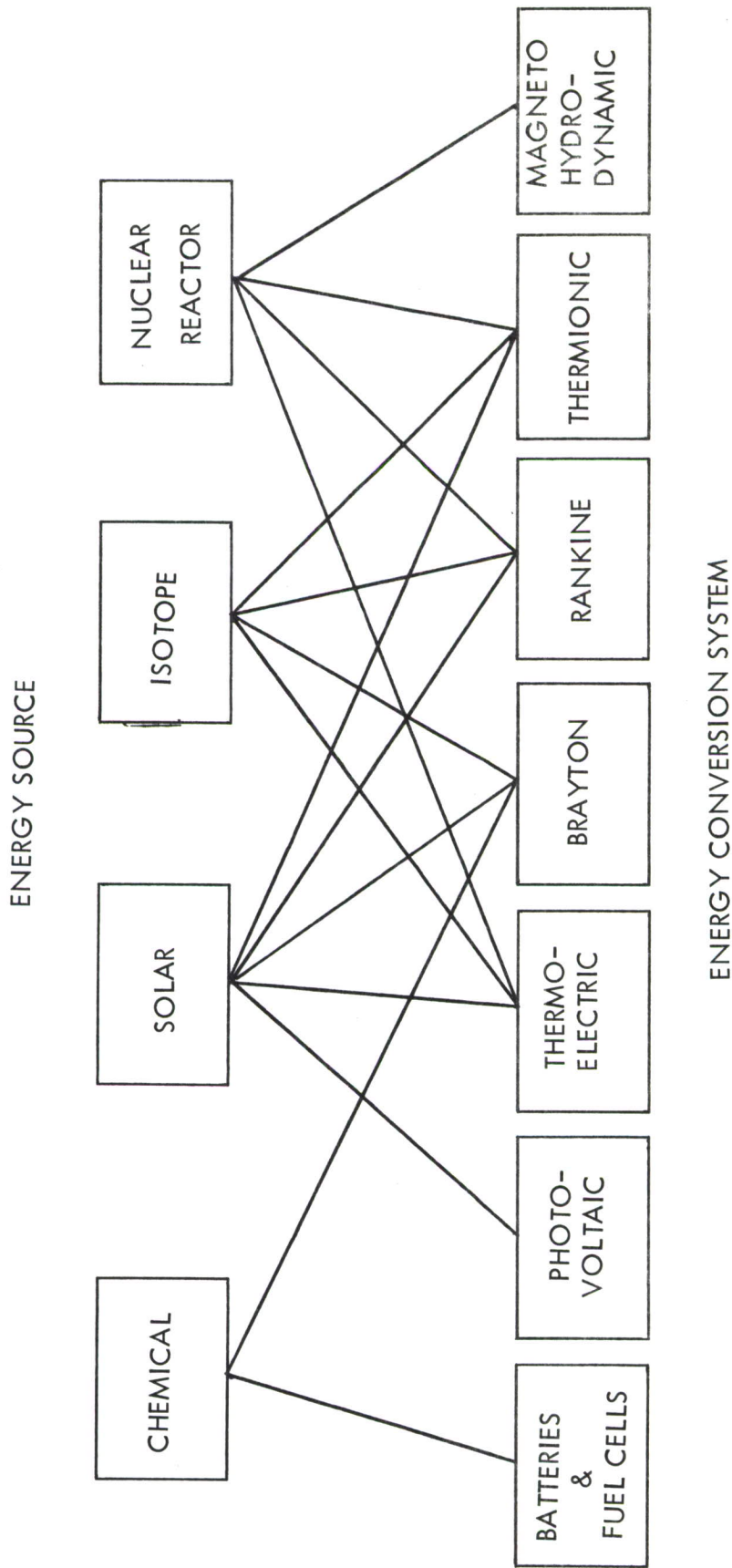


FIGURE 1 CANDIDATE POWER SOURCES FOR SMALL UNATTENDED APPLICATIONS

TECHNICAL LIBRARY
 BLDG. 313
 ABERDEEN PROVING GROUND, MD.
 STEAP-TL

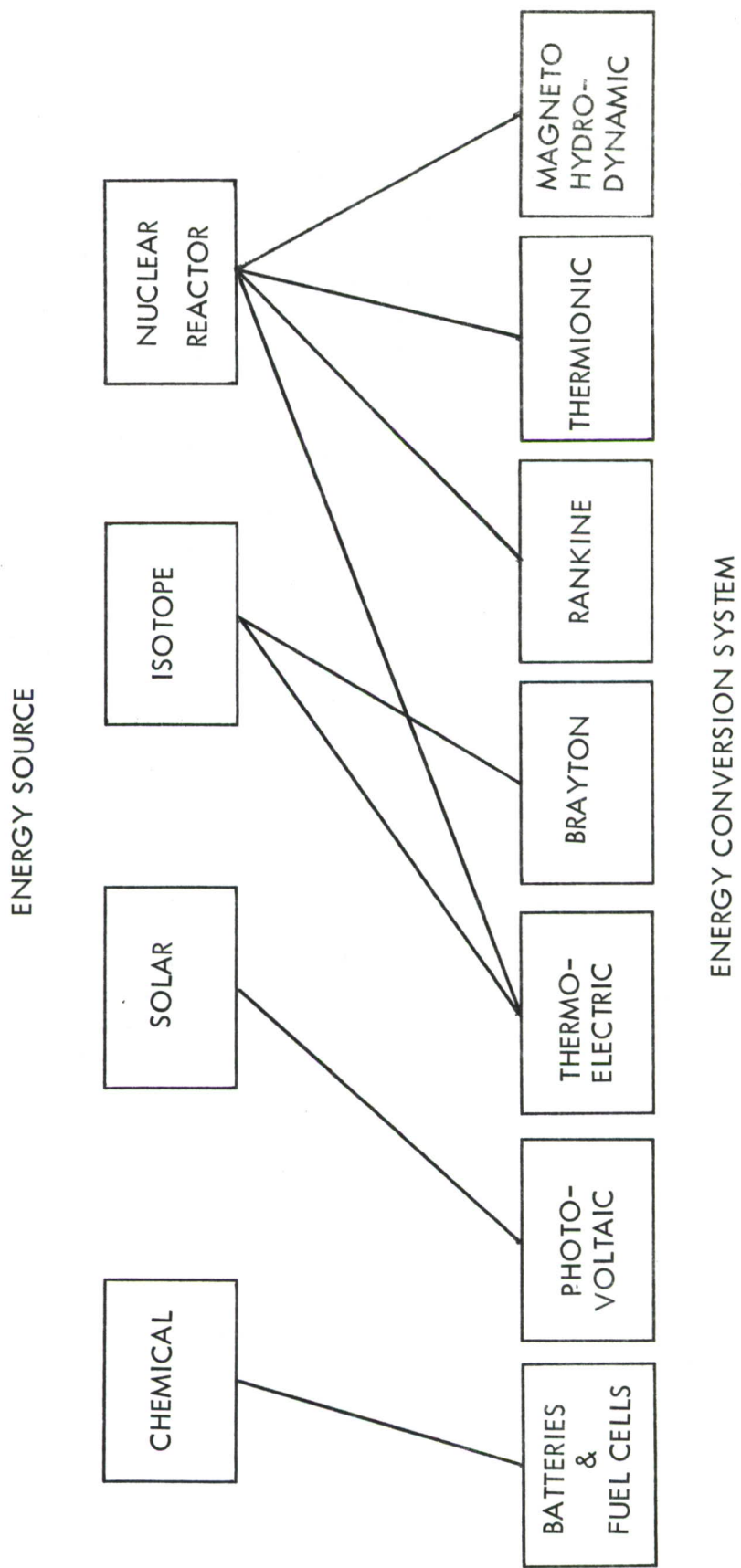


FIGURE 2 POWER SOURCES SELECTED BY NASA FOR FURTHER DEVELOPMENT

In a different environmental context, a report⁴ by the National Academy of Sciences concludes that two basic types of energy systems in the 1-100 kW range are available to meet current naval undersea needs. These are underwater power cable systems and conventional, aqueous electrolyte batteries. The report further concludes that two additional basic types of energy systems are now sufficiently advanced to meet naval undersea needs in the short-run, 5-to 10-year time frame. These are hydrogen-oxygen fuel cells and heat-dynamic converters. In the long run, the National Academy believes that isotope-fueled systems employing static or dynamic converters, small nuclear reactors, and high-performance primary and secondary electrochemical systems have promise for meeting naval undersea requirements.

The foregoing broad overview of current thinking is intended to illustrate that the present state of technological development has not revealed a single preferred power source, or even a few, to which development support should be directed, even though many agencies are directing their efforts toward specific requirements. This conclusion is supported by a current survey⁵ by the U.S. Army Mobility Equipment Research and Development Command (USAMERDC). Their report states:

"A similar survey made by USAMERDC in 1965 found that there was insufficient factual data available to reach a completely definitive conclusion. It was hoped that the technological advances in the intervening three years would have yielded the necessary data. Although this was found true to a certain extent, there were still several projections that had to be made in the present study, especially in the area of life and cost."

4 / Energy Systems of Extended Endurance in the 1-100 kW Range for Naval Undersea Applications, a Report by the Power of Energy Sources of the Committee on Undersea Warfare, National Academy of Science-National Research Council, September 1968.

5 / Special Study on Silent Electric Power Generators for Tactical Applications, Electrotechnology Laboratory, U.S. Army Mobility Equipment Research and Development Command, August 1968.

The brief survey which Booz-Allen Applied Research has conducted under the present study confirms that there are numerous theoretical papers on candidate sources and that there is a paucity of test data on actual conversion devices. While there are a number of industrial firms interested in the subject area, the state-of-the-art and the small market have combined to limit their efforts to the production of no more than a few prototype devices, usually under the auspices of a Government-sponsored research and development contract.

II. A REFERENCE BASELINE CONFIGURATION

The USAMERDC study contains a comprehensive comparative analysis of 0.5-to 15-kW power sources which are considered to be candidate systems for development in the short and intermediate time frame. In addition, these candidate systems are compared with the present general purpose, military standard (MILSTD) family of reciprocating engine generator sets.

Army experience with its MILSTD sets is extensive and has revealed them to possess many favorable characteristics except for silence. Evaluation by USAMERDC of the MILSTD sets included consideration of silencing measures.

The choice of the MILSTD sets as a reference base seems appropriate, and they are so used in this report. Performance parameters for these units are well-established and documented. Such data provides a firm point of departure for assessment of candidate developmental systems where performance is less well-demonstrated. Data for these units, in a silenced configuration as developed by USAMERDC, are shown in Table 2.

TABLE 2
SILENCED MIL-STD ENGINE GENERATOR SETS
MAJOR TECHNICAL CHARACTERISTICS

Rating (kW)	0.5	1.5	3.0	5.0	10.0
Weight (lb.)					
STD	70	125	285	488	850
Silenced	165	300	885	1450	2200
Volume (ft. ³)					
STD	3.2	6.0	12.1	17.3	28.0
Silenced	10.7	11.0	22.1	33.6	60.5
Fuel Type	MIL-G-3056 MIL-F-5572				
Ambient Temperature Range	-65 ^o to +125 ^o F				
Altitude	Rated Output at 5000 ft, 107 ^o F 90% Rated Output at 8000 ft, 95 ^o F				
Time Between Overhaul	1500 hours				
Audibility	Inaudible at distances over 100 meters vs. HEL Jungle Ambient Noise Background				

III. CANDIDATE POWER SOURCES

We have attempted, albeit in limited depth, to review the current performance status and potential of a wide array of energy conversion devices. Our analysis included collection and review of published reports and telephone contact with a number of government agencies and industrial firms. The results of this effort are summarized in the material that follows.

1. ELECTROCHEMICAL POWER SOURCES⁶

This section reviews the state-of-the-art of electrochemical power sources which are considered pertinent to this study. Data is presented on batteries, fuel cells, and thermoelectric devices.

(1) Conventional Batteries⁷

Conventional batteries have a number of operating advantages. They have no moving parts, thus are capable of silent operation. They can be operated over a wide range of ambient conditions and operate at relatively low temperatures. They have a high reliability. Failure usually occurs one cell at a time in such a way that operation can be extended with degraded output for some period of time. Both primary (nonregenerable) and secondary (regenerable) cells are readily available in a wide variety of types, sizes, and configurations.

Conventional batteries, however, have a number of distinct disadvantages. Their energy densities and specific energies are low compared with other energy sources and conversion systems. They usually provide only a few watts per pound and a few kilowatts per cubic foot. Their operating power levels are limited by internal electrode, electrolyte, and separator losses, and these losses increase rapidly with load. The features of various primary and secondary cells now available are summarized in Tables 3 and 4.

⁶ / Prospects for Electric Vehicles, A Study of Low-Pollution-Potential Vehicles - Electric, Department of Health, Education and Welfare, National Center for Air Pollution Control, Arthur D. Little, Inc., May 1968.

⁷ / NAS-NRC report, op. cit.

Table 3 (Cont'd)

Magnesium-cuprous chloride	Mg	Cu ₂ Cl	MgCl ₂ + sea water	20-100	1.4	1.0-1.3	150	15-20	0.7-1.0	---	0.1-50 hr	high drain rates; activated by introduction of water; less expensive than Mg-AgCl cell
Zinc-chlorine	Zn	Cl ₂ (C)	ZnCl ₂ , NH ₄ Cl	30-120	2.1	1.3-1.9	105	20-25	1.6-1.8	---	6 hr	high drain rates; other non-reserve-type worked on for torpedo and submarine applications in past
Thermal cells	Ca	PbCrO ₄ (Ni)	LiCl, KCl fused	---	2.8	2.0-2.6	280	5-10	0.3-0.6	---	few mins.	high drain rate; activation by melting electrolyte
Ammonia activated	Mg	AgCl	KSCN, NH ₃	-60-125	2.2	1.5-2.0	180	10-30	1-2	---	0.1-2 hr	high drain rate; activated by introduction of ammonia
Zinc-lead	Zn	PbO ₂	H ₂ SO ₄	0-140	2.5	2.0-2.3	---	20-26	---	---	several days	high drain rate; activated by introduction of electrolyte
<u>Experimental types (non-reserve)</u>												
Magnesium-organic depolarizer	Mg	m-dinitrobenzene	MgBr ₂	0-130	1.65	0.9-1.3	250	40-80	2-4.5	---	>12 mo	one of the more promising of a number of cells using organic cathodic depolarizers
Aluminum dry cell	Al	MnO ₂	AlCl ₃ , (NH ₄) ₂ Cr ₂ O ₇	---	1.7	1.0-1.6	---	---	---	---	---	higher capacity and voltage than Leclanche cell; wasteful corrosion of Al a problem
Magnesium bismuth oxide	Mg	Bi ₂ O ₃	MgBr ₂	---	1.6	1.0	---	---	---	---	---	surprisingly small drop off of voltage with time

* For the most part based on data from various battery manufacturer's handbooks and ref. 2 and 3.

^b Based on active components in cell.

^c Does not include O₂ from air.

^d After cell has been filled with electrolyte.

^e Most cells have not been optimized for power density but rather energy density; in most instances maximum power density can be maintained only for a few minutes at a time.

^f Estimated distributors or wholesale cost.

Table 4

SUMMARY OF SECONDARY BATTERY CHARACTERISTICS

Type	Anode	Cathode	Electrolyte	Temp. °F	Open circuit voltage (V)	Typical operating voltage (V)	Theoret- ical energy density (Wh/lb)	Actual energy density (Wh/in. ³)	Maximum power density (W/ in. ³)	Cost ^a (\$/kWh)	Opera- ting Life	Typical no. of cycles	Remarks			
<u>Conventional</u>																
Lead acid	Pb	PbO ₂	H ₂ SO ₄	-40-140	2.2	1.7-2.1	80-115	5-20	0.4-1.2	15-30	1-2	0.09(60)	2-14 yr	1500	conventional lead storage cell; presently used for submarines, automobiles, etc.	
Edison	Fe	Ni oxides	KOH	-10-140	1.6	1.1-1.4	135	7-15	0.7-1.2	---	---	0.08(230)	6-20 yr	2000	much longer life than lead acid but lower capacity (Wh/lb) and more expensive	
nickel-cadmium	Cd	Ni oxides	KOH	-40-140	1.35	1.0-1.3	105	12-15	0.7-1.0	15	1.5	0.21(700)	4-6 yr	1000-2000	available as completely sealed cell	
silver-zinc	Zn	AgO	KOH, ZnO	0-140	1.8	1.3-1.6	205	30-80+	1.8-5.6	170	7.2	8.40(800)	6-18 mo	10-200	high capacity and very high drain rates; low cycle life; expensive	
silver-cadmium	Cd	AgO	KOH	-10-140	1.4	1.0-1.3	120	16-33	1.4-3.0	---	---	2.50(950)	1-3 yr	300-500	greater number of cycles than silver zinc	
alkaline manganese-zinc	Zn	MnO ₂ (C)	KOH	-40-140	1.5	1.1-1.4	185	20-30	2-3	6	0.4	---	(200)	1-3 yr	200	available as completely sealed cell; cycle life dependent strongly on depth of discharge
<u>Experimental</u>																
sodium-sulfur	Na	S	modified alumina	550	variable	1.5-2.0	350	150	8	---	---	---	---	---	laboratory stage	
lithium-chloride	Li	Cl ₂	fused chloride	450-650	4.1	3.5-4.0	1000	250	---	---	---	---	---	---	laboratory stage	
lithium-chloride	Li	AgCl	AlCl ₃ , LiCl in propylene carbonate	<165	3.0	2.3-2.8	230	25-90	1.5-2.2	---	---	---	~1 yr	50-200	high cell voltage, still in laboratory stage	
lithium-fluoride	Li	NiF ₂	propylene carbonate	<165	3.0	2.5	750	100	---	---	---	---	---	---	high cell voltage still in laboratory stage	

^a First figure - cost per kWh of energy drawn from battery during anticipated cycle life; bracketed figure - initial cost.

The National Academy of Sciences considers that magnesium-silver-chloride primary cells and silver-zinc, lead-acid, silver-cadmium, and nickel-cadmium secondary cells are of interest for naval undersea applications. NASA has primary interest in silver-zinc, silver, cadmium, and nickel-cadmium secondary cells. The state of the art of some of these and similar devices is summarized in excellent fashion in the Arthur D. Little study.

(2) Fuel Cells

In a review⁸ of government-sponsored fuel-cell research and development covering the period 1950-1964, John I. Thompson and Co. (NASA Contract No. NASW-1039) found that nearly 200 contracts had been awarded to 90 contractors up to December 1963. This effort had resulted in the publication of nearly 800 reports describing the work performed. Since the date of the report, fuel-cell research and development has continued to expand and fuel-cell technology has continued to advance. The state of the art is still evolving rapidly and, though some devices have advanced sufficiently for application, selection of a particular system remains a difficult and risky problem. The advantages, disadvantages, and potential of specific approaches and devices are still subject to a wide range of interpretation.

The Energy Study Group, in its survey⁹ of the state of the art in fuel-cell research and development, concluded that only two classes of these devices were sufficiently advanced to justify a development effort. These were hydrogen and sodium amalgam cells, but the sodium amalgam cell was considered economically attractive only for special applications. The study further concluded that the only other type of cell for which development might be considered is the dissolved-fuel type, such as methanol. However, it was felt that development of the dissolved-fuel type should be postponed in deference to determination of the potential of some of the hydrocarbon cells.

8 / Fuel Cells, A Review of Government-Sponsored Research, 1950-1964, National Aeronautics and Space Administration, NASA SP -120, 1967.

9 / Interdepartmental Energy Study, op. cit.

The USAMERDC study reports upon their analysis of three different fuel-cell systems: (1) low-temperature alkaline electrolyte, (2) low-temperature acid electrolyte, and (3) high-temperature molten carbonate electrolyte systems. All of these are, of course, indirect systems in that hydrogen is extracted from the basic fuel for use in the fuel cell. Their selection for evaluation is based, among other things, upon the opinion that direct systems are not sufficiently advanced for reasonable projection of their ultimate performance characteristics.

Prototypes of catalytic, steam-reforming hydrogen generators for each of the three systems have been operated by USAMERDC, thus providing data for comparative evaluation purposes. Partial oxidation and thermal-cracking devices were not considered because of their low efficiency, but the report indicates that an intensive research program to combine the best qualities of all the fuel-conditioning methods is in effect.

USAMERDC considers the low-temperature alkaline system to be the most advanced, though most complex, of the three systems evaluated. The major problem with this process lies in obtaining a fuel acceptable to the alkaline electrolyte. To accomplish this, the course taken by the majority of alkaline fuel-cell developers is as shown in Figure 3.

The low-temperature acid system is considered to be less complex than the alkaline system and the acid system, employing a phosphoric acid electrolyte, is preferred by USAMERDC over the alkaline cell from an operational point-of-view. The acid cell, however, has severe materials problems. High loadings of a precious metal catalyst are required to achieve reasonable performance, resulting in a more expensive device.

The least complex of the three systems, and potentially the most efficient in large sizes (over 10 kW), is the high temperature molten carbonate system. The high operating temperature and the corrosive nature of the molten salt pose material problems, however.

In the views¹⁰ of still another analyst, the hydrogen-oxygen, hydrazine-oxygen, and sodium-amalgam-oxygen systems are considered to be the only systems that have advanced to the state where

^{10/} "Fuel Cells: Their Status and Future Outlooks," E. Yeager, Chemical Engineering Progress, September 1968.

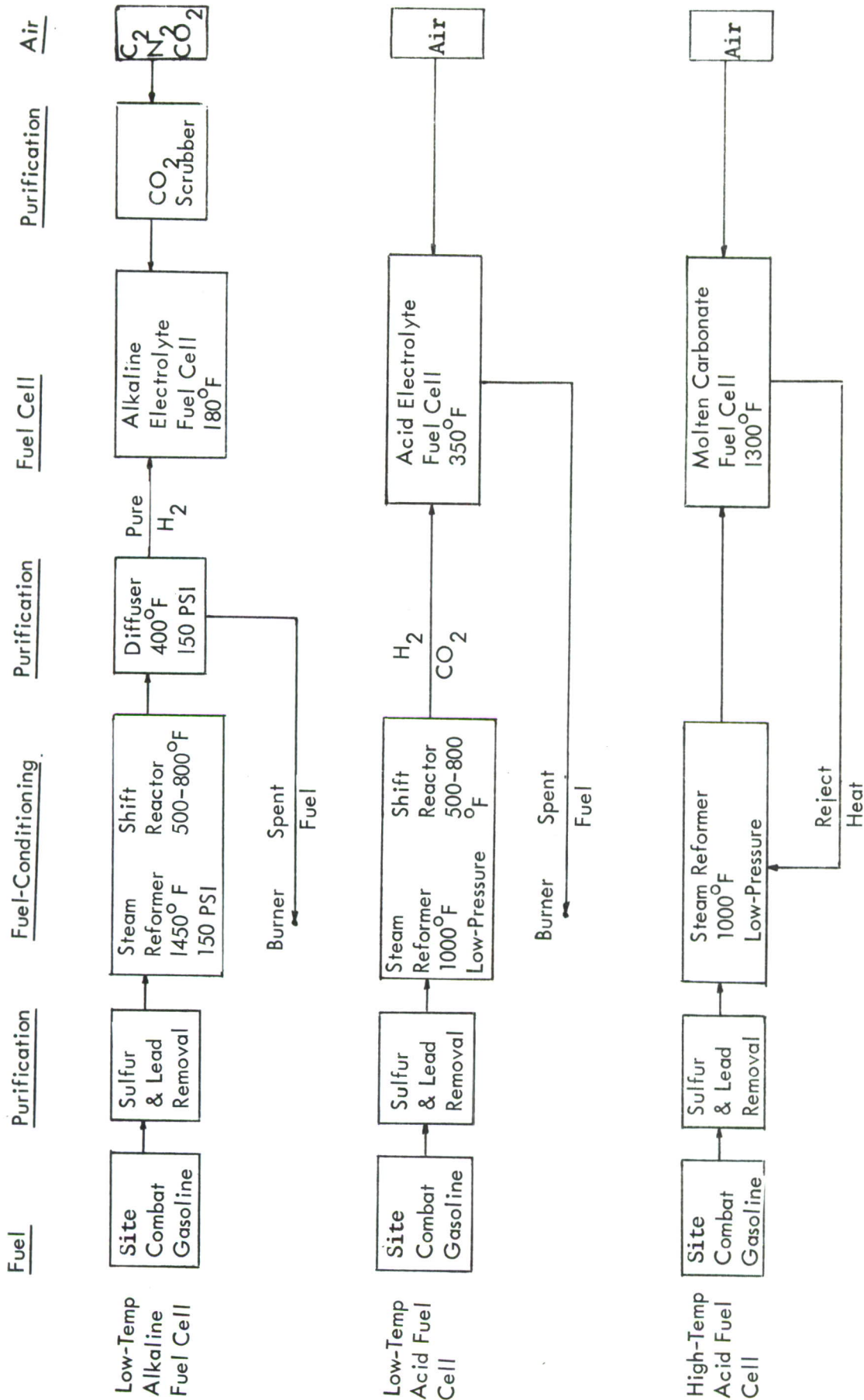


FIGURE 3 Simplified Flow-Charts of Fuel-Cell Systems

they are ready for application. Status of typical cells, as presented by this analyst, is shown in Tables 5 and 6. From the foregoing, there appears to be some consensus as to the current status and potential of fuel-cell systems, at least relative to broad classes of systems.

The hydrogen-oxygen cells of Union Carbide, Pratt-Whitney, and Allis-Chalmers, shown in Table 5, operate with strongly alkaline electrolyte. These are typical of the low temperature alkaline cell class considered by USAMERDC and other analysts. This class of device requires a purifier which, as reported by USAMERDC, has an investment cost on the order of \$500 to \$700 per kilowatt of fuel cell. Cost reductions of the order of 50 percent are thought to be possible in the long-run.

The General Electric cell shown in Table 6 uses an ion exchange membrane which is equivalent to an acid electrolyte. Systems of this class generally have high catalyst costs and require expensive current collectors. USAMERDC estimates that such costs should be reduced by 50 percent in the short-run (2-5 years) by improvements in power density, reduction of catalyst loading, and development of less expensive current collectors.

Table 7¹¹ illustrates the performance achieved by typical fuel cells which have been produced by each of the foregoing manufacturers. The units shown range in power output from about 50 watts to 2 kilowatts.

The hydrazine-oxygen cells of Union Carbide (see Table 6) use carbon electrodes containing catalysts while the cells of Monsanto and Allis-Chalmers use porous metal electrodes. The electrolyte in each case is a concentrated caustic (sodium or potassium). The cost of hydrazine is a constraint upon utilization of this type of cell.

The sodium-amalgam-oxygen cell of Table 7 provides a high cell voltage with power densities and volumes comparable to, or better than, hydrogen-oxygen cells. The cell operates efficiently on air without a necessity for carbon dioxide removal. Its principal disadvantage is the cost of sodium, which makes its power output rather expensive.

11/ 1967 NASA/JITCO Study, op. cit.

TABLE 5
TYPICAL FUEL-CELL SYSTEMS: HYDROGEN-OXYGEN

Systems	Electrodes	Electrolyte	Temp. °C	Remarks
A. U. S.				
Union Carbide	C + catalysts	KOH	20-65	Low cost for catalysts.
Pratt-Whitney	Ni + catalysts	KOH	180-240	Project Apollo.
General Electric	Pt	ion membrane	20-80	Project Gemini; high cost for Pt catalysts.
Allis-Chalmers	porous metals + catalysts	KOH	20-95	Electrolyte in porous mat., spec. water control-removal sys.
B. Foreign				
Raney, nickel (Varta, USSR, Siemens, Brown-Boveri)	Raney nickel anode, usually silver or silver alloy cathode	KOH	20-90	Not as advanced as U. S. counterparts.
Quadrus (ASEA, Sweden)	Ni + catalysts	KOH	20-100	Submarine applic. antic.; 200 kW unit under const.
Tokyo Shibaura	Pd diffuser anode, Ni + catalysts cathode	KOH	30-100	Not as advanced as U. S. counterpart.

Typical operating voltages for hydrogen-oxygen cells listed are 0.75-0.90 V. Hydrogen and oxygen requirements are 0.087 to 0.105 lb/kWH and 0.70 to 0.84 lb/kWH, respectively, depending on the operating voltage.

TABLE 6
TYPICAL FUEL-CELL SYSTEMS OTHER THAN HYDROGEN-OXYGEN

System	Electrodes	Electrolyte	Temp. °C	Typical oper. voltage	lb. /kWH anode	lb. /kWH cathode	State of development, Remarks
Hydrazine - oxygen ¹	Porous metals, carbon + catalysts	KOH	20-70	0.85	1.25	0.75	Advanced: Union Carbide, Monsanto Allis-Chalmers.
Sodium amalgam - oxygen	Steel anode; carbon + catalysts cathode	NaOH	20-70	1.50	1.22	0.43	Advanced: Kellogg, Yuasa, Japan Storage Battery.
Hydrocarbon - oxygen ²							
a. Pd diffuser anode	Pd diaphragm anode; Ni + catalysts cathode	NaOH	250	0.80	0.22	0.80	Early: Pratt-Whitney.
b. Phosphoric acid	Pt or Pt alloys	Phosphoric acid	150-200	0.30	0.59	2.10	Early: General Electric, ESSO, others.
c. Fused carbonate	Porous metals + catalysts	Fused carbonates	500-650	0.70	0.25	0.91	Intermediate: Texas Instruments, Institute of Gas Technology.
d. Ionic conducting solid	Pt	Yttrium zirconate	800-1000	0.70	0.25	0.91	Early: Westinghouse.
Alcohol - oxygen	Pt or Pt alloys	Phosphoric acid	50-80°C	0.80	0.22	0.80	Early, ESSO, others.

¹Hydrazine stored as a 60%-by-weight aqueous solution. ²Assuming butane or a higher saturated hydrocarbon.

TABLE 7
PERFORMANCE OF H₂ O₂ FUEL-CELL UNITS

Cell	Approximate electrode dimension, in.	Rated single-cell data		Unit power, watts	Weight, pounds	Life, hours
		A/sq ft	Volts			
Union Carbide:						
1961.....	6×6	40	0.8	560	...	150
1964.....	12×14	50	.8	^b 320	...	>2600
General Electric IEM:						
Hope, 1962.....	7×10	15	.6	200	28	100
Gemini, 1965.....	7×8	40	.73	1000 (peak)	68	>400
Pratt & Whitney:						
1962.....	5 diam.	155	.87	280	...	>690
Apollo, 1965.....	.....	...	.87	1400 2300 (peak)	220	>500
Allis-Chalmers:						
1962.....	11×6½	85	.8	1500	...	3000
1965.....	4×7½	150	.75	^b 45	14.5	.....

The molten carbonate cell is considered by USAMERDC to be the least expensive device of those evaluated. These high-temperature systems do not require a purifier or a precious metal catalyst. USAMERDC projects some additional cost reduction for these systems with advanced state-of-the-art.

(3) Biocells

Biocells are normally classified by the specific relationship of the biological microorganism to the process of electron transfer into indirect and direct categories. In the indirect cell, the microorganism catalyzes the formation of a fuel which is in turn used in a conventional fuel cell. In the direct cell, the substrate containing the microorganism acts as an electron acceptor or donor and is an integral part of the electrical circuit. The energy employed by the direct cell may derive from electro-mechanical metabolism, wherein electrons are shunted from the biological metabolic oxidation-reduction reactions to the external circuit, or from redundant energy normally shed by the microorganism in the form of heat, light, and chemicals.

Phenomena associated with biological fuel cells, or biocells, have been studied for years. Galvani, as early as 1771, investigated the reverse effect of an electric current on biological processes. Grove, who is considered by many to be the inventor of the conventional oxygen-hydrogen fuel cell, experimented with biological electricity in 1839.

In spite of an extended history, biocells have not progressed rapidly to a state of successful practical application. This slow rate of progress is due in part to the sensitivity of biocatalysts. They may be poisoned by changes in pH, temperature, or concentration. They must afford good electron transport among the electrolyte, substrate and electrodes. The mechanism of electron transport is the primary factor limiting development of biologically catalyzed fuel cells. The potential associated with conventional fuel cells **has** accelerated their development in recent years. This development will hasten the development of the biocell, in particular, the indirect biocell. Nevertheless, an extended and expensive development will be required before the potential may be transformed to practical application.

2. THERMOELECTRIC DEVICES

Thermoelectric devices provide direct conversion of heat to electromotive force by use of a heat source, heat sink, and dissimilar materials. The conversion process is complex, and includes five identified phenomena which take place simultaneously: the Seebeck effect, the Joule effect, the conduction of heat, the Peltier effect, and the Thompson effect.¹² Common materials consist of combinations of dissimilar metals, metal and semiconductor, and p-type and n-type semiconductors. The latter is illustrated in Figure 4. Thermoelectric devices are usually categorized by energy source and include carbonaceous or fossil-fuel-fired, isotope, solar and nuclear reactor generators. General characteristics of some of these devices are shown in Table 8.¹³

The materials currently used in thermoelectric devices are upper-temperature limited and accordingly achieve only low efficiencies. The best laboratory devices, operating at high temperatures, have efficiencies of roughly ten percent, while commercial units range downward to less than two percent efficiency.

(1) Fossil-Fuel-Fired Thermoelectric Devices

Commercial thermoelectric devices have been available in small sizes since about 1957. In 1962 and 1963, natural gas or propane-fired generators with outputs of about four to 15 watts became commonplace, and operated successfully in field service. Applications have been diverse and include power for railway caboose radio and lights, cathodic protection for gas and petroleum wells, microwave relay stations, remote weather stations, and wire line repeaters. Life expectancy claims for these small units range upward to 10 years. However, available commercial units carry warranties of full-rated output power for about one year. This is attributable in part to lack of operational experience.

^{12/} Zemansky, Mark W., Heat and Thermodynamics, 4th Ed., McGraw-Hill Book Co., New York, 1957.

^{13/} "Interdepartmental Energy Study," op. cit.

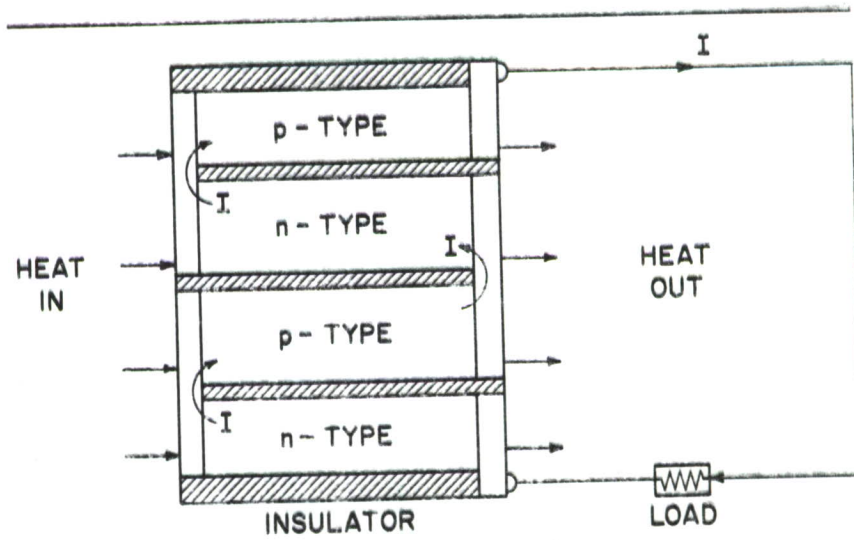


FIGURE 4 THERMOELECTRIC CONVERTER

TABLE 8
PARTIAL LIST OF THERMOELECTRIC GENERATORS

P _o (watts)	Temperature (nominal ° F)		Fuel	Duty	Efficiency (percent)	Remarks
	T _A	T _c				
2.5-3.5	620	115	Isotope Po ²¹⁰	Continuous (space).	5.8	PbTe material in compression, weight 4 pounds, radiation cooled, SNAP III, January 1959.
3	400	100	Nuclear wastes.	Continuous (marine).	4.0	BiTe material, metallurgically bonded, water cooled.
2.5, 5, 10, 60	900	150	Radioisotope Sr ⁹⁰ .	Continuous.....	16.0	Includes SNAP-7 series PbTe <i>n</i> -type, <i>p</i> -type material.
4, 8, 15	1,000	1400	Propane or natural gas.	Cyclic (marine and terrestrial).	1.6	80 to 100 watt-hours per pound fuel, natural convection cooled, \$30 to \$60 per watt.
10	400	180	Propane.....	.....do.....	2.0	BiTe material, metallurgically bonded, air cooled.
12	1860	1250	Hydrocarbon.	Continuous (terrestrial).	1.7	Cathodic protection use, air cooled, pressure hot junctions.
30	400	100	Propane.....	Cyclic (marine).	3.0	BiTe material, metallurgically bonded, water cooled, weight 40 pounds.
45	950	400	Leaded gasoline.	Cyclic (terrestrial).	-----	PbTe <i>n</i> -type material, proprietary <i>p</i> -type material, forced convection cooled.
150	1950	1500	.....do.....	.....do.....	-----	PbTe <i>n</i> -type material, PbSnTe <i>p</i> -type material.
267	850	280	Propane.....	.....do.....	1.4	Forced convection cooling, specific power = 7.5 watts per pound; burner heat flux = 8 watts per cm ² ; pressure contacts, burner efficiency = 39 percent.
260	1,100	300	.....do.....	.....do.....	2.4	Specific power = 6.9 watts per pound; PbTe <i>n</i> -type material, and <i>p</i> -type material.
500	1930	1700	Nuclear.....	Continuous (space).	11.7	GeSi material, bonded junctions.
5,000	1,000	1200	Hydrocarbon.	Cyclic (terrestrial).	-----	-----

¹ Estimated values.

Since 1962, much larger devices have been produced, ranging upward to 200 and 500 watts. Units as large as 1.5 kilowatts have been proposed. Typical among such devices are those developed or under development by the Minnesota Mining and Manufacturing Company as shown in Table 9. Performance parameters claimed for some of these units are shown in Table 10.

The USAMERDC study discusses a number of thermoelectric device problem areas which have not been fully resolved. These include thermopile degradation (laboratory tests indicate power degradation of 20 to 25% per thousand operating hours); accessories; control instability; and visual, infrared, and aural signatures. Problems associated with accessories and control instability are due in part to the lack of experience in commercial applications. Problems associated with visual, infrared, and aural signatures are important only to applications in operating in a combat environment. The current status of operational hardware evaluated by USAMERDC indicates that systems with a useful life of more than 1,000 hours, including more than 100 start-stop cycles, can be built. However, evaluations have not extended to extremely cold ambient temperature operation and storage.

(2) Isotope Thermoelectric Generators¹⁴

Isotope-fueled thermoelectric generators have advantages which make them of interest in applications where long life and reliability are important. Table 11 presents some of the various devices of this nature which have been developed, primarily under the sponsorship of the Atomic Energy Commission.

The first series of these devices were the SNAP-3 (Systems for Nuclear Auxiliary Power) units.¹⁵ The first four of these were Po-210-fueled demonstration units built in 1959. These demonstrated an overall efficiency of 5.8 percent, which is higher than could have been attained from

^{14/} Radioisotope-Fueled Thermoelectric Generators, " F. Hittman and C.C. Silverstein, Engineering Developments in Energy Conversion International Conference on Energetics, The American Society of Mechanical Engineers, New York, 1965.

^{15/} Interdepartmental Energy Study, op. cit.


TABLE 9
3M THERMOELECTRIC DEVICE SUMMARY

Number	Device Name and General Description	Application	Heat Source	Watts
B-30	BASO Pilot Light Gas Solenoid Valve Control	Gas Appliances	Gas Flame	—
3M-3	Coast Guard Generator -Utilizes Basic 3M-1 Design Principles	Coast Guard Light	Propane	10
3M-4	Experimental High Power Generator	Signal Core Exp	Propane Burner	150
3M-5	"Man-Pack" High Power-to-Weight Field Power Supply	Navy-Marine Corp. Field Use	Propane Burner	250
3M-6	Light Weight, Compact Power Package	Terrestrial	Propane Burner	1.25
3M-7	Experimental "Flat-Plate" Generators; Fore-runner of 3M Brand T/E 6	Experimental	Propane	2-15
3M-8	"Super Aztec", Cylindrical Array of B-30	Portable Power Use	Kerosene	1.5
3M-12	"Aztec" Array of Six B-30 Couples	Radios	Kerosene Lamp	0.15
3M-14	Lightweight Kerosene-Fueled Flat-Plate Generator	Portable Power Use	Kerosene Burner	30
3M-15	Flat-Plate Two-Watt 3M Brand Generator	Commercial	Propane Burner	2
3M-16	Model 505 3M Brand Commercial Thermo-electric Generator	Commercial	Propane Burner	4
3M-17	Model 510 3M Brand Commercial T/E Generator	Commercial	Propane Burner	8
3M-18	Model 515 3M Brand Commercial T/E Generator	Commercial	Propane Burner	15

TABLE 9 (CONTINUED)

Number	Device Name and General Discussion	Application	Heat Source	Watts
3M-19	Model 520 3M Brand Commercial T/E Generator	Commercial	Propane Burner	30
3M-20	Sixty-Watt 3M Brand Commercial T/E Generator	Commercial	Propane Burner	60
3M-21	Semi-automatic Battery-Charging System Utilizing 3M-19 Generator	Army Dugway Sampling Dev.	Propane Burner	30
3M-22	Developmental 200-Watt Generator	Experimental	Propane	200
3M-23	Lightweight Kerosene-Fueled Cylindrical Generator	Military Field Use	Kerosene Diesel Fuel Jet Fuel	100
3M-24	Two-hundred Watt 3M Brand Commercial Thermoelectric Generator	Commercial	Propane	200
3M-25	Lightweight Kerosene-Fueled Cylindrical Generator	Terrestrial	Kerosene, Diesel Fuel Jet Fuel	25
3M-26	Lightweight NAVY 300-Watt 35# Backpack	Terrestrial	Kerosene, Diesel Fuel Jet Fuel	300
3M-28	Lightweight 560-Watt Field Power Supply	Military Field Use	Kerosene, Diesel Fuel Jet Fuel	560
3M-29	Thirty-Watt Battery-Charging System Utilizing 3M-19 Generator	Coast Guard Battery Chg.	Propane	30
3M-2000	Thermoelectric Furnace (Bonded Flat-Plate)	Gas Furnace Contained Power	Natural Gas Flame	25

TABLE 10
SPECIFICATION CHART - THERMOELECTRIC GENERATORS

Number	MODEL Description	ELECTRICAL CHARACTERISTICS				FUEL CONSUMPTION			PHYSICAL DATA		
		Load ² Power ² Voltage		Load ² Current	Power ² Range	Propane	Natural Gas		Weight	Dimensions	
		Watts	Volts	Amps	Watts	Lbs./Hr.	Gal./Hr.	Ft. ³ /Hr.	Lbs.		Inches
505	Thermoelectric Generator	9	1	9.0	8.5-10.0	.073	.017	1.23	28	A	12
	With 605-12 Converter-Limiter	5.3	12	.44	4.7-6.4					B	18
	With 605-24 Converter-Limiter	5.0	24	.21	4.4-6.0					C	12
										D	—
510	Thermoelectric Generator	15	2	7.5	14-18	.13	.023	1.9	31	A	12
	With 610-12 Converter-Limiter	11.2	12	.93	9.9-13.5					B	18
	With 610-24 Converter-Limiter	12	24	.50	10.6-14.2					C	12
										D	—
515	Thermoelectric Generator	28	3.8	7.3	26-32	.18	.042	3.5	50	A	12
	With 615-12 Converter-Limiter	20.5	12	1.7	18.5-24					B	18
	With 615-24 Converter-Limiter	21.5	24	.90	20-25					C	12
										D	30
520	Thermoelectric Generator	50	6	8.3	46-60	.30	.071	7.0	130	A	16 ⁴
	With 621-6 Limiter	50	6	8.3	46-60					B	21
	With 620-12 Converter-Limiter	41	12	3.4	36-50					C	18
	With 620-24 Converter-Limiter	43	24	1.8	38-52					D	36
530	Thermoelectric Generator	100	12	8.3	92-120	.60	.14	14.0	300	A	32
	With 631-12 Limiter	100	12	8.3	92-120					B	25
	With 630-24 Converter-Limiter	82	24	3.4	74-96					C	22.5
										D	36
540	Thermoelectric Generator					1.20	.28	28.0	700	A	58
	With 641-6 Limiter	200	6	33	188-240					B	24
	With 641-12 Limiter	200	12	16.5	188-240					C	20
	With 641-24 Limiter	200	24	8.3	188-240					D	36
	With 640-48 Converter-Limiter	163	48	3.4	147-192						

1. Fuel consumption may vary slightly depending upon air shutter adjustment.
2. Values are typical at 75° F. ambient temperatures, under a fixed matched load at constant gas pressure.
3. Typical power output range of generator for a variation in ambient temperature from +125° F. to -25° F.
4. Thirteen inches for generators without converter-limiter.

Warranty Power — Between ambient temperatures from: -25° F. to 125° F., all generators are warranted to produce typical power within the following limits: Without converter-limiter, ±7% • With Limiter only, ±7% • With converter-limiter, ±15%

For typical power at various temperatures, see our "Power versus Ambient Temperature" curve. Copies of this curve can be obtained from 3M.

Limiter Adjustment — Voltage limiters are adjustable as follows:

Voltage Range	Model Numbers
13 - 15	605-12, 610-12, 615-12
13 - 18	620-12, 631-12
26.5 - 29.5	605-24, 610-24, 615-24
24 - 30	620-24, 630-24, 641-24

TABLE II
SUMMARY OF SNAP DEVICES

Designation	Use	Power (watts)	Size* (inches)	Weight (pounds)	Isotope	Isotope's Half-life	Generator Life
SNAP-3	Demonstration device	2.5	4-3/4x5-1/2	4	Polonium-210	138 days	90 days
SNAP-3A	Satellite power	2.7	4-3/4x5-1/2	4.6	Plutonium-238	89.6 years	5 years
Undesignated	Axel Heiberg weather station	5	18x20	1680	Strontium-90	28 years	2 years minimum*
SNAP-7A	Navigational buoy	10	20x21	1870	Strontium-90	28 years	2 years minimum
SNAP-7B	Fixed navigational light	60	22x34-1/2	4600	Strontium-90	28 years	2 years minimum
SNAP-7C	Weather station	10	20x21	1870	Strontium-90	28 years	2 years minimum
SNAP-7D	Floating weather station	60	22x34-1/2	4600	Strontium-90	28 years	2 years minimum
SNAP-7E	Ocean-bottom beacon	7.5	20x21	600	Strontium-90	28 years	2 years minimum
SNAP-7F	Offshore oil rig	60	22x34-1/2	4600	Strontium-90	28 years	2 years minimum
SNAP-9A	Satellite power	25	20x9-1/2	27	Plutonium-238	89.6 years	5 years
SNAP-13	Demonstration device	12	2-12x4	4	Curium-242	162 days	90 days
SNAP-15A	Military use	0.001	3x3	1	Plutonium-238	89.6 years	5 years
SNAP-19B	Nimbus-B weather satellite	30	22x10	30	Plutonium-238	89.6 years	5 years
SNAP-21	Deep sea use	10-20	18x44 max	644-1066	Strontium-90	28 years	5 years
SNAP-23A	Terrestrial uses	25-100	25x25	900	Strontium-90	28 years	10 years
SNAP-27	Lunar landings	60	18x18	30	Plutonium-238	89.6 years	5 years
SNAP-29	Various missions	500	-	500	Polonium-210	138 days	90 days

*Diameter times height.

a fossil-fueled device because of the elimination of stack-gas losses. Since 1959, a number of isotope-fueled devices have been developed not only for space but also for underwater and terrestrial applications.

The SNAP-7 series of generators are intended to evaluate the feasibility of Sr-90-heated devices for long-lived, buoy-based, underwater use or for remote terrestrial applications. The weight of these units probably removes them from consideration for remote area applications. The SNAP-21, 23, 27, and 29 series of devices, however, may well warrant serious consideration. The SNAP-23 system is specifically oriented toward remote terrestrial application. Design goals for these units specified that the thermoelectric (TE) converter must produce 60 watts power output at 24 volts over a five-year lifetime. Following demonstration of successful SNAP-23 converters, the SNAP-23A program was initiated with a 10-year lifetime goal. In addition, conceptual designs for 25- and 100-watt converters were sought.

The SNAP-27 power supply, although intended for lunar exploration, is designed to provide 56 watts for a minimum of one year. This entire power package, including fuel capsule, weighs only 38 pounds. This light weight is due largely to extensive use of beryllium components.

Major problems associated with isotope-powered devices include economics, fuel availability, safety, and handling, as well as the problems of thermoelectric converters.

(3) Photovoltaic Devices

The production of an electromotive force by incidence of radiant energy, commonly light, upon the junction of two dissimilar materials, is termed the photovoltaic effect. Direct energy conversion from solar radiation has proved to be an effective technique for satellite power levels below 1 kW.

Until recently, silicon photovoltaic cells were the only practical solid-state device for this purpose. The more recently developed thermoelectric (TE) flat-plate solar generator, employing the p-n junction, is superior, with regard to cost, power, degradation of performance with operating time, and thermal cycling. A comparison of costs is as follows:

Comparison of Photovoltaic and TE Panel Arrays

	<u>Photovoltaic</u>	<u>Present TE</u>	<u>Future TE</u>
Cost (\$/w)	450	135	30
Specific Power (w/lb)	6.0	7.5	12.5
Operating Temp. (°K)	300°-325°	500°-550°	

In spite of space power utilization, experience with solar-powered devices is relatively limited. Test data indicate that TE device power performance degrades by about 25 percent in 1000-1200 hours of operation. Tests also indicate that open circuit electromotive force and internal resistance are unaffected by thermal cycling.

The high cost of solar arrays, coupled with the intermittent and variable nature of terrestrial solar energy, make photovoltaic devices unattractive for power generation in remote areas.

3. DYNAMIC POWER SOURCES

Dynamic converters have, historically, represented the primary energy conversion devices. The technology of these systems continues to evolve and they, along with fuel cells, may well constitute the systems of greatest potential for Limited War Laboratory exploitation.

(1) Rankine Cycle Engines

Rankine cycle engines are receiving current attention for application as energy conversion devices, both for small electric power sources and for automotive propulsion. Performance characteristics for prototype steam electric power sources developed by the Thermo Electron Corporation are illustrated in Tables 12, 13, and 14. The 100- and 300-watt units have been evaluated by MERDC, and the larger unit will be delivered for their evaluation. In addition, MERDC has operating experience with mercury and organic compound devices.

TABLE 12

100-WATT STEAM-ENGINE-DRIVEN GENERATOR SET		
CHARACTERISTICS	ACTUAL PERFORMANCE PRESENT PROTOTYPE	PROJECTED PERFORMANCE NEXT GENERATION UNITS
Power Output	100 watts at 12 and 28 v, dc 1/4 hp at 1800 rpm	120 watts 0.3 hp at 1800 rpm
a. Electrical		
b. Engine Shaft		
Weight	29 lbs	22 lbs
Size	16" x 16" x 12-1/2"	14" x 14" x 12"
Fuel		
a. Type	JP-4, CITE, Gasoline, JP-5, Kerosene, Naptha	JP-4, CITE, Gasoline JP-5, Kerosene, Naptha
b. Flow Rate	0.5 lb/hr	0.45 lb/hr
c. Capacity*	0.5 gallon	0.82 gallon
d. Operating Time between Refueling at Full Power**	7 hours	12 hours
e. Specific Fuel Consumption	2 lbs/BHP-hr	1.5 lbs/BHP-hr
Efficiency, Overall (Electrical Power Output/Fuel Flow Rate x Heating Value)	3.7%	5%
Life	100-300 hours	1000 hours
Sound Pressure Levels	Inaudible at 100 meters	Inaudible at 25 feet
Control System***	Parasitic Load - Principle Fully Developed	Same

*Can be readily connected to an external fuel supply.

**Operating time between refuelings is extended for operation at less than rates power output.

***Set uses standard military alternator, electrical controls, no engine governor.

TABLE 13

300-WATT STEAM-ENGINE-DRIVEN GENERATOR SET		
CHARACTERISTICS	PRESENT PROTOTYPE	PROJECTED PERFORMANCE NEXT GENERATION UNITS
Power Output	300 watts at 28 v, dc 2/3 hp at 1800 rpm	300 watts, at 28 v, dc 2/3 hp at 1800 rpm
a. Electrical		
b. Engine Shaft		
Weight	42 lbs	29 lbs
Size	14" x 14" x 14"	Same
Fuel		
a. Type	JP-4, CITE, Gasoline, JP-5, Kerosene, Naptha	JP-4, CITE, Gasoline JP-5, Kerosene, Naptha
b. Flow Rate	~1.15 lbs/hr	0.8 lb/hr
c. Capacity*	1.5 gallons	1.5 gallons
d. Operating Time between Refueling at Full Power**	~8 hrs	12 hrs
e. Specific Fuel Consumption	1.62 lbs/BHP-hr	1.2 lbs/BHP-hr
Efficiency, Overall (Electrical Power Output/Fuel Flow Rate x Heating Value)	~5%	7.2%
Life	300 to 1000 hrs	1000 to 2500 hrs
Sound Pressure Levels	Inaudible at 100 meters	Inaudible at 50 feet
Control System***	Parasitic Load - Fully Developed	Same

*Can be readily connected to an external fuel supply.

**Operating time between refuelings is extended for operation at less than rated power output.

***Set uses standard military alternator, electrical controls, no engine governor.

TABLE 14

1.5-KW STEAM-ENGINE-DRIVEN GENERATOR SET		
CHARACTERISTICS	ACTUAL PERFORMANCE PRESENT PROTOTYPE	PROJECTED PERFORMANCE NEXT GENERATION UNITS
Power Output a. Electrical b. Engine Shaft	1.5 kw at 28 v, dc 3 hp at 3600 rpm	1.5 kw at 28 v, dc 3 hp at 3600 rpm
Weight	120 lbs	Less than 100 lbs
Size	20" x 20" x 24" long	16" x 18" x 22" long
Fuel a. Type b. Flow Rate c. Capacity* d. Operating Time between Refueling at Full Power** e. Specific Fuel Consumption	JP-4, CITE, Gasoline, JP-5, Kerosene, Naptha 4.2 lbs/hr 3 gallons 4.5 hrs 1.40 lbs/BHP-hr	JP-4, CITE, Gasoline, JP-5, Kerosene, Naptha 2.95 lbs/hr 1.8 gallons 4 hrs 0.95 lb/BHP-hr
Efficiency, Overall (Electrical Power Output/Fuel Flow Rate x Heating Value)	6.5%	9.3%
Life	To be determined	Greater than 1000 hrs
Sound Pressure Levels	To be determined	Inaudible at 100 meters
Control System***	Fully automatic operation; simple start-up in 1-2 minutes	Fully automatic operation; simple start-up in 1-2 minutes

*Can be readily connected to an external fuel supply.

**Operating time between refuelings is extended for operation at less than rated power output.

***Set uses standard military alternator, electrical controls, no engine governor.

Data¹⁶ on several automotive steam engines either built or studied since 1950 are shown in Table 15. The engines shown are semi-closed-cycle systems requiring some make-up water, and all are piston-type expanders. Lubrication is accomplished with conventional hydrocarbon oils. The automotive engine data is of interest to the Limited War Laboratory only because improved technology that may be developed for these larger devices may have application in smaller power output ranges.

The use of steam as a working fluid is of interest because it is widely available and its characteristics are fairly attractive for use in Rankine cycle systems. It is, however, a poor lubricant and is not compatible with conventional hydrocarbon oil lubricants. Mercury, as a working fluid, has a high allowable temperature and is a relatively good lubricant. It has the disadvantages of toxicity and incompatibility with many metals, as well as limited availability. Organic fluids have relatively high specific volume and are compatible with most conventional metals. Organic fluids are, however, subject to chemical decomposition at high temperatures.

The operating experience of MERDC has confirmed most of the fluid problem areas indicated above. In addition, control of engine speed presents difficulties that have not been resolved. Seals, particularly for steam systems, present a continuing problem.

(2) Brayton Cycle Devices

Operational Brayton cycle machines in the small power ranges of interest to the Limited War Laboratory have not been developed. While the technology is well-known and projections of output down to low levels have been made, the basic technical problems with these systems in small sizes will likely exclude them from consideration in the foreseeable future.

^{16/} Study of **Unconventional** Thermal, Mechanical, and Nuclear Low-Pollution-Potential Power Sources for Urban Vehicles, Department of Health, Education, and Welfare, National Center for Air Pollution Control, Battelle Memorial Institute, 1968.

TABLE 15
DATA ON SEVERAL AUTOMOTIVE STEAM ENGINES EITHER BUILT OR STUDIED SINCE 1950

Developer or Researcher	Engine Reference	Rating hp at rpm	Rated Pressure, psia Temperature, F	Specific Weight lb/hp(s)	Specific Volume ft ³ /hp(s)	Maximum Efficiency, percent	Start-Up Time sec	Torque Ratio (c)	Power-Surge Ratio	Specific Cost, \$/hp(s)
Williams Engine Co.	49	150 at 2400	$\frac{1000}{1000}$	5.4	0.14	--	PO<30	3.4	1.67	44
McCulloch Corp.	50	120 at 1200	$\frac{2000}{900}$	8.0	--	23	FPO<30	--	1.25	--
Gibbs Hosick Trust	51	60 at 2500	$\frac{2000}{850}$	--	--	--	--	2.3	--	--
Richard J. Smith	52	250 at 6000	$\frac{1000}{700}$	--	--	28	FPO-14	1.8	--	--
Thermo Electron Engineering Corp.	53(d)	100 at 1680	$\frac{1200}{1250}$	5.0	--	28	--	1.1	--	--
Microtech Research Co.	54(d)	175	$\frac{1500}{1100}$	17.2	0.67	16	FPO-500	--	--	--
General Dynamics/Convair	55(d)	500	$\frac{1200}{1000}$	--	0.16	22	--	--	1.5-2.0	--
S. W. Gouse, Jr.	25, 56(d)	--	--	5-10	--	25-30	--	--	--	3(?)
Battelle/Northwest	57(d)	50	$\frac{2500}{670}$	--	--	24	FPO<10	--	--	--

(a) PO = time to power output; FPO = time to full power output.

(b) Torque ratio = the ratio of stall torque to rated torque.

(c) Power-surge ratio = the ratio of short-term, "burst", power to continuous rated power.

(d) Paper studies only.

(3) Stirling Cycle Engines

Stirling cycle engines have received renewed interest as power sources in recent years. In fact, as early as World War II, the N. V. Phillips Laboratories of Eindhoven, Netherlands undertook the development¹⁷ of a modern version of the Stirling engine as a means of producing electrical power in remote areas. The principal developments in the United States have been carried out by the General Motors Corporation under a licensing agreement with Phillips. Performance parameters of typical devices manufactured by Phillips and General Motors are shown in Table 16.

The Battelle study, in its review of the current and projected state-of-the-art of Stirling Cycle devices, concluded that:

".... Thus the Stirling engine is considered to be a potentially acceptable vehicular power plant. In relation to present passenger car engines, the primary factors limiting the use of Stirling engines are the relatively high first cost, weight, and size and the large radiator that is required...."

In its study¹⁸ of energy sources for undersea applications, the National Academy concluded that:

"Both fuel cells and the Stirling reciprocating dynamic converters show significant potential for use as an undersea energy system. A rational choice can be made only after a detailed study and comparison of many missions and uses. Since many millions of dollars are involved in developing and qualifying either converter, final choice should be based on such a detailed study and comparison. It is recommended that parallel programs in both systems be pursued until the final choice is made."

17/ Battelle Study, Ibid.

18/ NAS-NRC Study, op.cit.

TABLE 16
TYPICAL STIRLING-ENGINE DATA

Developer	Model No.	No. of Cylinders	Rating, hp(s) at rpm	Max. Brake Thermal Efficiency, percent	Envelope Volume ^(a) , ft ³	Specific Volume ^(a) , ft ³ /hp(s)	Weight ^(a) , lb	Specific Weight ^(a) , lb/hp(s)
GM Research	GPU-2	One	7.5 at 3600	23	3.04	0.40	90 ^(b)	12.0
GM Research	GPU-3	One	10.0 at 3000	27	4.89	0.49	188	18.8
Philips	3015	One	40.0 at 2500	39	6.40	0.16	550	13.8
GM Electromotive	8015	Four	380 at 1500	30	130.00	0.34	5000	13.2
Philips	Marine	Four	120 at 3000	40 (calc.)	23.20	0.19	725	6.0
GM Allison	PD-67	One	7 at 3000	30	3.50 ^(c)	--	186 ^(c)	--

(a) Reciprocating unit only, including combustor and preheater. Excludes fuel pump, water pump, combustion air blower, motor, radiator and fan assembly, working-fluid reservoir, starter motor, ignition system, and fuel control.

(b) Excludes flywheel also.

(c) Includes 4 hp(e) generator.

In its discussion of Stirling cycle engines, the USAMERDC report states that:

"Stirling cycle power plants in semi-militarized configuration have been run for over 1,000 hours without major difficulty. Fundamentally, there are no problems with the Stirling cycle that have not been solved to the extent that practical hardware can be built and operated. The hardware is a complex mechanical system requiring strong design discipline in order to seal the working fluid and maintain good control over the system under dynamic operating conditions."

The views¹⁹ of still another analyst are somewhat more sobering, however:

"There are many difficulties in making a practical Stirling engine. High temperatures are essential to keep the size of the engine down, but this makes lubrication a serious problem because of the "dry" high-temperature operating conditions. Also the working lifetime of such a machine in the field is not likely to be more than a few hundred hours between overhauls unless a radical breakthrough in design is forthcoming."

4. WIND-POWERED ELECTRIC GENERATORS²⁰

Wind-powered electric devices have not been significantly pursued as energy sources for at least two decades. Wind-driven generator sets for farm power are still being manufactured, however. The potential of these devices for Limited War Laboratory application is difficult to assess, primarily because of the unavailability of worldwide data as to the energy source.

^{19/} "Power for Remote Areas," Harry Z. Tabor, International Science and Technology, May 1967.

^{20/} Battelle Study, op. cit.

5. THERMIONIC CONVERTERS²¹

Thermionic conversion of heat to electricity is based upon application of the Edison effect—the escape of electrons from a heated surface, termed the emitter. A second electrode, termed the collector, is placed near the emitter to collect the escaping electrons. The number of electrons emitted increases exponentially as the temperature of the emitting body increases. Unfortunately, the device is space-charge limited. Space-charge compensation consists of introducing positive ions and reducing the interelectrode distance.

The following characteristics are advantages of thermionic converters:

- . There are no moving parts
- . Operating temperatures up to 4000°F are possible
- . Waste heat can be rejected at high temperatures
- . The power-to-weight ratio is relatively high.

Experience with practical applications is extremely limited. However, flame-heated converters have operated for more than 300 hours. Power densities of two-to-ten watts per square centimeter and efficiencies of four-to-nine percent have been attained.

Flame-powered devices in the full range of power outputs of interest to the Limited War Laboratory have been designed but only prototype modular units of low output have been manufactured. Specific performance data on these units is considered extremely experimental in nature, and the state-of-the-art appears to offer little promise in satisfying Limited War Laboratory requirements, at least in the short-run.

21/ Battelle Study, op. cit.

IV. COMPARATIVE DATA

An advanced draft copy of a study on silent power sources, supplied by the USAMERDC Electrotechnology Laboratory, is an outstanding source of comparative evaluative data concerning power sources for remote areas. Unfortunately, these data do not cover the full range of devices reviewed in this survey, nor is the objective of USAMERDC the same as that of LWL. However, the USAMERDC report is the most comprehensive of those available and is based upon actual test and operating experience with candidate devices. Accordingly, extracts from the comparative tables contained in the USAMERDC report are reproduced on the following pages.

TABLE 17

Audibility Data Sheet

(Tabulated data indicate distance in meters at which source is inaudible vs. jungle ambient background)

System	KW	0.5		1.5		3.0		5.0		10.0		15.0
		2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20
Years From Present →	→											
SILENCED ENGINE-GENERATOR	100	100	100	100	100	100	100	100	100	100	100	100
STIRLING CYCLE	100	50	100	100	50	100	100	100	100	50	100	100
CLOSED RANKINE CYCLE	50	30	100	100	60	100	70	100	100	80	100	100
CLOSED BRAYTON CYCLE	100	100	100	100	100	100	100	100	100	100	100	100
THERMOELECTRIC	100	40	100	100	50	100	75	100	100	100	100	100
OPEN BRAYTON CYCLE SILENCED	100	100	100	100	100	100	100	100	100	100	100	100
LOW TEMPERATURE FUEL CELL ACID	30	30	50	30	30	50	30	75	50	100	100	100
LOW TEMPERATURE FUEL CELL ALKALINE	50	30	60	30	30	100	50	100	100	100	100	100
HIGH TEMPERATURE FUEL CELL	50	30	50	30	30	70	50	70	50	100	100	100

TABLE 18

Weight Data Sheet

(Units of tabulated data are pounds)

System	KW →	0.5		1.5		3.0		5.0		10.0		15.0	
		2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20
Years From Present →													
SILENCED ENGINE-GENERATOR	165	148	270	885	796	1450	1305	2200	1980	4550	4095		
STIRLING CYCLE	150	125	240	400	350	550	460	985	770	1405	1140		
CLOSED RANKINE CYCLE	65	50	110	240	180	360	255	740	465	1105	680		
CLOSED BRAYTON CYCLE	200	180	220	320	280	400	330	650	510	870	675		
THERMOELECTRIC	50	42	120	270	240	470	390	995	795	1385	1180		
OPEN BRAYTON CYCLE SILENCED	200	95	110	275	140	325	190	410	295	530	410		
LOW TEMPERATURE FUEL CELL ACID	100	60	115	525	300	800	450	1500	820	2200	1250		
LOW TEMPERATURE FUEL CELL ALKALINE	100	80	150	500	375	700	560	1360	980	1945	1400		
HIGH TEMPERATURE FUEL CELL.	350	200	280	850	500	1200	700	2100	1100	3000	1500		

TABLE 19
 VOLUME DATA SHEET
 (Units of tabulated data are in cubic feet)

System	kW	0.5		1.5		3.0		5.0		10.0		15.0	
		2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20
Years From Present →	→												
Silenced Engine-Generator		11	11	11	11	22	22	34	34	61	61	102	102
Stirling Cycle		7	5	12	10	16	13	20	16	32	25	44	36
Closed Rankine Cycle		5	4	9	8	14	12	20	17	33	26	44	33
Closed Brayton Cycle		12	9	16	11	20	14	25	17	39	25	49	32
Thermoelectric		4	4	9	8	16	14	26	20	45	35	62	49
Open Brayton Cycle (Silenced)		10	5	11	6	13	7	15	9	18	12	24	18
Low-Temperature Fuel Cell (Acid)		3	2	7	4	18	10	27	15	48	28	70	40
Low-Temperature Fuel Cell (Alkaline)		4	2	9	5	18	13	27	20	50	36	69	50
High-Temperature Fuel Cell		14	10	20	13	33	20	40	24	60	33	75	40

TABLE 20
FUEL-CONSUMPTION DATA SHEET

(Units of tabulated data are in pounds of fuel per hour at rated load)

System	kW	0.5		1.5		3.0		5.0		10.0		15.0	
		2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20
Years From Present →													
Silenced Engine-Generator		1.6	1.6	3.4	3.4	5.3	2.7	8.8	4.1	15.0	8.2	9.4	9.4
Stirling Cycle		0.8	0.7	1.5	1.4	2.8	2.6	4.6	4.2	8.3	7.7	11.8	11.0
Closed Rankine Cycle		1.6	1.2	4.0	3.0	6.6	5.0	9.7	7.7	16.0	13.0	31.4	17.3
Closed Brayton Cycle		1.5	1.2	2.6	2.3	5.8	5.2	8.5	7.5	14.8	12.8	21.5	17.2
Thermoelectric		2.5	1.8	5.4	3.9	9.8	6.9	15.7	11.0	30.9	31.0	46.0	31.0
Open Brayton Cycle (Silenced)		3.5	2.5	6.0	4.0	8.0	6.0	10.0	8.0	18.0	15.0	23.0	20.0
Low-Temperature Fuel Cell (Acid)		.46	.31	1.2	.8	2.8	2.0	4.0	3.0	7.4	5.6	11.4	8.7
Low-Temperature Fuel Cell (Alkaline)		.35	.33	.9	.8	2.2	1.9	3.6	2.9	6.9	5.4	10.2	8.0
High-Temperature Fuel Cell		1.0	0.7	2.3	1.4	4.6	2.4	6.3	3.1	10.8	5.0	15.0	7.0

TABLE 21
MISSION WEIGHT DATA SHEET
(Tabulated data indicate total weight in pounds for 72-hour mission)

System	kW	0.5		1.5		3.0		5.0		10.0		15.0	
		2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20
Years From Present	→												
Silenced Engine-Generator		322	305	628	598	1403	1206	2224	1715	3520	2800	5367	4915
Stirling Cycle		229	189	425	383	675	611	981	832	1732	1464	2095	2142
Closed Rankine Cycle		222	168	528	400	883	666	1208	949	2172	1611	2996	2206
Closed Brayton Cycle		350	298	521	449	885	791	1152	1010	1956	1642	2768	2193
Thermoelectric		293	224	665	506	1217	915	1880	1392	3710	2657	5397	3902
Open Brayton Cycle (Silenced)		522	338	769	468	991	684	1206	906	1985	1616	2535	2172
Low-Temperature Fuel Cell (Acid)		154	93	318	194	800	497	1158	736	2173	1323	3231	2016
Low-Temperature Fuel Cell (Alkaline)		186	114	296	227	721	564	1029	839	1997	1459	2849	2116
High-Temperature Fuel Cell		453	264	679	423	1297	736	1794	993	3088	1540	4320	2144

TABLE 22
MISSION VOLUME DATA SHEET

(Tabulated data indicate total volume in cubic feet for 72-hour mission)

System	kW	0.5		1.5		3.0		5.0		10.0		15.0	
		2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20	2-5	10-20
Years From Present →													
Silenced Engine-Generator	14.7	14.7	19.0	19.0	19.0	35.1	32.5	55.4	44.5	97.3	82.0	124.8	123.0
Stirling Cycle	9.0	8.0	16.0	14.0	23.0	20.0	31.2	27.2	54.4	47.4	66.4	59.6	
Closed Rankine Cycle	8.5	7.0	18.0	15.0	30.0	24.0	43.6	39.4	77.8	49.6	100.0	77.8	
Closed Brayton Cycle	16.0	12.0	23.0	17.0	34.0	27.0	47.4	39.4	75.8	58.6	105.0	76.8	
Thermoelectric	10.0	8.5	22.0	18.0	39.0	31.0	70.8	53.6	123.4	91.0	174.0	127.4	
Open Brayton Cycle (Silenced)	21.2	11.0	26.2	17.0	35.4	22.2	39.4	31.4	62.8	48.6	80.0	66.8	
Low-Temperature Fuel Cell (Acid)	5.0	2.5	10.4	6.0	25.0	15.0	38.2	26.2	70.4	42.4	103.6	62.4	
Low-Temperature Fuel Cell (Alkaline)	4.8	3.0	11.5	7.0	24.0	18.0	37.2	31.2	72.4	50.6	94.6	72.4	
High-Temperature Fuel Cell	17.0	12.0	26.0	17.0	44.0	26.0	62.4	35.2	93.6	45.4	12.8	62.4	

TABLE 23
TIME-BETWEEN-OVERHAUL DATA

(Tabulated data indicate hours of operation between overhaul)



SYSTEM	KW 	ALL POWER SIZES	
		Years from Present 	2-5	10-20
SILENCED ENGINE-GENERATOR		1500	5000
STIRLING CYCLE		1500	2500
CLOSED RANKINE CYCLE		2500	2500
CLOSED BRAYTON CYCLE		3000	6000
THERMOELECTRIC		1500	2500
OPEN BRAYTON CYCLE (SILENCED)		3000	6000
LOW-TEMPERATURE FUEL CELL (ACID)		2500	5000
LOW-TEMPERATURE FUEL CELL (ALKALINE)		2500	5000
HIGH-TEMPERATURE FUEL CELL		2500	5000

TABLE 24
LIFE CYCLE POWER COST DATA (Based on 3KW-AC unit)

(Tabulated data are dollars per KW hour)

SYSTEM	KW →	ALL POWER SIZES		
		Years from Present →	2-5	10-20
SILENCED ENGINE-GENERATOR			0.69	0.31
STIRLING CYCLE			1.78	0.51
CLOSED RANKINE CYCLE			1.38	0.51
CLOSED BRAYTON CYCLE			1.54	0.60
THERMOELECTRIC			3.90	1.30
OPEN BRAYTON CYCLE (SILENCED)			1.01	0.38
LOW-TEMPERATURE FUEL CELL (ACID)			1.70	0.46
LOW-TEMPERATURE FUEL CELL (ALKALINE)			2.11	0.63
HIGH-TEMPERATURE FUEL CELL			1.85	0.34

TABLE 25
ESTIMATED DEVELOPMENT COST

(Prototype to type-classification - values in table expressed in
millions of dollars)

SYSTEM	KW →	ALL POWER SIZES	
		Years from Present →	
SILENCED ENGINE-GENERATOR		2-5	10-20
		0.5	1.5
STIRLING CYCLE		2.0	4.2
CLOSED RANKINE CYCLE		3.5	5.5
CLOSED BRAYTON CYCLE		8.0	10.0
THERMOELECTRIC		2.0	4.0
OPEN BRAYTON CYCLE (SILENCED)		6.0	10.0
LOW-TEMPERATURE FUEL CELL (ACID)		11.0	15.0
LOW-TEMPERATURE FUEL CELL (ALKALINE)		9.0	13.0
HIGH-TEMPERATURE FUEL CELL		10.0	15.0

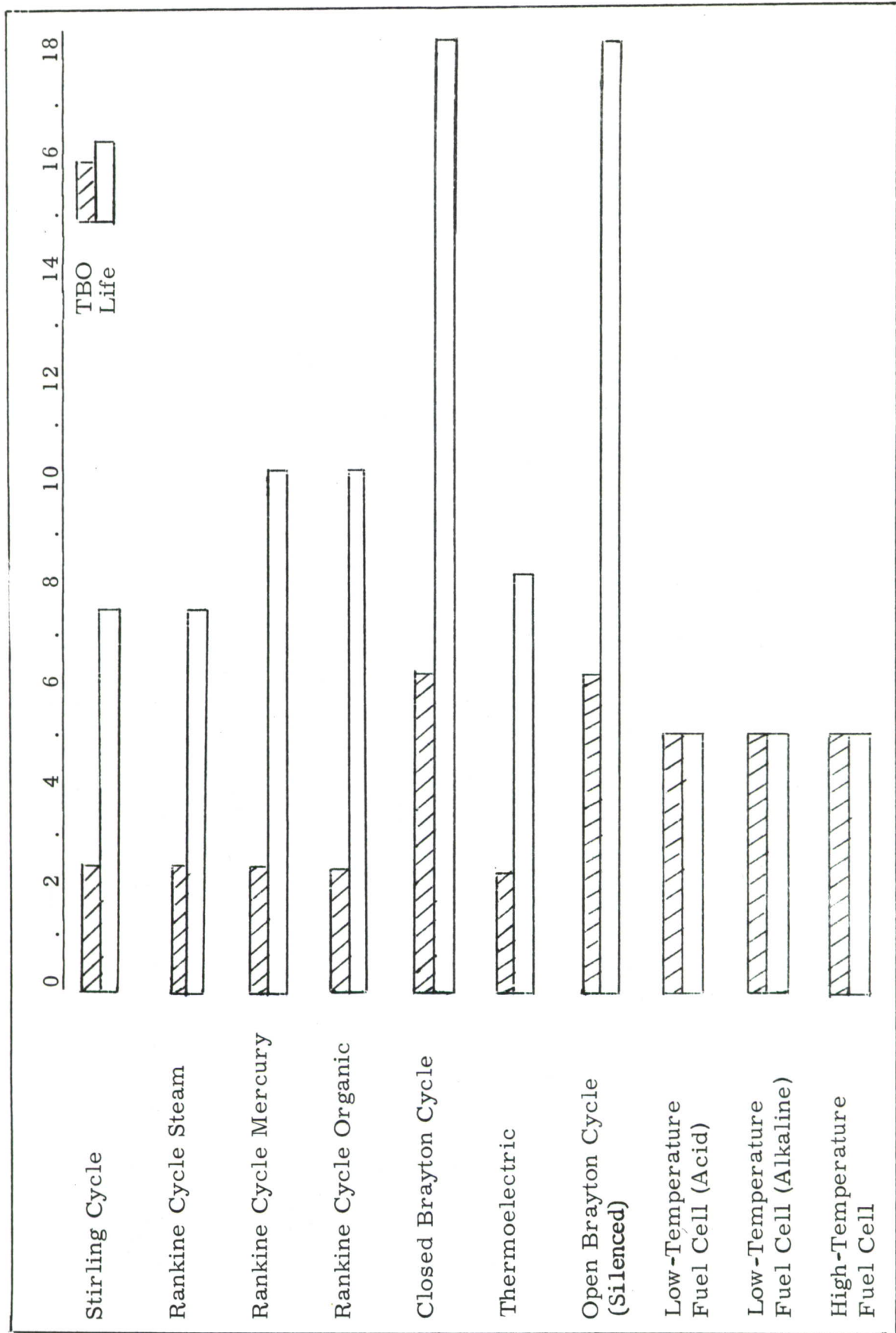


FIGURE 5. PROJECTION OF OPERATING TIME (IN THOUSANDS OF HOURS)-BETWEEN-OVERHAUL (TBO) AND IN SERVICE LIFE FOR MID-TERM FUTURE (10-20 YEARS)

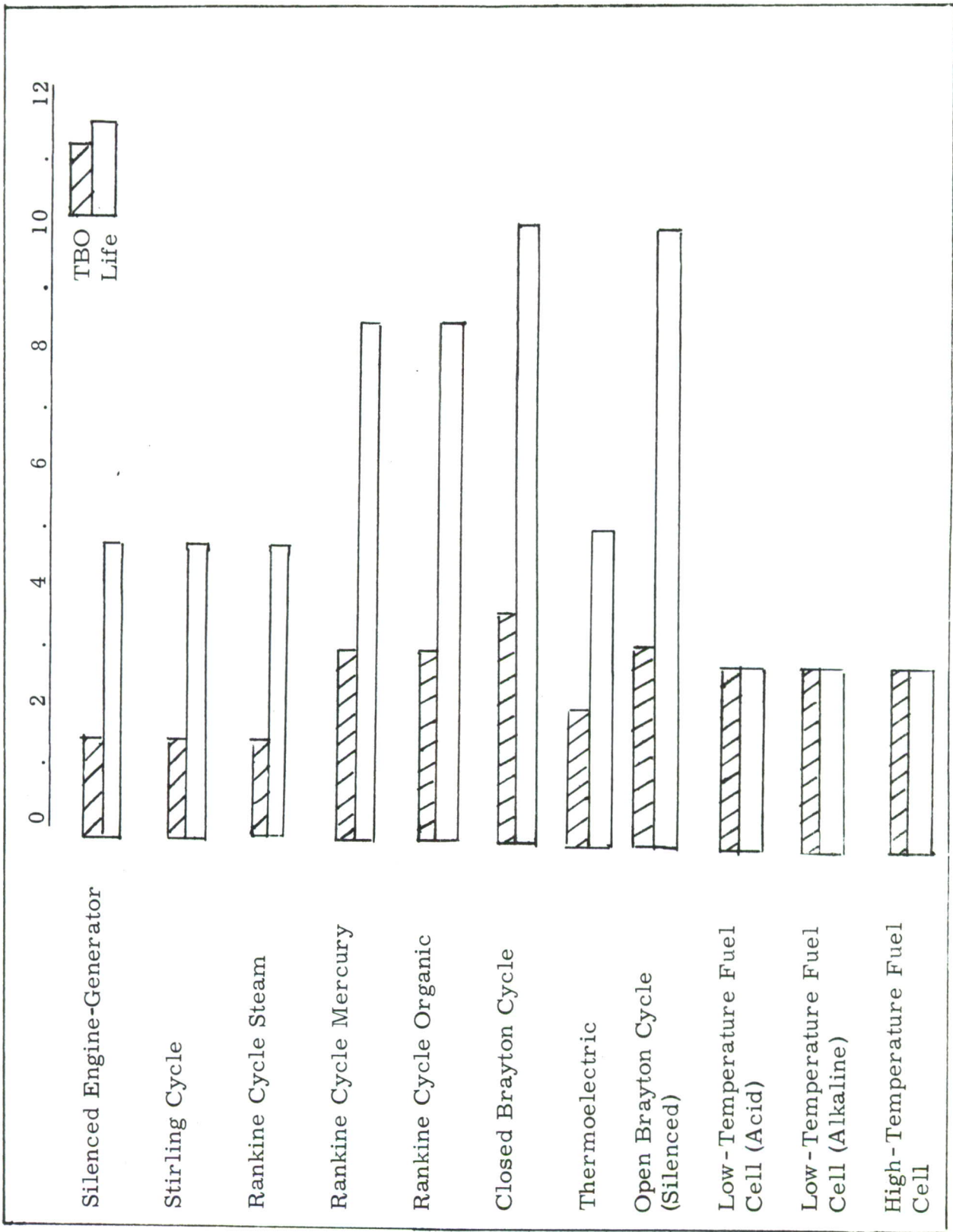


FIGURE 6. PROJECTION OF OPERATING TIME (IN THOUSANDS OF HOURS)-BETWEEN-OVERHAUL (TBO) AND IN SERVICE LIFE FOR THE NEAR-TERM FUTURE (2-5 YEARS)

V. CONCLUSIONS

There are several candidate devices having demonstrated capability and potential as power sources for remote areas in the range of power outputs from a few watts to two or three kilowatts. There is, however, a limited amount of test and operational experience, particularly commercial applications and military experience, with all of these candidates except for the general purpose Military Standard family of reciprocating-engine generator sets.

In the immediate future, the present general purpose Military Standard family of reciprocating-engine generator sets, preferably in silenced configuration, continues to appear attractive for military applications. Technology associated with thermoelectric devices make them attractive for relatively near-term remote area small power applications. They share with external combustion thermodynamic engines the ability to use indigenous fuels. Other factors tending to reduce logistics associated with their use are favorable, such as improving reliability and minimal maintenance. For the longer term, the fuel cell appears to offer many advantages for small power applications. For larger power requirements, a number of external combustion thermodynamic engines appear to be good candidates for remote area power generation.

Of the opinions expressed by experts in the field, those of the USAMERDC Electrotechnology Laboratory are given considerable credence. These opinions are that, from the standpoint of silent operation for military applications, closed-cycle Rankine devices of 500 watts to 3 kilowatts have considerable promise for the short-run, while fuel cells probably possess greater potential in the long-run. However, on the basis of the data acquired during this survey, it is concluded that no single class of device appears to offer potential so superior as to warrant its development to the exclusion of all others by the Limited War Laboratory. Selection of a single or set of candidates for further development can be made only from a firm and comprehensive definition of requirements for power sources in the range of power outputs considered.

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