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UNIVERSITY ROLE IN ASTRONAUT LIFE SUPPORT SYSTEMS: SPACE POWER SUPPLY SYSTEMS

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16. Abstract

MANY TECHNIQUES HAVE BEEN SUGGESTED FOR PROVIDING ELECTRICAL POWER ABOARD SPACECRAFT. THIS BROCHURE GIVES BRIEF DESCRIPTIONS OF SOME OF THE MORE PROMISING SCHEMES. AN ATTEMPT HAS BEEN MADE TO LIST THE MAJOR ADVANTAGES AND DISADVANTAGES OF EACH OF THESE SCHEMES, AND TO IDENTIFY THE PARTICULAR AREAS IN WHICH IT APPEARS LIKELY THAT FURTHER RESEARCH WORK MAY PROVE FRUITFUL. SPECIAL ATTENTION HAS BEEN PAID TO THOSE RESEARCH AREAS THAT APPEAR SUITABLE TO BE UNDERTAKEN AT COLLEGES AND UNIVERSITIES. CHEMICAL, SOLAR AND NUCLEAR POWER SOURCES ARE CONSIDERED, TOGETHER WITH THE APPROPRIATE THERMOELECTRIC, THERMIONIC AND TURBOELECTRIC CONVERSION SYSTEMS.

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FOREWORD

The Bioenvironmental Systems Division, Life Sciences Program Office, Office of Manned Space Flight of the National Aeronautics and Space Administration, is vitally interested in fostering and developing new ideas and concepts which will advance the technology of life support and protective systems. Many excellent, productive concepts and operating subsystems have been brought to fruition in NASA laboratories and by associated contractors. However, involvement of academic laboratories and personnel has not been as strong as was originally hoped. The above fact may be a consequence of the academic personnel not being aware of the critical problem areas in life support and protective systems, nor were they cognizant of the fact that NASA is interested in joining with colleges and universities to develop new ideas to solve future space flight problems.

This brochure on Space Power Supply Systems is intended to introduce the reader to some of the existing technology utilized in space power requirements applications. We encourage you to study this brochure. If in your research, you have already developed new ideas, theories, concepts, etc., which would be applicable to NASA's effort, we hope you will feel inclined to contact us to see whether a joint research effort can be pursued.

Walton L. Jones, M.D.
Deputy NASA Director
for Life Sciences

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INTRODUCTION

It is the objective of this brochure to help stimulate interest and ideas in space power systems at the university level. Hopefully, one way to do this is to present, in brief, state-of-the-art developments, state future goals, and finally, to point out problem areas that are in need of solutions.

A major portion of the material presented in this brochure has been in some way either initiated, developed, and/or funded by two government agencies, namely the National Aeronautics and Space Administration (NASA) and the Atomic Energy Commission (AEC). Consequently, the space power systems described here will center around those systems that have been chosen and supported by these two agencies.

I. SPACE POWER SYSTEMS[1]

Space power systems are made up of two prime building blocks. First, an energy source and second, an energy conversion system.

Energy sources can be divided into four categories: Chemical, Solar, Radioisotope, and Nuclear Reactor.

Energy conversion systems fall into seven basic divisions: Batteries & Fuel Cells, Photovoltaic, Thermoelectric, Brayton, Rankine, Thermionic, and Magnetohydrodynamic (MHD). This list is not all inclusive but it does represent the most promising ones.

The first two energy conversion divisions, Batteries & Fuel Cells and Photovoltaic, have to date seen extensive use. The third division, namely, Thermoelectric, is growing rapidly in popularity and use. The other four energy conversion systems, however, are relatively new and most of today's hardware has not been flight tested.

Technically, each of the four energy sources can be combined with each of the seven energy conversion systems to form a potential power system. But, the number of possible combinations is too great to consider each one seriously. What NASA has done instead is to narrow down the number of combinations to 15 of the most interesting with regards to the space program (see Figure 1-1).

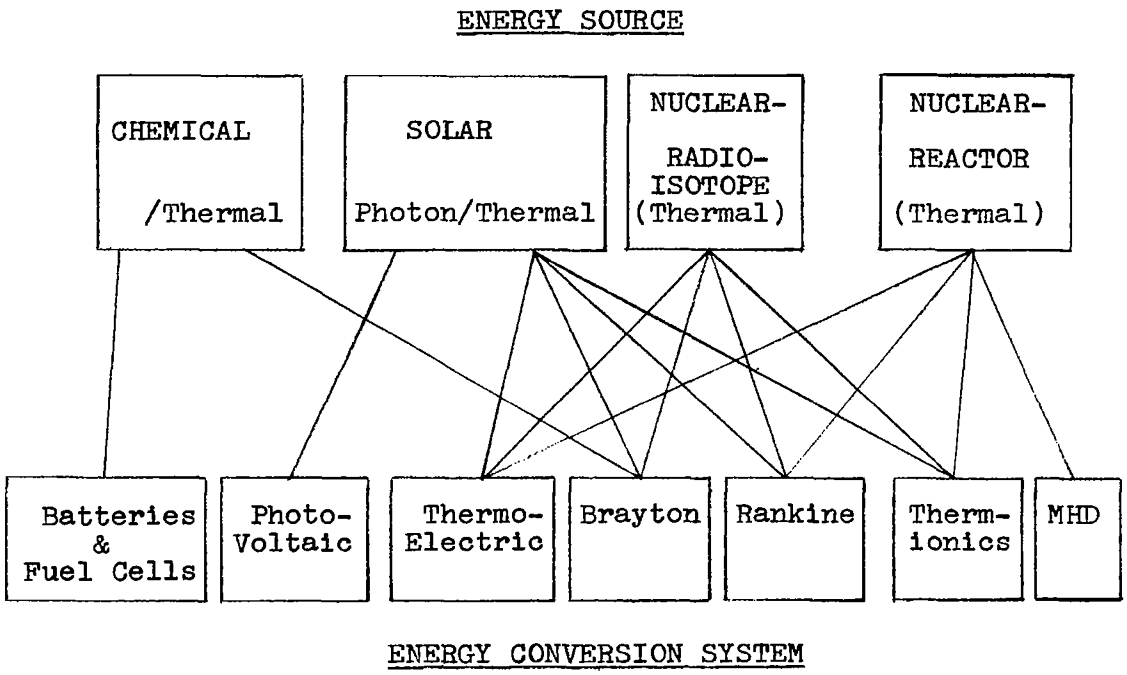


Figure 1.1 Space Power Systems : 15 Most Interesting Combinations [1]

Of these 15 systems NASA has further narrowed down the list to 8 systems which are expected to meet most of NASA's future needs. These eight systems will receive 80 to 90 percent of future funds to be allocated to space power development (see Figure 1.2).

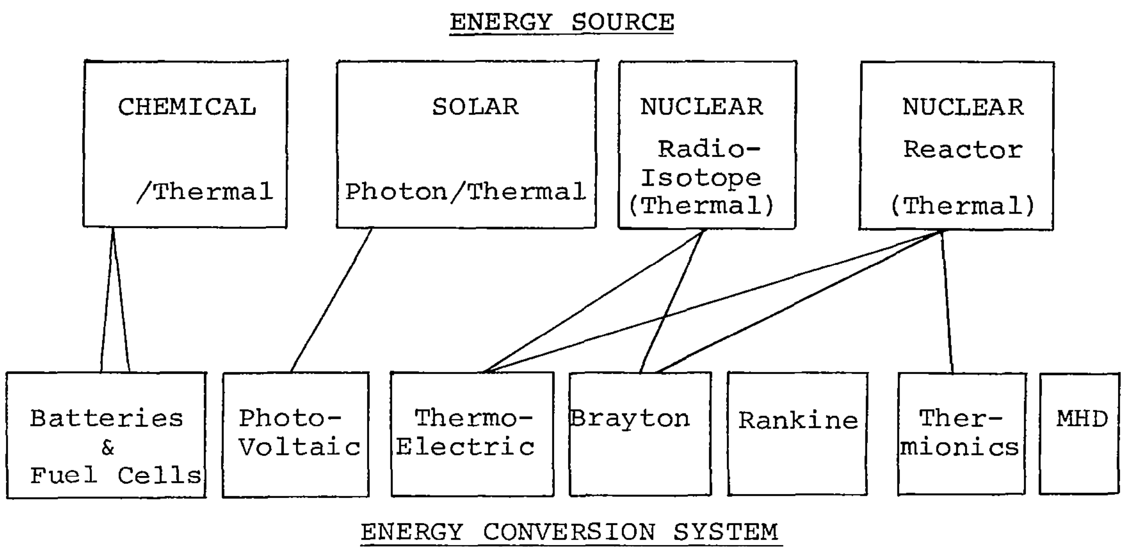


Figure 1.2 Space Power Systems: 8 Most Promising Combinations[1]

The specific power ranges covered by these eight systems are listed in Table 1.1 below.

Table 1.1 Probable Power Range of Systems of Principal Interest[1]

	Probable Power Range In KW				
System	.01-2.0	2-10	10-25	25-50	50
Solar Cells	X	X	X	X	
Isotope Thermoelectric	X				
Isotope Brayton		X			
Reactor Thermoelectric			X		
Reactor Brayton				X	X
Reactor Thermionic					X
Batteries	Required for energy storage with all the above systems or as a short duration space power system e.g. Mercury, Gemini, or Apollo.				
Fuel Cells					

It should be recognized that it is very unlikely for any one particular system to satisfy all power requirements for any particular space mission. Rather, a combination of systems is necessary to satisfy the conditions of power level, mission duration, work function, and environment. The particular characteristics of each system will be covered briefly in later sections. A block diagram of most of the possible system configurations that can be expected is summarized in Figure 1.3 below.

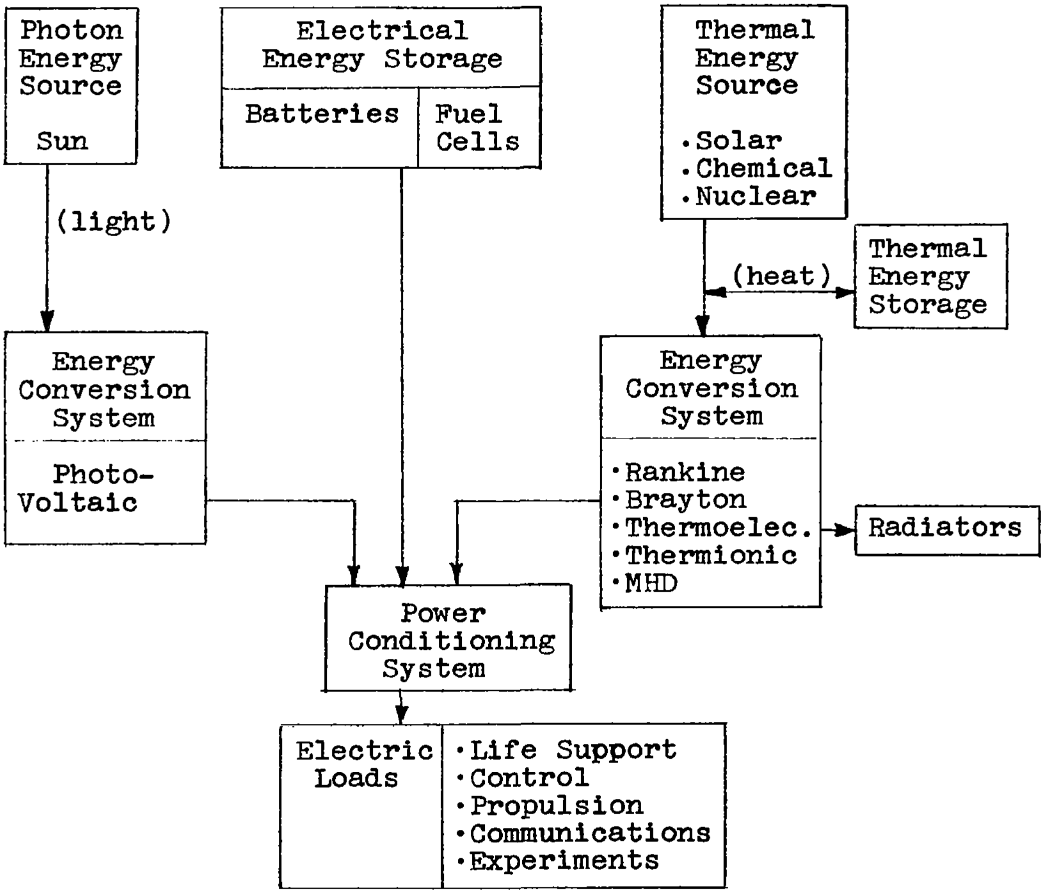


Figure 1.3 Space Power Systems and Components[1]

Of all the elements shown above in Figure 1.3, Thermal Energy Storage has been given the least consideration due to the advanced technology of fuel cells and batteries. Little interest is being encouraged in this area and it will not be covered in this brochure. Also not covered in this report is Magnetohydrodynamic (MHD) energy conversion system. The reason is that the technology in this area is not expected to be ready for practical use until well into the future. Moreover, the large energy levels inherent with MHD systems are not in immediate demand except for propulsion applications where megawatts are called for.

Figure 1.4 below gives a rough correlation between system power range and mission times to point out graphically a particular choice for an energy conversion system.

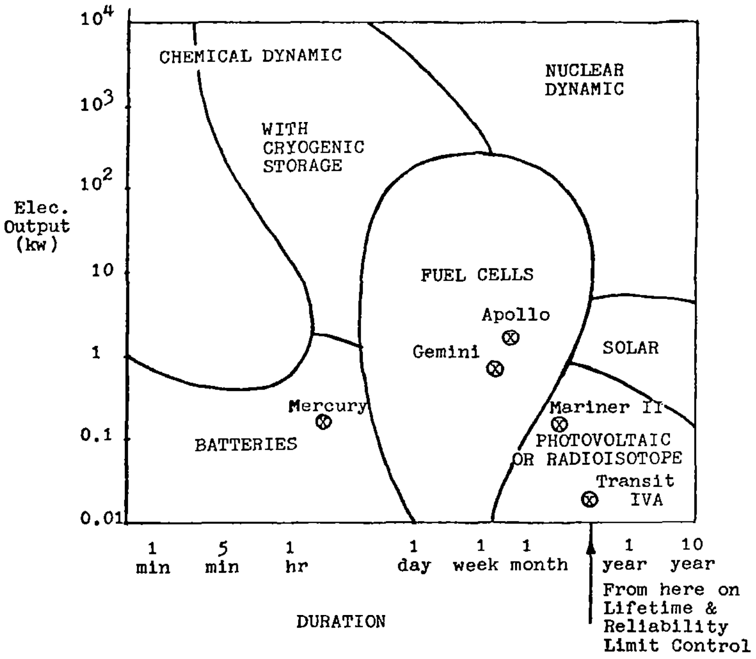


Figure 1.4 Comparison of Space Power Sources[2]

Briefly, what Figure 1.4 implies is the following:[2]

1) Solar cells, photovoltaic devices and radioisotopes are best suited for low power and long-life requirements.
2) Fuel cells are favorable for relatively low loads (1-10kw) and short flight times (1-30 days), e.g., Gemini and Apollo programs.
3) Direct chemical fuels are required for high loads over short output times.
4) Nuclear reactors are best suited for large power requirements over an extended period of time.

II. CHEMICAL POWER SYSTEMS[3,4]

In general there is a need for batteries in any particular space power system. It is hard to imagine any space system, especially involving manned vehicles, where batteries will not be called upon (space suits, portable equipment, etc.). Obviously the choice of a particular system depends on its intended use. For example, in the case of Earth orbiting satellites used for communication, navigation, weather observation, etc., economic considerations make long cycle life more important than light weight.

Judging from past experience it is possible to predict that power requirements will continue to increase, creating a greater need for light weight, highly efficient power systems.

The need to store more energy may mean higher capacity cells, although this need may be met to an extent by using more existing batteries connected in parallel. Parallel batteries though, rather than a larger single one, would result in increased weight. However, this is offset by an increase in reliability, since failure of one battery would not cause total mission failure.

-- Construction

The galvanic or electrochemical cell is the oldest source of sustained electrical power. Galvanic cells connected electrically in series, parallel, or in combinations thereof, constitute batteries.

The construction of all practical cells is generally the same, consisting of two active electrodes, an ionically conductive electrolyte and usually a separator (see Figure 2.1 below).

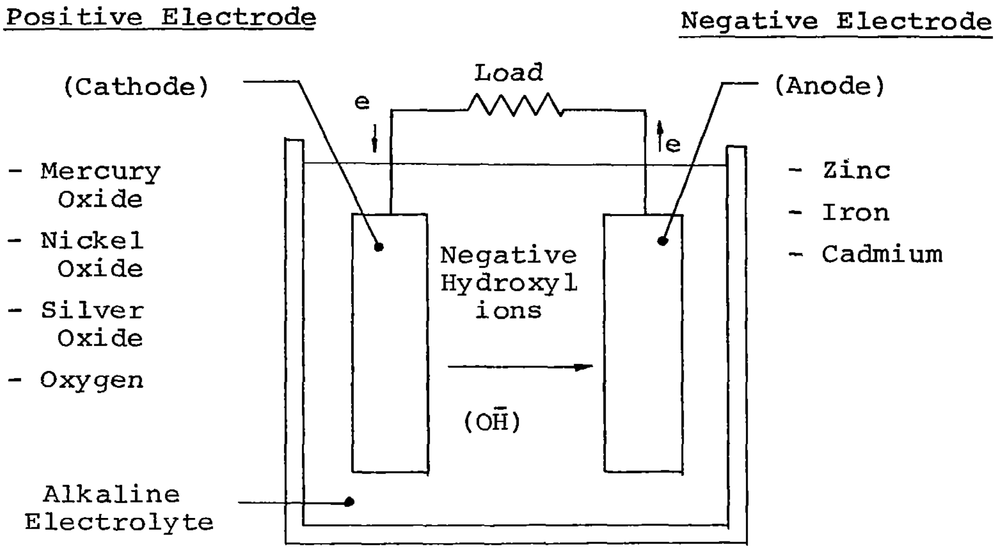


Figure 2.1 Alkaline Batteries [1]

The separator (not shown in Figure 2.1 but illustrated in Figure 2.2) prevents contact between negative and positive active materials and acts as a carrier and immobilizer for the electrolyte. All these elements are enclosed in a case.

Basically, the ingredients of a cell are packaged in such a way that the reaction process, in particular that of electron transfer, cannot proceed unless an external load is applied across the two electrodes, the anode and the cathode. This is a general description of simple conventional cells. Some may incorporate auxiliary electrodes, electronic controls, gas regulating devices, and hermetic seals to avoid leadage to the vacuum of space. All these design features combine to give galvanic cells and batteries an important characteristic: exhaust products can be monitored, controlled, and kept within the cell enclosure.

Most working cells are packaged in three basic forms: rectangular, cylindrical, and "button-cell" (low length-to-diameter ratio). Rectangular cells generally have a greater variety of voltage ranges available and are usually assembled together in parallel in order to obtain a desired capacity. Cylindrical cells are conveniently stacked in rows or hexagon-close-packed for greater utilization of volume. Button cells may be pressure stacked or welded in series forming a long cylinder stack for a higher voltage.

-- Operation

All electrochemical batteries and fuel cells operate on the same principle, namely, a mutual oxidation-reduction (redox) reaction. This reaction is a chemical change in which there is a transfer of electrons from one reactant to the other. The reactant losing electrons is oxidized, and the one accepting electrons is reduced. When these reactants are combined, under the proper conditions, the reaction occurs spontaneously with the evolution of heat.

-- Cell Voltage

The theoretical open-circuit voltage of a galvanic cell is determined solely by the thermodynamics of the chemical reaction between the enclosed reactants and is independent of the quantities of material present. Normally, the chemical reactions taking place at the cathode and anode can be considered separately, and each can be characterized by a standard electrode potential equation. Under standard conditions (25°C) the cell voltage is the algebraic sum of the electrode potentials of the two electrodes. Upon discharge the cell potential drops. This drop from the zero-current cell potential can be anticipated by use of appropriate theoretical relationships. In general, where cell reactions and electrode processes are precisely understood, the agreement between measured values of cell voltage and theory is excellent.

-- Performance[4]

Space-battery development suffers from a lack of performance characteristic data usable by power-supply designers. This is further complicated by a lack of standardization of cells, of testing conditions, and of data reporting. (A detailed discussion of data requirements and deficiencies in existing design data, and recommendations for a format for expressing data can be found in Ref.4, Chapter 3). In general, design data are required on the electrical characteristics, failure modes, and on charge-control requirements of secondary batteries. Of these, broad programs have been implemented mainly for the investigation of failure modes. Even this, in spite of extensive testing, has not provided quantitative information about the rates of the individual failure processes.

Definitions of failure are critical in determining the impact of service conditions on life, since a combination of unfavorable service conditions and failure criteria can lead to rapid performance failure, although no physical failure has occurred. Once the fundamentals leading up to battery failure have been established one may expand to include specific problem areas such as electrode reactions, solubility and migration problems, and separator composition and structure.

A promising technique that requires further investigation involves making an empirical analysis of test data and using cryptoanalytical devices in order to identify statistical regularities. This information then may be used to construct predictive procedures for use in cell acceptance programs. The existing technique of production sampling and testing to destruction is inadequate.[5]

-- <u>Failure Modes</u>

Individual battery systems are subject to individual types of failures. However, a number of failures are common to most batteries designed to deliver large amounts of energy as distinguished from reference cells and other low current cells). They are as follows:[4]

1) Separator deterioration
2) Loss of capacity due to crystal growth; present in many types.
3) Loss of active material from the electrodes due to mechanical separation, erosion, solution and redeposition.
4) Perforation of the separator by dendrite growth of metallic materials leading to short-circuits.
5) Mechanical damage resulting from mishandling, severe environmental conditions or generation of internal pressure.
6) Carbonation of electrolyte resulting from a vent or leak in the cell case.
7) Continuous conductive path (leaking) between two or more series connected cells due to leaking electrolyte.

Principal system limiting problems associated with batteries include the following:[6]

- inability of hermetic seals and separators to operate 2 years or more.
- a narrow useful temperature range.
- charge-discharge control and environmental protection problems.

It can still be said that though batteries have been in use for years, the technology is still, in many cases, developed as an art and not as a science.

-- Battery Classification[4]

Functionally all types of batteries can be classified as being primary or secondary in regards to their application to space power systems.

Primary batteries are meant to deliver most of their energy in one short period of time (often in 10 minutes or so). They are short lived, have high energy density, high current capacity, good reliability and find particular use during the period of vehicle launching.

Secondary batteries are those that can be recharged and used again. Reliability, longevity and rechargeability are more important than high current performance. They are used for emergency power supplies and to supplement solar energy supply systems in the event the light source is interrupted.

2.1 Summary

-- Batteries[7]

Primary batteries, such as silver-zinc (AgZn) and zinc-oxygen (ZnO_2), continue to play an important role on missions with low energy requirements. Except when they are needed for very short periods (as on launch vehicles), they usually handle peak loads or provide emergency standby power. Energy densities ranging from 30 to 90 w-hr/lb and amounting to a mere 10 to 20 percent of the theoretically obtainable values, are highly dependent on the rate of discharge. Efforts to improve them have been disappointing. The range of operating temperatures also is fairly limited and in most space applications this leads to critical problems of temperature control.

Secondary batteries, being rechargeable, have a broad range of applications. The nickel-cadmium (NiCd) type has less than half the energy density of the silver-zinc (AgZn) type, but its longer life cycle more than makes up for this disadvantage on extended missions. Another type of secondary battery in wide use at the present time is the silver-cadmium (AgCd) type.

-- Primary Fuel Cells[7]

At present, the hydrogen-oxygen fuel cell for space is limited to 1 to 5 kw. Specific dry weights of 50 to 75 lb/kw have been achieved (at efficiencies of 50 to 60 percent), specific fuel consumption at rated power lies in the range from 0.8 to 0.9 lb/kw-hr, and cell lifetimes of 1000 to 2500 hr have been demonstrated. By the mid-70's, lifetimes of 4500 hr may be possible.[7]

The selection of the fuel cell over other power systems for the Gemini and Apollo projects was based on the fuel cells considered superior efficiency, and the diverse characteristics of the missions which rendered unacceptable power systems having exposed components or requiring orientation.[8]

2.2 Primary Batteries for Space[3]

-- Zinc-Mercuric Oxide (Zn-HgO)

The earliest U.S. space cells were commercial mercury cells developed during the early part of W.W. II.

Typical cell parameters were as follows:

- 1.35 volt open-circuit, typical operation at 1.3 volt
- current density, 40 amp-hr/lb
- energy density, 53 watt-hr/lb

Figure 2.2 below shows the construction of a common type commercial cell.

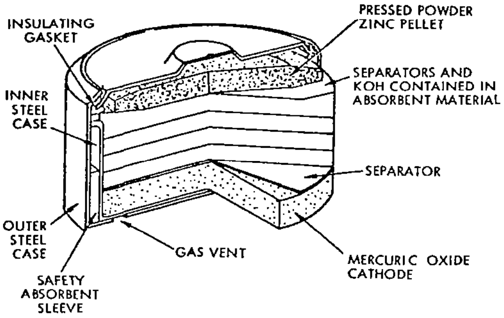


Figure 2.2 Flat Pellet or "Button" Structure Mallory Alkaline Zinc-Mercury Oxide Cell.[4]

The performance curves shown in Figure 2.3 on the following page are illustrative, not only of zinc-mercuric batteries but of most other cells as well, though the numerical values will differ from case to case. Notice that the resistance of the external load determines the rate as well as the voltage at which electricity is drawn from the cell. The lower this resistance, the shorter is the discharge period and the lower is the voltage. Thus the efficiency and the energy density are decreased as the external resistance is decreased.

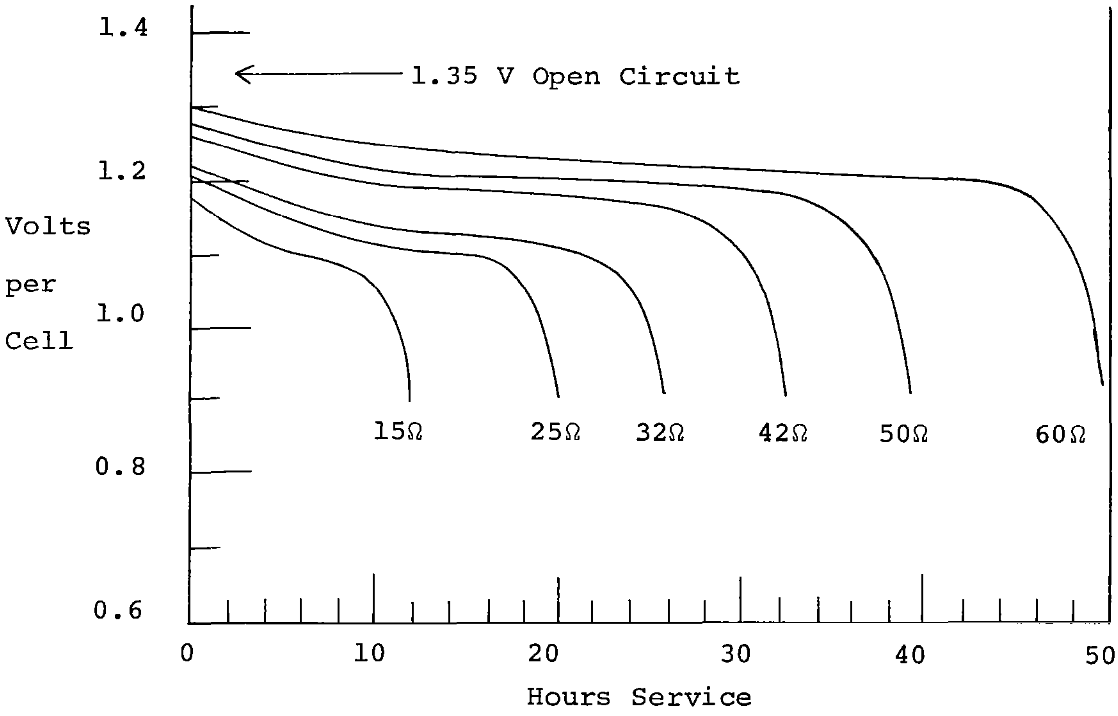


Figure 2.3 Typical Discharge Curves for a 0.20 cu-in Alkaline-Zinc-Mercuric Oxide Cell[3]

Although these cells may still be used in specific instances, little if any research or development is being done on them. The main reason for this is that they can be easily replaced by silver zinc oxide cells which have much higher energy densities.

- Silver-Zinc (Ag-Zn)[4, 6]

The silver-zinc system has been developed into a highly reliable primary battery of the reserve type (i.e., activated immediately prior to use) with energy densities up to 80 watt-hr/lb and is often used in launch vehicles. Performance in this application is generally excellent except for the relatively high internal heat dissipation.

The silver-zinc alkaline cell generally exhibits poor voltage regulation. This is characteristic of the silver electrode. Consequently, two distinct voltage plateaus are obtained on charge and discharge (see Figure 2.4). The open circuit voltage of these two plateaus are approximately 1.9 and 1.6 volts respectively.

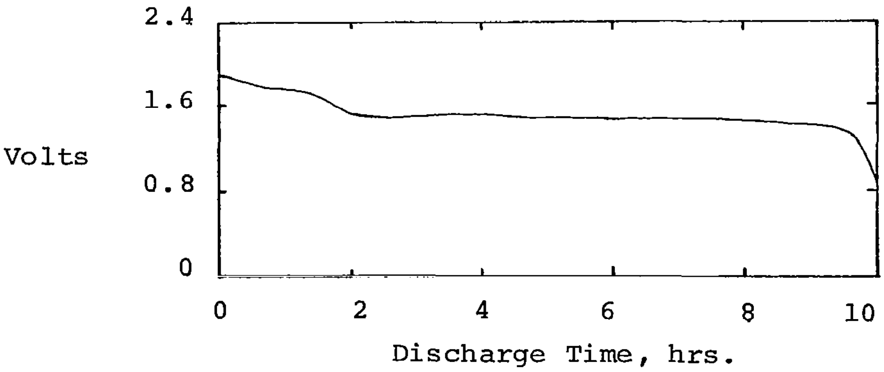


Figure 2.4 Discharge of Silver-Zinc Cell[3]

Of the major primary batteries in current use, Ag-Zn batteries have the highest charge-discharge voltage potential.

The solubility of zinc oxide and the zinc electrode in potassium hydroxide is one of the major limitations to the extended operation of silver-zinc cells. The dissolution and replating of zinc during cycling of cells has been the object of extensive investigation.

Despite this problem the Ag-Zn battery is electrochemically reversible to a limited degree.

Hydrogen and oxygen gas may be evolved in the silver-zinc cell during charge, discharge and stand. In sealed cells this evolution of gas may result in premature cell failure due to case rupture. Auxiliary electrodes have been used in experimental sealed cells to control internal gas pressure. The principal use of auxiliary electrodes is for hydrogen recombination. Without auxiliary means, hydrogen recombination proceeds slowly at the silver electrode, whereas oxygen recombination at the zinc electrode proceeds somewhat more rapidly. Thus, there is an imbalance resulting primarily in a hydrogen gas buildup.

A primary silver-zinc battery is often manufactured in the dry-charge condition and electrolyte is added just prior to use. This particular feature should lead to many useful applications on future space missions. As an example of what has already been researched to date there is the concept of a dry-tape cell.

A silver-zinc cell is constructed using a silver-peroxide-impregnated tape, an electrolyte-impregnated tape and a zinc-block electrode (see Figure 2.5).

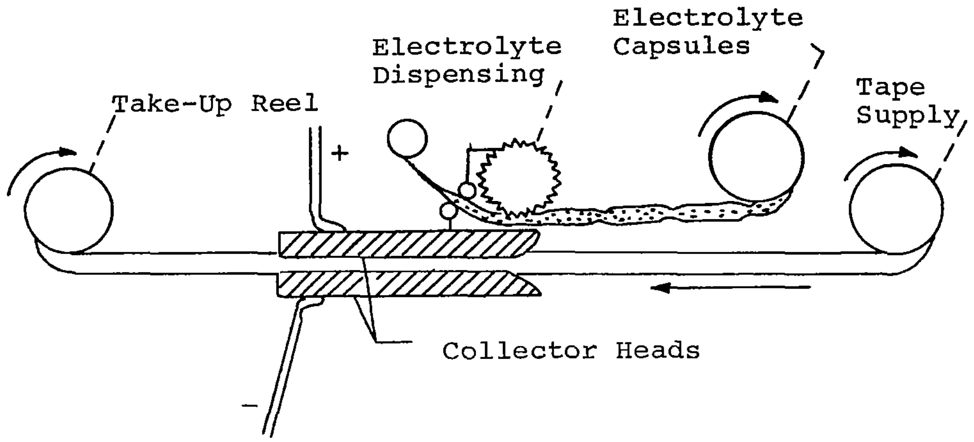


Figure 2.5 Features of the Dry Tape Battery[3]

The tapes are kept separated until used and are driven by an electric or spring-wound motor. In this manner fresh materials are constantly being added to the cell as it discharges, and the cell takes on the characteristics of a fuel cell[9]. This particular scheme, however, has recently been abandoned after much research and development.

Besides being a reliable primary battery much development has gone into making silver-zinc a reliable secondary battery as well. As such, the silver-zinc secondary battery is the highest energy density battery in common use. However, it does not have the good cycle life of the nickel-cadmium secondary battery. Silver-zinc cycle life is still measured in hundreds of cycles as compared with thousands of cycles for nickel-cadmium batteries.

- Zinc-Oxygen ($Zn-O_2$)[3]

The cathode materials for the two above cases are metal oxides--mercuric oxide and silver oxide. It has long been recognized that oxygen itself would be a satisfactory reactant, and that it need not be built into a battery but can be derived from the air. Such air "oxidant" zinc batteries are standard equipment for railway signals. Under normal conditions they can operate for a year. However, their power output or rate of discharge has been very low due to the slow rate of reaction of oxygen. Now that relatively high-rate oxygen electrodes have become available through research on fuel cells (see section 2.4), high-rate zinc oxygen cells are a practical possibility, and they are being developed for NASA. In space, the oxygen must be carried along, of course.

Typical operating voltage for these cells will be 1.2 volts per cell. The energy density is expected to range from 120 watt-hr/lb for an 8-hour discharge period to perhaps 150 watt-hr/lb for a week-long discharge, including the total weight of the self-contained battery.

Limited rechargeability (50 cycles at 20% depth of discharge) has been demonstrated in the laboratory.

2.3 Secondary Batteries for Space

-- Nickel Cadmium (Ni-Cd)[3, 4]

The Nickel-Cadmium battery is best characterized by its high survivability and long cycle life. Typically used as a secondary battery in long-life applications, even though it is heavier than the silver-cadmium battery (described in the next section),it presently receives the greatest use.

In satellite applications, the discharge rates have varied from approximately a 1-hour to a 5-hour rate. However, the actual range of the system's capability is somewhat wide, since it may be used at much higher currents corresponding to a 10-minute rate. The minimum rate at which the nickel-cadmium system may be used is determined by the self-discharge rate which varies considerably with temperature. Rates of several hundred hours are quite plausible.

Typical conservative battery specific weights for an earth orbiting satellite are as follows:[6]

1) 2 watt-hr/lb for a 300 mile orbit
2) 5 watt-hr/lb " " 2500 " "
3) 10 watt-hr/lb " " 20,000 "

For a typical 90 minute orbit NASA has obtained on the order of 18,000 cycles (3 years) at about 20% depth of discharge (based on rated capacity) but as few as 250 cycles at 75% depth.

The advantages of the Nickel-Cadmium couple over other secondary batteries include the following:
(see Figures 2.6 to 2.10)

1) small voltage excursion
2) high rate charge acceptance
3) long cycle life
4) long shelf life
5) low temperature operation

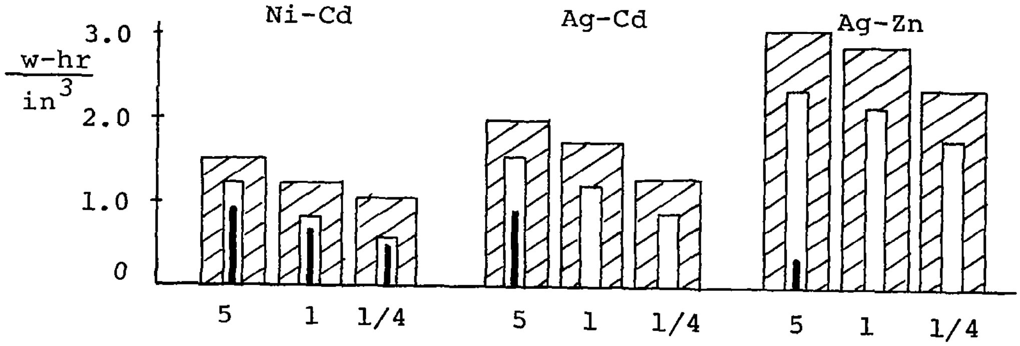
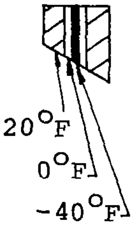


Figure 2.6 Energy per unit Volume vs. Discharge Rate[10]



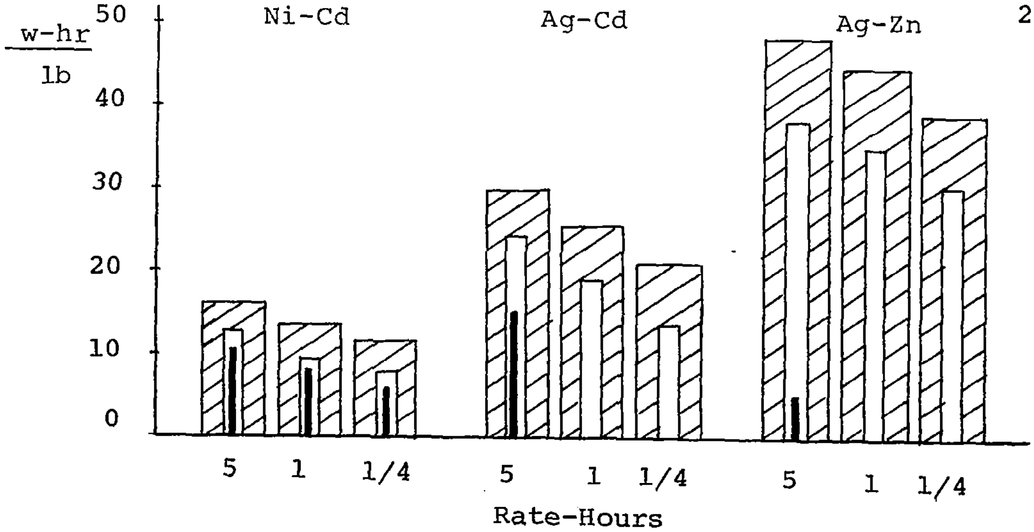


Figure 2.7 Energy per unit Mass vs. Discharge Rate[10]

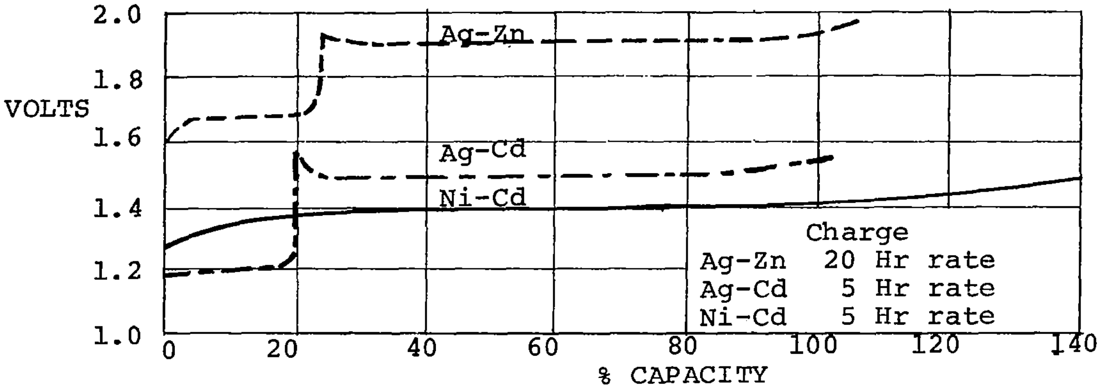


Figure 2.8 Voltage Charge Characteristics[10]

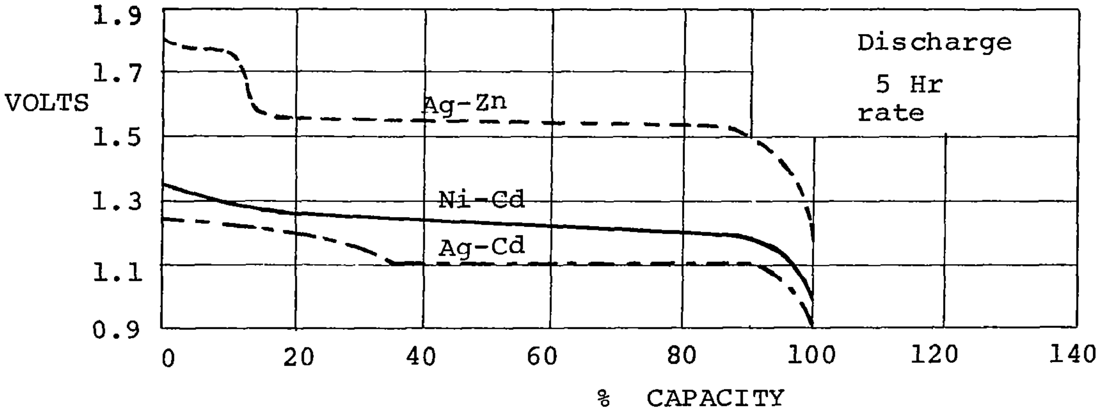


Figure 2.9 Voltage Discharge Characteristics[10]

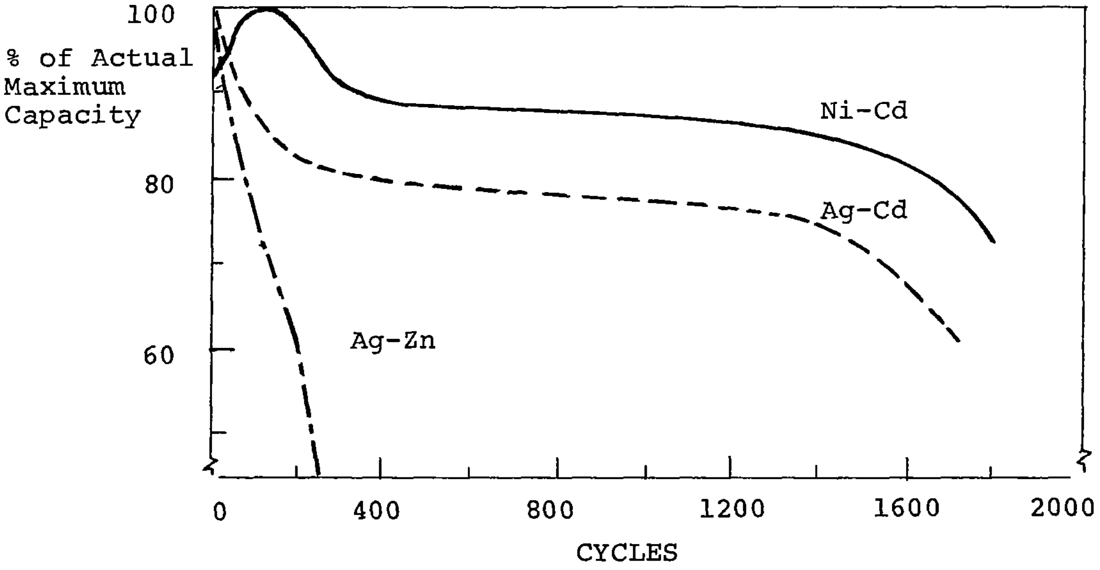


Figure 2.10 Capacity vs Cycle Life[10]

Improvements in the Ni-Cd cell have been the development of inert separators, more reliable seals, and greater uniformity in the manufacture of plates (i.e., electrodes). Hermetically sealed cells are designed to operate in the electrolyte-starved condition, leaving considerable surface for oxygen evolution recombination at the negative cadmium electrode. However, oxygen evolution also occurs near the "charge" voltage of the positive nickel electrode. As a result the voltage rise at the end of the charge is not sharp and does not clearly indicate completion of charging, particularly at the high temperatures. This complicates charge control systems based upon voltage. However, cells are able to tolerate useful continuous over-charge levels.

In contrast to acid batteries where a hydrometer is a fairly good indicator for state of charge, no satisfactory device is available for this purpose applicable to Ni-Cd cells. Coulometers (i.e., amp-hr. meters) and equivalent external devices work up to a point, except that the state of charge of a cell varies with temperature. An indicator electrode can be used to sense the onset of oxygen evolution, which occurs at 80-90% of full charge. Such third electrodes (in addition to the two working electrodes) are now available for controlling the end of fast charging.

Just as over-charging causes gassing (predominantly O_2), over-discharging also causes gassing (predominantly H_2) and might damage or break a cell. Here again the remedy is an auxiliary electrode connected to the cadmium plate. A fuel-cell type fourth electrode can use up hydrogen faster than the cadmium electrode. Thus, both recombination and sense auxiliary electrodes may be desirable in galvanic cells.

Oxygen evolution is exothermal and consequently raises the battery temperature. From the system design standpoint, the heat-evolution rate in Ni-Cd batteries is of tremendous importance in aerospace applications.

Batteries vary in heat dissipation over their charge-discharge cycle, depending upon the state of charge. The rates of evolution or absorption are nonlinear with cell voltage. A Ni-Cd battery can be operated with high performance over a temperature range of approximately -40°F to 80°F, but for other types of batteries the optimum operating range is less. Thus, the battery temperature has a great influence upon the thermal-control subsystems of a space craft, and may be a primary factor in the determination of thermal-control-design concepts. Therefore, in order to operate space batteries with both high-efficiency and high-performance, detailed knowledge of the heat-evolution rate is required throughout the operating cycle. As yet no fully adequate method exists for predicting heat-evolution rates as a function of time.

Ni-Cd batteries are composed largely of ferromagnetic materials having a strong residual magnetism and, as current-carrying devices, also produce an induced magnetic field which increases exponentially with load current. The effects of this varying magnetic field upon experiments must be taken into consideration at the initial system design stage.

One of the weakest parts of the cell, for long life, is the ceramic-to-metal seal. Other types of seals have been proposed or are being investigated, but their success is not known. These include bonded rubber and neoprene seals and graded cermets.

Currently, several manufacturers produce standard lines of nickel-cadmium cells satisfactory for most uses. However, quality control is poor. Capacities of cells in a production lot may vary 5 to 10 percent and lot-to-lot variations are often larger. The two greatest unsolved problems are seal integrity and divergence in performance characteristics of apparently identical cells after prolonged operation. Other significant problems are associated with construction errors.

It is presently doubtful whether 5-year batteries will be produced. One problem is that it takes 5 years to find out. What is needed then are meaningful methods for accelerated testing.

--Silver Cadmium (Ag-Cd)[3, 4, 10]

The silver-cadmium couple has been viewed as a compromise between the long-life and low-energy density Ni-Cd system and the short-life, high-energy density Ag-Zn cell (see Figure 2.6,2.7 and 2.10).

Both the Ag-Cd and the Ag-Zn systems exhibit poor voltage regulation, a characteristic attributed to the silver electrode. Cell geometry, materials, and methods of construction of both the silver electrode and separators for Ag-Cd and Ag-Zn cells are similar. The Ag-Cd system yields less energy than the Ag-Zn system since its operating potential is approximately 0.4 volts lower (see Figure 2.9). This is a consequence of changing from the short-lived zinc-electrode to the more stable cadmium electrode. A lower cell voltage for Ag-Cd means a more difficult task for system voltage regulation.

The chemistry of the cadmium electrode is nearly identical in both the Ag-Cd and Ni-Cd cells. However, the construction of the cadmium electrode is usually different. A porous nickel plaque is common in Ni-Cd cells whereas most Ag-Cd cells employ pressed power or pasted cadmium electrodes.

Ag-Cd is presently the only system which can make cyclic orbital satellite applications free of residual magnetic properties. It has been flown in a number of satellites, generally with good success. Ag-Cd cells are rarely used in primary applications. However, as a secondary battery, Ag-Cd cells have an advantage of energy density approximately twice that of the Ni-Cd cell and a cycle life 1 to 2 orders of magnitude greater than the Ag-Zn cell. In addition, the Ag-Cd cell, unlike the Ni-Cd system, will tolerate only limited amounts of overcharge (reference Figures 2.8).

The wet stand life for Ag-Cd is approximately 1 to 2 years. Precise data on the relationship between current, voltage, temperature, and pressure are not available, it is believed, for Ag-Cd cells.

When considering actual energy densities achieved in satellites thus far, capacities of Ag-Cd cells (6 - 8 watts-hr/lb) have been noticeably higher than those of Ni-Cd cells (1/2-2 watts-hr/lb). These more energetic cells have lasted 2 to 2.5 years thus far, approaching lives close to Ni-Cd cells (3 years). Ni-Cd cells run typically 16 cycles/day; Ag-Cd cells may run 3 cycles or so. This means a longer charging time and a lower charging rate is required. It is doubtful whether Ag-Cd would have been flown in space even now, had it not been for the fact that non-magnetic batteries were needed that would not interfere with sensitive magnetometers.

2.4 Primary Fuel Cells for Space

-- Summary[6,11]

The hydrogen-oxygen fuel cell is considered particularly adaptable to short duration manned missions for the following reasons:[6]

a) high efficiency (50 to 60 percent thermal or 60-75 percent voltage)

b) high energy density (1650 watts-hr/lb of reactants)[11]

c) absence of large external surfaces requiring orientation

d) they present no problem during docking or other maneuvers

e) water is a by-product of the chemical reaction

Hydrogen-oxygen reactant consumption is on the order of 1 lb/Kw-hr. Tankage adds about another 0.5 lb/Kw-hr for small systems. For these reasons, the hydrogen-oxygen fuel cell was selected for the Apollo and Gemini programs.

The principal factors limiting the output of fuel cells at this time are:[8]

- increased corrosion and erosion of membrane cells as a function of temperature and power.
- polarization losses.
- state of manufacturing techniques and quality control methods.

To date, three hydrogen-oxygen fuel cell concepts have received the greatest support from the government. They are the Gemini ion-exchange fuel cell, the Apollo and Lunar Excursion Module (LEM) Bacon type fuel cell, and the capillary fuel cell.

-- An important feature of the Gemini ion-exchange fuel cell is that it can be started and operated at room temperature. Actually, this relatively low operating temperature is not a matter of choice. It is dictated by the fact that the organic membranes used in the cells are unstable at higher temperatures. In fact, organic membranes degrade under almost all conditions, though the rate of degradation can be kept low enough to obtain a useful life time. The ion-exchange fuel cell appears to have one fundamental weakness: The electrical resistivity of known membranes is about 10 times that of free or immobilized aqueous KOH. As a result, the efficiency of the reactant is lowered, so that more reactant is needed per kilowatt-hour (kwh) power output. This also means higher tankage weight and a higher radiator load, since the inefficiency appears as heat.

Nevertheless, the organic membrane system was the lightest available power source for the Gemini program. All the fuel cell systems have operated adequately during the Gemini missions.

-- The Apollo Bacon type fuel cell has already proven itself aboard the many Apollo missions flown to date. Except for a suspected component malfunction, unrelated to the basic cell design, that resulted in the explosion of the oxygen fuel tank aboard the

Apollo 13 spacecraft, the fuel cells have all operated as planned.

-- The capillary fuel cell currently shows the greatest promise for long life, reliability, and adaptability to a range of operational requirements. This cell was in early conceptual stages at the time the ion-exchange and the Bacon fuel cells were selected for the Gemini and Apollo programs, and thus it was not selected.

The capillary fuel cell, while not yet a flight accepted system, is a prime candidate for the Space Shuttle application planned for the late 1970's, where its long-life capability permits reusability. Fuel cell technology work for the near future will emphasize increasing the demonstrated life of the cell beyond the 3,000 hour point, and on seeking a major advance in the peak to average power capability of this fuel cell.

-- Description

A fuel cell is a device for converting the chemical energy of reaction between fuel and oxidant directly to electrical energy. The basic principle is similar to that of the flashlight battery or any other primary cell (see Figure 2.11).

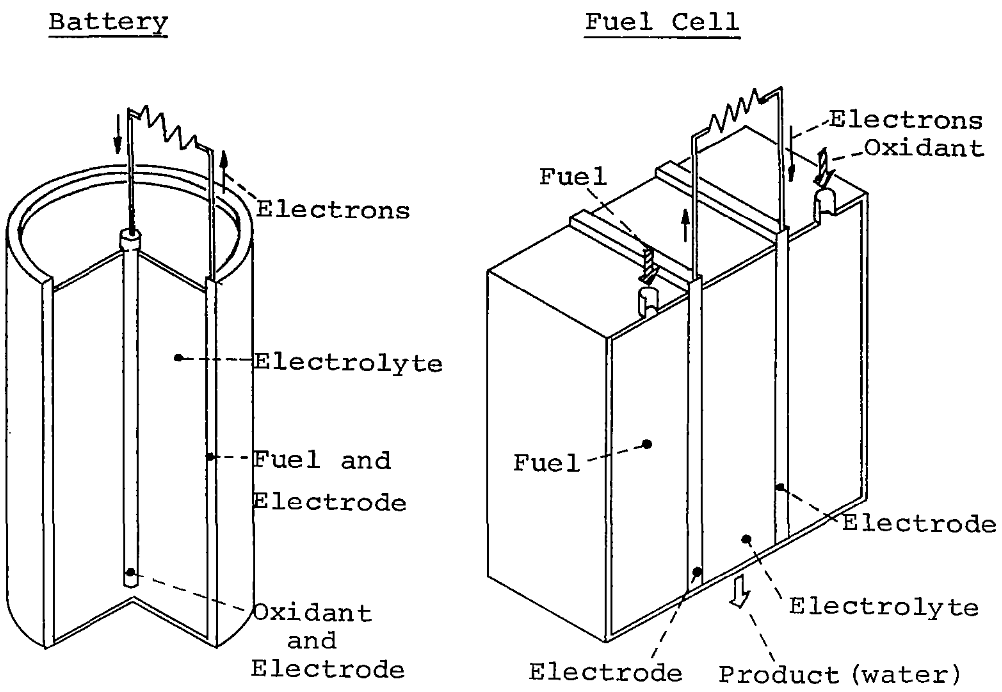
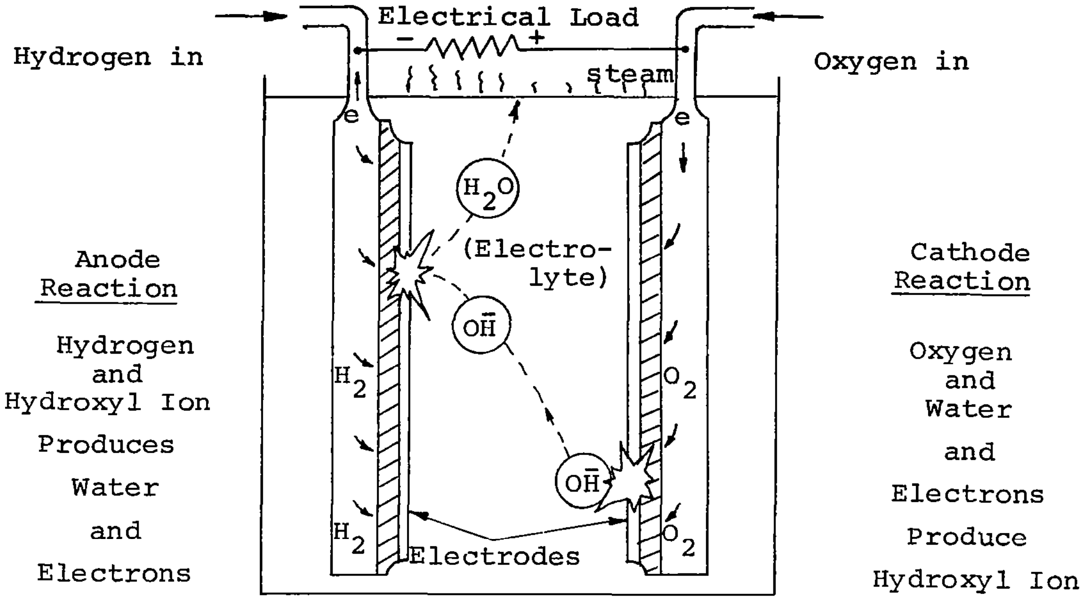


Figure 2.11 Comparison of Battery and H_2-O_2 Fuel Cell[9]

A fuel cell has two conducting electrodes immersed in an electrolyte of potassium hydroxide dissolved in water. Hydrogen is fed to one electrode (the anode) and oxygen to the other (cathode). The result of this is the reaction of oxygen and hydrogen to form water and a flow of electrons to an external load (see Figure 2.12).



Hydrogen & Oxygen = Water & Electric Power

Figure 2. 12 Basic Fuel Cell [3]

Unlike electricity produced by conventional heat cycles, the efficiency of energy production by primary fuel cells is not limited by a Carnot-type relation and thermal efficiences of 60% have been obtained in practice at useful power levels.

The fuel cell continues to supply current as long as reactants are fed in and products are removed. Recharging is accomplished by refilling the fuel and oxidant storage tanks while the cell is running, if necessary.

The total electrically available energy stored in hydrogen and oxygen is about 1650 watts-hr/lb of reactants, much more than the 200 watts-hr/lb of active materials in high-energy primary cells such as the silver-zinc oxide cell. Even with the allowance for weight of fuel cells and storage tanks, fuel cell systems using hydrogen and oxygen still give more watt-hours per pound than the best available alternatives for certain space applications.

The weight of a battery for a given duty is proportional to the product of power required and the duration of the required power. For a given power rate, a doubling of mission time requires a doubling of battery weight. Fuel cell systems, however, have two parts: a fixed weight of energy converter and a variable weight of energy storage. A fuel cell has to be big enough to supply the required power, but extra weight for increased time involves only the extra weight of reactants and tanks. Thus, fuel-cell systems are favored over batteries for missions of a few weeks duration. On the other hand, solar cell battery systems and nuclear energy supplies require a large initial weight for a given power, but need little extra weight for increased mission time. They are favored for even longer mission times. Depending on the size of the power unit, it has been estimated that fuel-cell systems offer the least weight configuration for flights of less than 6 hours to as long as 3 months.

-- Gemini ion-exchange system [3]

The Gemini on-board power system is based on a fuel cell that contains an ion-exchange membrane (see Figure 2.13). Water formed at the cathode is removed by wicks. Since the membrane is a pseudo-solid, the porosity of the membrane need not be closely controlled. Also, the fuel-cell sandwich can be made quite thin and light weight.

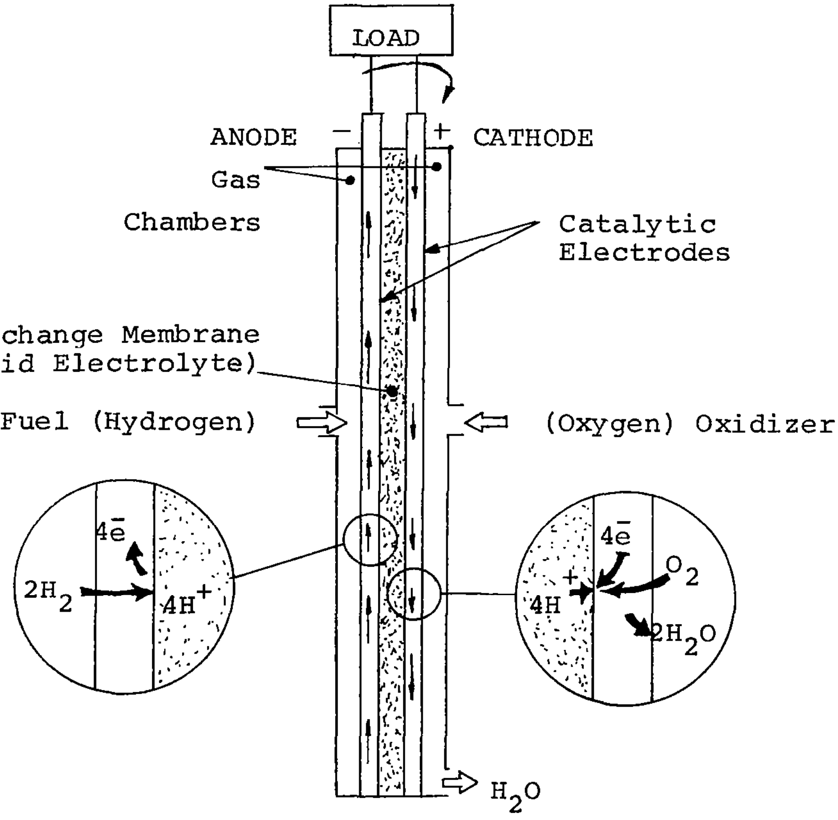


Figure 2.13 Pseudo-Solid Electrolyte Fuel Cell[3]

More than 30 cells are connected in series to form a stack with an output of about 28 volts. Three stacks in parallel form a section in a canister (see Figure 2.14). For more or less power the number of sections or stacks in parallel can be changed accordingly. Hydrogen and oxygen are stored as super-critical fluids, thus minimizing flow problems in zero gravity. They are preheated before entering the fuel-cell sections.

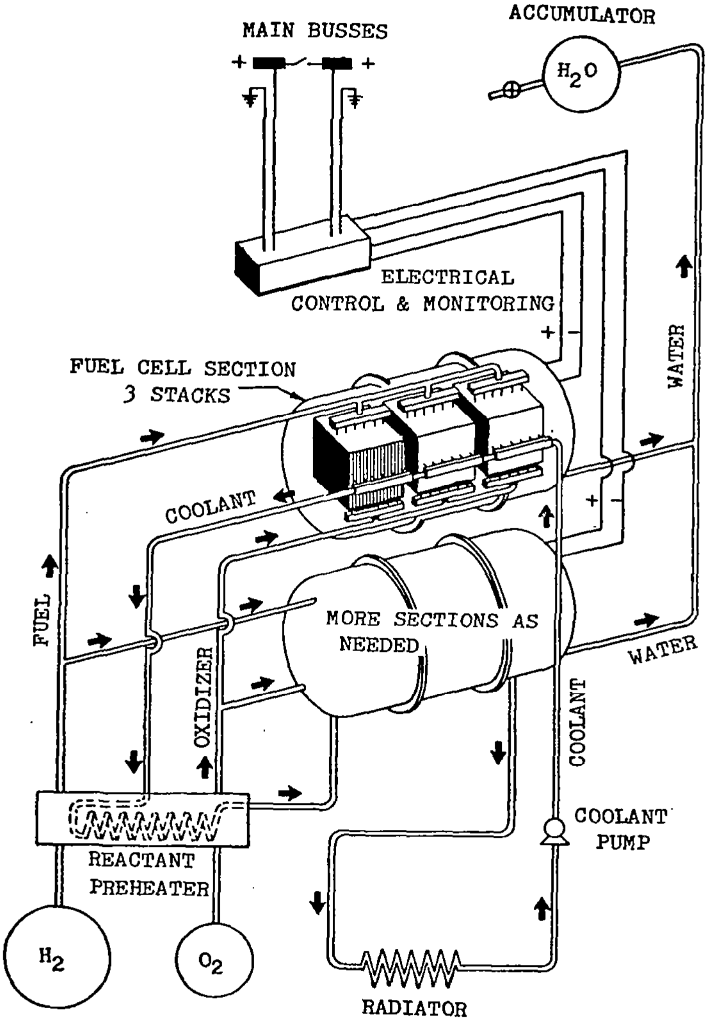
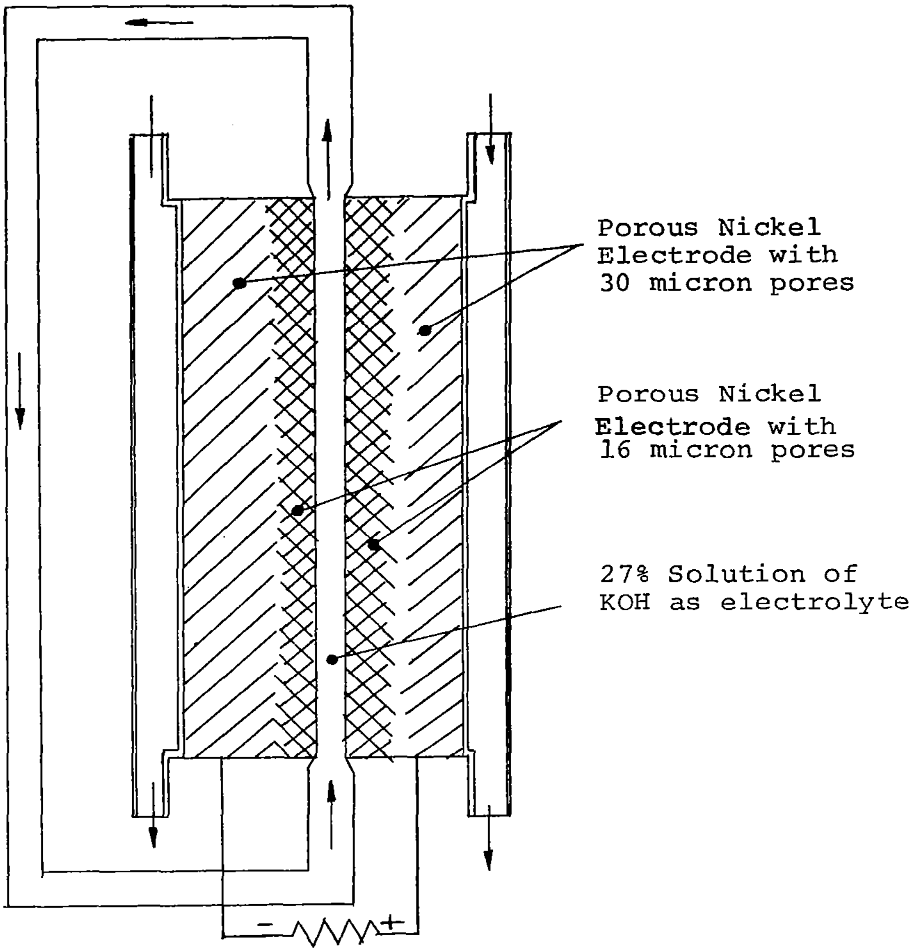


Figure 2.14 Gemini Fuel Battery (simplified schematic)[3]

Since neither reactant can be 100% pure, impurities accumulate in the stacks during use. To remove them, the gases are vented or purged as needed. Temperature is controlled by a liquid coolant that flows through tubes in each cell. An electronic monitoring and control unit activates valves to regulate gas and coolant supplied. Since the gases are not recirculated and water is removed passively (by wicks), parasitic power demand is low.

-- Apollo System [3, 11]

The Apollo fuel-cell system is a modification of the Bacon fuel cell. It operates with concentrated KOH and at a temperature above 400°F. Since the electrolyte is not immobile, care must be taken to avoid flooding the electrodes with free liquid. This problem is solved by using dual-porosity, sintered-nickel electrodes, the outer pores being relatively large and those in contact with the electrolyte being narrow (see Figure 2.15).



Hydrogen Electrode Reaction	Net Cell Reaction	Oxygen Electrode Reaction
$H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$	$O_2 + 2H_2 \rightarrow 2H_2O$	$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$

Figure 2.15 Bacon Type Fuel Cell[12]

The modified Bacon cell was developed by Pratt and Whitney Aircraft for the Apollo project. It has the highest efficiency of any known hydrogen-oxygen space-tested fuel cell.

One disadvantage of the design as it stands now is that parasitic power consumption is quite high, resulting partly from the fact that hydrogen must be recirculated to remove the water that is produced. This exit gas mixture is cooled externally to the cell stack, to condense the water and then separate it from the hydrogen gas in a centrifuge. Work is under way to reduce the parasitic power needs. The water from these power plants have been free from bacterial growth and is usable for human consumption.

The Apollo system operates around 400° to 500°F. To do so at 3 or 4 atmospheres pressure requires about 80% KOH, which is a solid at room temperature. Hence one of the problems is start up and shut-down of modules. This must be done with great care and is time-consuming. There is also the danger of mechanical failure due to the unavoidable phase change. Another problem is a result of operation in the vicinity of 500°F. The cathode corrodes with resultant nickel ion transport to the anode and dendrite growth, ending with electrical shorts in cells. These reactions, however, can be impeded and the life of a system prolonged.

Table 2.1 summarizes the performance of the Pratt & Whitney fuel cell system for the Apollo project. Three of these power plants, which are fully automatic, supply all the electricity for life support, guidance, and communication, and provide drinking water for a two-week lunar mission.

Table 2.1

Apollo Fuel Cell System
Pratt & Whitney PC 3A-2 Powerplant[11]

1)	Watt-hrs/lb reactants	1220 (at 1420 watts)
2)	Power	563-1420 watts
3)	Maximum Power	2295 watts at 20.5V
4)	Voltage	27-31V
5)	Number of Cells	31
6)	Duration	400 hours
7)	Nominal temperature	400°F (204°C)
8)	Heat & Water removal	hydrogen circulation
9)	Cell Pressure	50 psia
10)	Reactant gas pressure	10 psi above cell pressure
11)	Weight	220 lbs

-- Capillary (Asbestos) System[3]

Capillary systems based upon the "static water vapor pressure method" of removing water may be thought of as second-generation space fuel-cell power systems, and are being developed by several companies.

In these systems asbestos is used as an electrolyte retainer. The combination of asbestos and KOH electrolyte, like an ion exchange membrane, obviates the need for closely controlled pore sizes to avoid flooding or drowning the pores with electrolyte.

A simple but clever system was devised by Allis-Chalmers for passive or static moisture removal (see Figure 2.16)

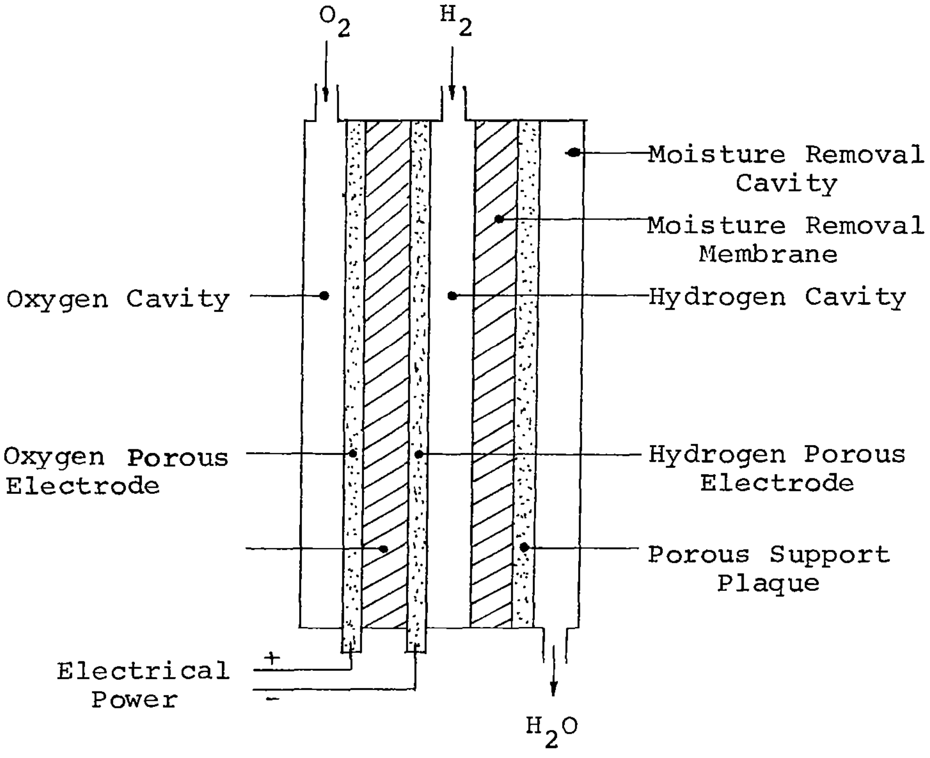


Figure 2.16 Fuel Cell Construction Using Static Moisture Removal System 3

In this system, a second asbestos membrane is located in the hydrogen gas space. As the vapor pressure of water increases in the electrolyte membrane, water evaporates to this separator membrane, which contains more concentrated KOH solution. It, in turn, gives off water vapor to a cavity that is kept at a partial vacuum. The water can be evacuated to space, as in the Gemini fuel-cell, or condensed and collected as in the Apollo fuel-cell.

Provision has been made for sampling the water, either by a test for pH factor or by conductivity, to determine whether to transfer it from the small collector to a reservoir or to dispose of it. Thus far, the pH has been 9-10 which may be too high for drinking. However, this pH can be lowered by passing the water through an ion-exchange bed for final cleaning in order to obtain potable fuel-cell water.

The asbestos fuel-cell system represents a compromise between the convenience of room-temperature and the cell efficiency of higher temperature operation. Thus far, the only noticeable material problem is the slow deterioration of asbestos. The system does not need an auxiliary heat source for starting, and its overall efficiency equals or exceeds that of the modified Bacon cell. As might be hoped for in a second-generation system, it is more convenient to operate, appears to be more flexible for a wider range of applications, and it is less prone to be permanently damaged or wrecked by a number of possible malfunctions or conceivable misuses. Present modules consist of 33 pairs of cells, each pair having a common water-removal chamber. The operating temperature range is 194-212°F.

2.5 Recommendations for University Research

- Investigate new materials for ion-conductive solid electrolyte to replace liquid electrolytes. Possibly, the electrolyte would be in a single crystal form. Some of the advantages of this discovery would be as follows:[13]
  - avoid polarization problems by eliminating depletion or buildup of ions at the electrodes.
  - increase shelf life by eliminating loss of active ingredients in electrolyte, i.e., drying-up.
- Techniques are needed for non-destructive, accelerated, and predictive testing of batteries.[13]
- The application of cryptoanalytical devices and techniques to battery test data in order to determine an analytical battery model against which actual batteries may be compared.[13]
- It would be very useful to know the state of charge of a battery, but no satisfactory method of measurement is available for this purpose (except in the special case of the fully charged condition). No simple, measurable parameters have been found yet that correlate with the state of charge independent of temperature, charge-discharge rate, and use history.[7]

- The need continues for a scheme to optimize charge control so that charge currents can be reduced proportionally as the battery approaches full charge.[15] The criteria governing charge current, with consideration for long cell life, should be the prevention of gas pressure buildup.
- Produce non-gassing batteries by identifying metals or alloys that have high hydrogen overpotentials for use as battery elements. A large distinctive overpotential would simplify the detection of a fully charged state so that charging can be terminated before hydrogen gas formation can start.[13]
- Batteries vary in heat dissipation over their charge-discharge cycle, depending upon the state of charge. As yet no fully adequate method exists for predicting heat-evolution rates as a function of time. This information is important in the determination of thermal control design concepts for spacecraft.[4]
- Sterilization of all spacecraft components is required to avoid contaminating planetary bodies (other than the moon) with living organisms from the Earth. The established method so far for sterilization is to heat-cycle the assembled battery source for three cycles to 135°C (275°F) for a total of 200 hours.[3] As a consequence of this procedure electrodes, separators, and case materials degenerate or degrade in form and service.

What are needed then are new battery components that can survive sterilization and still meet specifications.

- Among the affected battery components to suffer from a sterilization test, the separator probably suffers the most of all. Research tests to date indicate that a polyethylene-based material serves well as a heat-sterilizable separator. What is needed still is a modification of this new separator that will also stop silver-oxide diffusion.[14]
- The most advanced fuel cell system to date is the capillary-asbestos system. Still the performance of this system is limited by the slow deterioration of asbestos. What is needed here is a fiber material to replace asbestos as an electrolyte retainer. Operating temperatures up to 150°C are desired for higher cell efficiency. (Asbestos is reactive in KOH at temperatures over 100°C.)[13]
- In order for fuel cells to become competitive with solar and nuclear systems on a pounds-per-kilowatt basis for missions of more than 90 days, non-cryogenic reactants are needed. The reactant must be easily reduced to hydrogen and oxygen, which then supply a conventional H_2O_2 cell. This new reactant should yield easily to remove by-products and should not cause electrode deterioration or further add to general system complexity.

A typical reactant pair now under consideration is aerrozine (a 50-50 mixture of hydrazine and UDMH) and nitrogen tetroxide (N_2O_4).[15]

III. SOLAR POWER SYSTEMS[8, 16]

Silicon (Si) solar cell power systems have been developed into a high state of reliability. In conjunction with batteries they have served as the primary power source for all unmanned orbital and interplanetary missions. The silicon solar cell has remained unchallenged for unmanned space craft service because of several significant advancements in solar cell technology[8]:

1. Improved resistance to radiation damage and higher cell efficiencies as the result of shifting to N/P cells from the earlier P/N cells. Recent data indicate a drop in efficiency of approximately 30 percent over a 5 year period.
2. Improved manufacturing procedures.
3. Improved inorganic adhesives for securing protective cover glasses to the cells.

Other types of cells, considered to have certain advantages over silicon cells, such as cadmium telluride (CdTe) and gallium arsenide (GaAs) are currently in various stages of experimentation. Cadmium sulfide (CdS), until recently, was thought to be a likely material to challenge the exclusive use of silicon. However, CdS thin-film cells have not lived up to expectations and have since been dropped from further consideration.

A relatively recent development in solar cells has been the lithium-diffused radiation-resistant silicon cell. Work on this originated in 1962 and the properties and possibilities of the lithium cells are still receiving some attention.

Despite all the claims, in the final analysis the factors that will determine which type cell will be best suited for space applications will be efficiency and usable life-time. Important is the efficiency of energy conversion, more so than cell cost per watt, since maximum efficiency implies minimum system weight and size for a given power requirement.

There has been much recent technological effort aimed at resolving the problems associated with the packaging and deployment of large solar arrays and towards weight reduction. Solar cell arrays from the start of the space program to the present have improved from 5 watts/lb of array to approximately 10 watts/lb for arrays now in orbit. Power capabilities in the order of 30-35 watts/lb for roll-up arrays are now under development, and 40 watts/lb for folded panels with flexible substrates are predicted.

3.1 Solar Cell Systems[17, 18]

Solar cells are photovoltaic solar energy converters, generally semiconductor devices of the diffused junction type. They are small (1 cm x 2 cm usually) and are characterized by relatively low output voltages, and low short current capability. As a result it is necessary to combine thousands of cells to meet the various power requirements needed in space vehicle application. Since the voltage produced by a single solar cell is low, several cells must be connected in series to obtain the desired voltage. Such a connection, called a "string" is connected in parallel with several other strings to obtain the required power.

Batteries are used to provide the necessary operating power when incident solar energy is absent. The solar cell must provide sufficient voltage to assure charging rates compatible with system requirements. Figure 3.1 below gives a block diagram of a typical solar cell system with battery pack.

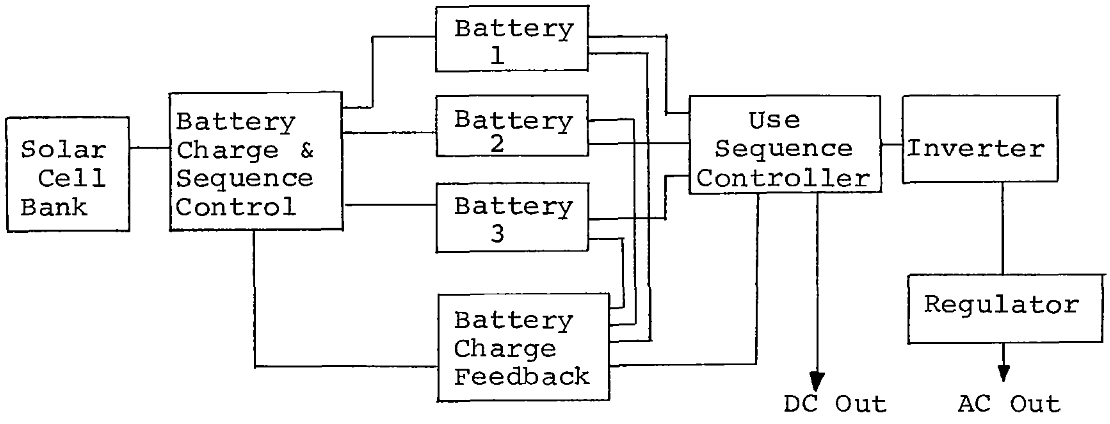


Figure 3.1 Solar Cell System with Battery Pack [18]

The advantages and disadvantages of solar cells are summarized in Table 3.1 below:

Table 3.1 Solar Cell Characteristics[18]

Advantages	Disadvantages
1. Cells light in weight, simple and reliable	1. May require temperature control, power change, - 0.6%/° C (-10 to + 170°C)
2. Cells have long useful life expectancy (up to 5 years)	2. Collectors require fixed load or operate at constant voltage when charging batteries
3. Direct solar energy to electrical power--no moving parts or heat cycle	3. Conversion efficiency-function of illumination level
4. Low cell impedance	4. Cells in series should be matched for current; in parallel matched for voltage
5. Adaptive to high density connection*	5. Heat must be dissipated to space
6. Efficiency improved by lead wire connection pattern (i.e., grid pattern)	6. Humidity sensitive, must be encapsulated
7. Low transient response time (10 usec rise - 20 usec decay)	7. Degradation due to radiation
8. Current varies linearly with light intensity	8. Systems relatively high in cost, $50-$500/watt
9. Performance relatively independent of pressure	

* See Figure 3.3

At present, solar cell systems are the only secondary power systems which can be considered proven flight hardware. Improvement of efficiency, refinement of temperature control, enhancement of radiation resistance, and development of techniques for producing large area, more flexible cells, will make them sufficiently competitive to occupy a portion of the space power spectrum (50 Kw max.) for some time.

Presently, almost all the solar cells sold each year are made of single-crystal silicon (Si). Substantial R & D effort has been applied to other crystalline materials as well, such as cadmium sulfide (CdS) and gallium arsenide (GaAs). Indium phosphide (InP), cadmium telluride (CdTe), and gallium phosphide (GaP) have also been investigated for solar cell use but with less effort. Conversion efficiencies for the materials considered to be important are shown in Table 3.2 below.

Table 3.2 Efficiencies of Some Solar Cell Materials[17]

Material	Theoretical Efficiency %	Max. Sunlight Efficiency %
Si	22	14
InP	24	3
GaAs	26	11
CdTe	23	6
GaP	19	1
CdS	18	8

The numbers in the above table have not changed very much over the past 10 years, and only small improvements can be expected here. However, major improvements can be expected in other areas such as weight, cost and reliability.

It can be seen from the table above that silicon and gallium arsenide (GaAs) have given the most promising results to date. Silicon of course is the material exclusively used for commercial solar cells and its characteristics will be discussed in the next section. While the present results with GaAs represent many years of effort, improvement in efficiency and reduction in cost is still necessary before the position of silicon for solar cells is challenged. However, for high-temperature operation (Venus or Mercury satellites and solar probes) and for high radiation areas,GaAs cells will be preferred over silicon cells. Because of the high cost of gallium and the difficulty in making GaAs crystals, such solar cells will probably always be more expensive than silicon cells.

3.2 Status of Silicon Solar Cells

Silicon solar cells are made in large quantities with sunlight efficiencies of better than 13 percent when measured under one atmosphere or air mass 1 (AM1) conditions. Under air mass zero conditions (AM0), meaning a vacuum, efficiencies of better than 11 percent have been obtained. At 25°C, single cells with a base resistivity of 1 to 2 ohm-cm typically yield an open-circuit voltage of 0.58 volts, a short circuit current of 27-33 ma/cm^2 at AM1 and 32-40 ma/cm^2 at AM0. The voltage and maximum power output in such cells degrade with temperature at the rate of 2.3 mv/°C respectively.[17]

The great majority of silicon solar cells made today are 2 x 2 cm in area and about 16 mils thick (this does not include the glass cover). It now appears that the 2 x 6 cm cell is achieving acceptance due to savings realized by its larger size. The front layer of the cell is usually n-type silicon, with the base material being p-type; this is the so-called n-on-p radiation resistant silicon cell.[16]

In order to perform efficiently in space power supplies, solar cells require glass coverslips. One reason for this is to protect the cell against radiation damage. Another reason is to increase the infrared emissivity of the cell in order to lower its operating temperature in space (see Figure 3.2). Solar cells with integral SiO_2 coverslips have been fabricated by a number of techniques. One of the latest and most promising is a process called high vacuum sputtering. Details of this proprietary process and test results are given in detail in reference 20.

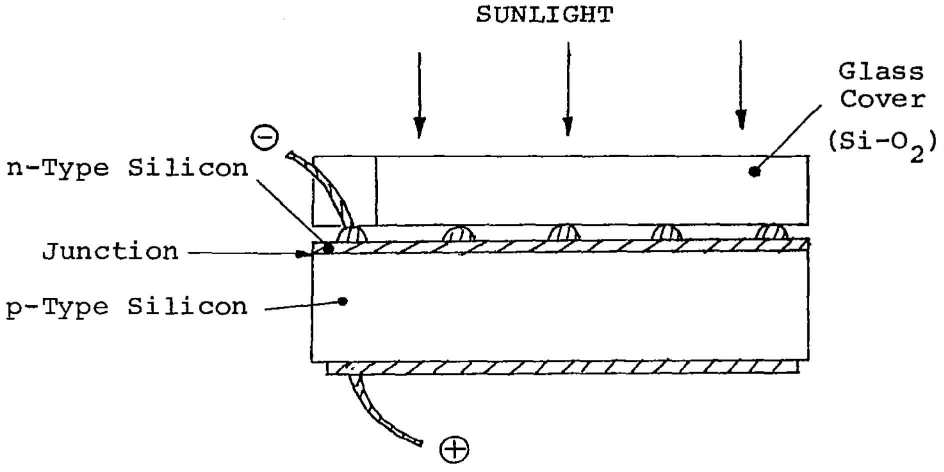
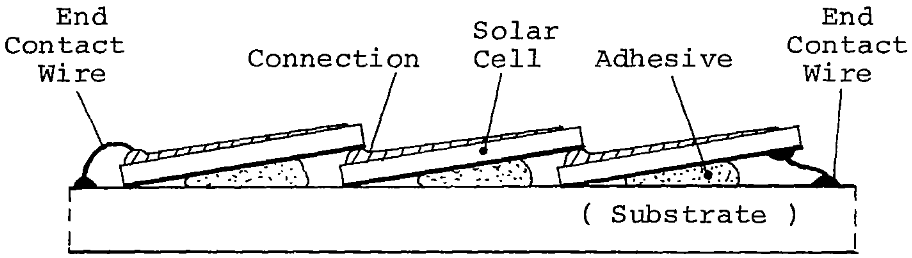


Figure 3.2 Cross Section of Silicon Solar Cell [19]

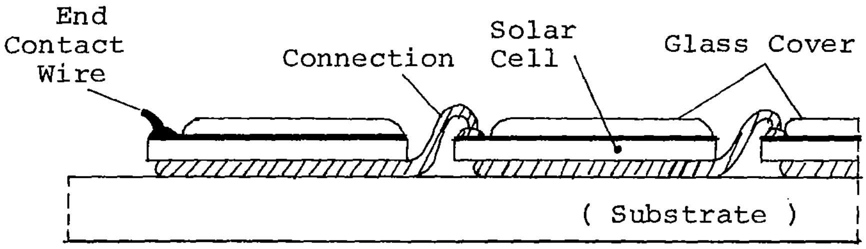
Silicon cells can be made as thin as 5 or 6 mils (thousands-of-an-inch). These thin cells have an advantage in terms of weight, increased radiation resistance, and a disadvantage in terms of a slight loss in efficiency (related to a drop in short-circuit current), and susceptibility to breakage.

An optimum cell thickness may be about 10 to 12 mils.[17]

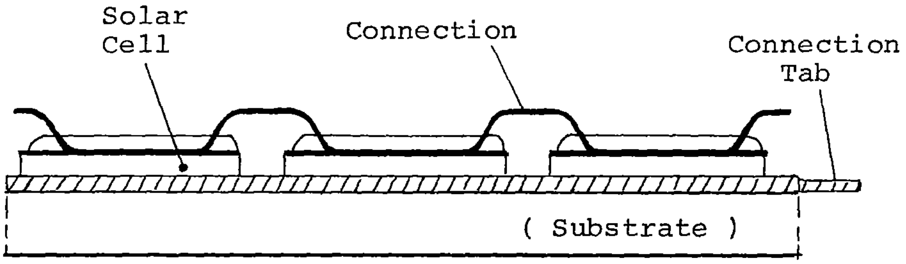
Although the sintered contact seems to be the most reliable to date, the problem of contacts to solar cells is still one of the most difficult to solve. Techniques for connecting cells in series and in parallel as well as in series-parallel are well in hand, using either shingling or flat lay-down methods with the latter applied in the majority of the systems (see Figure 3.3).[20]



a) Shingle Mounting



b) Flat Series Mounting



c) Flat Parallel Mounting

Figure 3.3 Solar Cell Interconnection and Mounting[21]

3.3 Large-Area Film-Type Cells

Two urgent requirements of future solar cells are lower cost and lighter weight. The present cost of silicon cells, in the $60 to $100 per watt range, makes their extensive use for large power solar arrays (up to 50 Kw) and for non-government terrestrial application unreasonable. The chief reason for the high cost is the need for single-crystal material in the cells. To meet this problem non-single-crystal films or "polycrystalline" materials such as CdTe and CdS have been developed. These thin film materials are much more imperfect than single crystals. They are formed either by evaporation or by chemical reaction on a substrate of plastic, aluminium (Al) or molydenum (Mo).[16,17]

Because of this construction technique film devices are basically light in weight thus making them more interesting for space applications. This light weight stems from the fact that only very thin layers are required for converting photon energy into electrical energy. Most of the 10 to 20 mils of silicon or gallium arsenide used in single crystal devices serve only as structural support.

-- Cadmium Telluride (CdTe)

The two main fundamental problems facing CdTe cells today are efficiency and stability. The efficiency of cells must be at least 5 percent before consideration of applications becomes possible, and 8 percent or more before it becomes probable.[16] So far, efficiency of 4.6 percent have been obtained for an area of 50 cm^2. This is still lower than the 9 percent which has been obtained with CdTe single crystals. The specific output power is typically 75 watts/lb. The temperature coefficient is rather large: efficiency increases 20 percent between 20° C and -8° C. Obtaining a good stability up to 80° C is still a problem. The stability under radiation, though little studied up to now, seems to be good. To summarize, by comparison with Si cells, present CdTe cells have[21]:

- An efficiency more than two times lower
- A specific power better by a factor of three
- A stability without or under irradiation that may not be regular, but is encouraging.

-- Cadmium Sulfide (CdS)

For CdS cells of 50 cm^2 area, efficiencies up to 6.9 percent on plastic substrates have been obtained (deteriorates to 4-5 percent in air). The efficiency is decreased as temperature increases, irreversibly over 150° C. For comparison, CdS cells have about the same properties (including physical structure) as CdTe cells, with a somewhat better efficiency and a stability which is nearly acceptable. The use of a Kapton plastic substrate and the preparation in one operation of cells as wide as 100 cm^2 are clearly important advantages of these cells, for which specific outputs of 90 watts/lb have been obtained (see Figure 3.4 and Table 3.3).

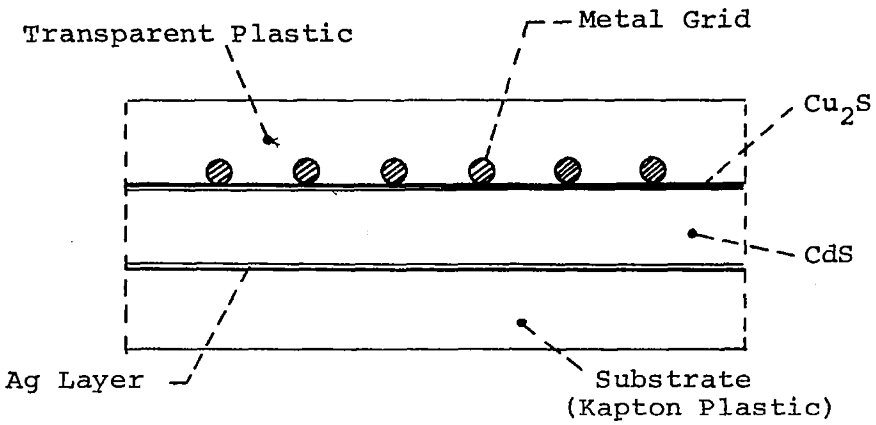


Figure 3.4 Cross Section of a Typical CdS Film Cell[19]

Table 3.3 Performance of Photocells[21]

Material	Efficiency (%)		Specific Power (w/lb)	Stability	
	Laboratory	Industry		without Irradiation	under Irradiation
Si Crystal	11-15	10-12	27	excellent	poor
CdTe Crystal	9				
CdTe Film	5		75	mean	good
CdS Crystal	9				
CdS Film	6-8	4-7	90	good	good

Unfortunately, cadmium sulfide thin film solar cells are subject to several intrinsic degradation mechanisms that gradually reduce their electrical output over long periods of time. So far only one of these mechanisms has been identified, the development of shorts by copper module formation when the cells are operated at open circuit voltage. This mechanism does not seem to apply when the cells are operated at maximum power or at even lower output voltages. Other failure modes are associated with cell construction. This is indicated by the steady increase in long term stability of these cells over the past few years by improvements in processing and process controls[22].

The present cost of manufacturing CdS cells is about $45 per watt. It is expected that the price of CdS cells will have to come down a good deal further to offset the extra cost of array structure and deployment mechanism needed for the larger CdS array, compared to a silicon array of equal generating capacity[16]. At this time indications are that this is not about to happen in the near future since government interest in developing CdS further has effectively come to an end.

3.4 Comparison of Thin Film and Si Photocells[19,21]

Up until 1970 CdS appeared to be the most advanced of the thin-film solar cells. What follows then are data based upon information collected up until early 1971.

Use of a plastic substrate has reduced cell weight to the vicinity of 0.06 lbs per ft^2 or about 1 ounce per ft^2. In comparison the thinnest state-of-the-art silicon solar-cell-cover-glass combination weighs about 0.17 lbs per ft^2, so that CdS cells are presently three times lighter than the lightest silicon cell. As a result, in spite of the low efficiency of the CdS cell, the weight per unit power of CdS is less than that for silicon.

Table 3.4 gives a summary of the technical characteristics of Si, CdTe, and CdS cells, with a tentative evaluation for the year 1970.

Table 3.4 Technical Characteristics of Si, CdTe and CdS[21] Plus a Tentative Evaluation for 1970

Material	Year	η (%)	Specific Weight** (lb/kW)	Specific Area (ft^2/kW)
Si	1964	12	133	108
	1967	12	110	108
single-crystal	1970*	(12)	(55)	(108)
CdTe	1964	3	--	--
	1967	5	20	258
thin-film	1970*	(6)	(16)	(215)
CdS	1964	4	--	--
	1967	6	13	215
thin-film	1970*	(7)	(11)	(183)
	1971	(further development abandoned)		

* Tentative evaluation based on 1967 data
** Including substrate

Table 3.4 does not take into account stability considerations or radiation effects. For CdS, stability could use further improvement. Consideration of radiation damage is important for Si but is expected to be less damaging to thin films.

From Table 3.4, the area-per-unit-power shows clearly the low efficiency of CdS relative to silicon; 215 ft^2/kW are required against 108 ft^2/kW for silicon (1967 data). Another interesting feature of CdS is the number of cells required to generate unit power. CdS requires 3400 cells to generate 1 kilowatt of power, while silicon requires 20,000 cells to generate the same amount. Consequently, the labor costs involved in assembling an array of CdS cells will be much less than the cost to assemble an array of silicon cells. Another advantage of the CdS film cell is flexibility. A cadmium sulfide film cell array can easily be rolled to occupy a very small volume.

Rollup array of up to 250 ft^2 have been built with thin-film CdS cells mounted on a fiber glass cloth substrate.

While CdS cells can be made as thin as 8 mils, difficulties in quality control during manufacture have kept production below 10,000 cells per year, as compared to 2,000,000 per year for Si. Also, efficiencies have tended to be only about half the 10 to 13 percent achieved by silicon cells in a space environment.[15]

From recent tests made at the MIT Lincoln Laboratory, it was concluded that the observed degradation in the current-voltage characteristics for CdS cells was caused by a combination of light and temperature and not by purely thermal stresses.

Recent satellite data taken from LES-5 and LES-6, satellites in synchronous orbit about the earth, show that experimental CdS cells (1 cmx 2 cm) degraded nearly 30 percent with respect to short-circuit current over a period of 400 days[22].

The primary remaining problem of CdS is that of stability. The major areas where stability is a problem are as follows[19]:

1) Storage degradation
2) Humidity damage
3) Thermal cycling failure
4) Ultraviolet light damage

Solutions to these problems have yet to be found.

While CdS cells are considered superior to silicon cells with respect to weight per unit area, their resistance to radiation damage and greater flexibility, silicon still has a higher conversion efficiency.

3.5 Radiation Damage to Solar Cells[17, 21]

Reliability is a most important factor in solar power supplies. Semiconductor devices in general are sensitive to radiation and solar cells are especially vulnerable because of their placement on the outer surface of any satellite. The radiation in space consists of electrons with energies from a few thousand electron volts (kev) to about 8 million electron volts (Mev), and protons from a few ev to well into the hundreds of Mev.

The effect of electron and proton bombardment from the Van Allen belts on silicon cells is now quite well known. It is characterized by an irreversible reduction of the electronic performance. The maximum output power of silicon solar cells decays with electron and proton radiation from a flat initial region (predictable by theory) to a region of inverse dependence on flux, 14 to 17% reduction per decade. This slope depends on the cell and the light source characteristics. N-on-P cells are 30 times better than p-on-n cells for electrons and 3 times better for protons.

Because of the nature of the damage it is possible to effectively increase "life" by adding to the area of the array. For example, a 17% increase in array area would increase "life" by a factor of 10; or the same power output would be achieved after intercepting ten times the particle flux.

3.6 Short Range Perspectives[17, 21]

The trend in silicon photocell technology is towards a decrease in the thickness and thus of weight. Some improvements of the substrate structures are still possible. Adequate structures for supporting these cells are not yet at hand.

In 1966, it was found that when a p-on-n silicon cell is made where the n-type dopant is Lithium that the output of a cell in a radiation environment can be very much higher than the best n-on-p cell (see Figure 3.5). Factors of 50 or 100 improvement have already been observed. Greater factors even to the point of complete resistance to space radiation are thought possible. However, radiation-resistant lithium-doped cells have been around for several years now, but so far no production qualified designs have been devised.

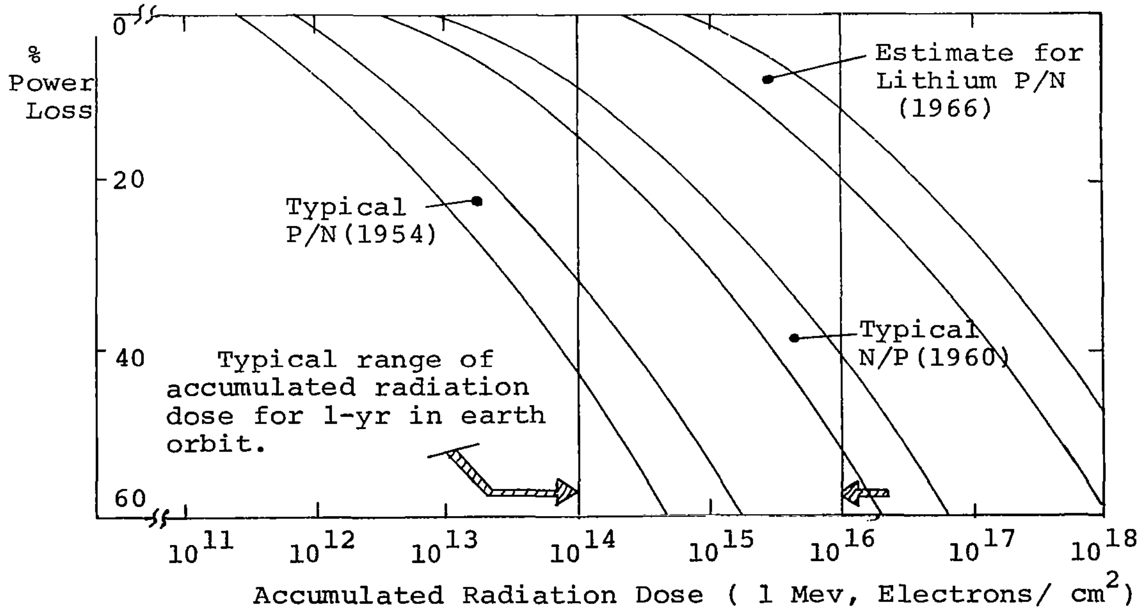


Figure 3.5 Percent Power Loss of Silicon Solar Cells Due to Radiation Damage[1]

The cost of thin film cells can be lowered a great deal in the case of mass production. A progressive but slow improvement of the efficiency can be expected. Films have been made on relatively flexible organic (Kapton) or metallic substrates with a resulting increase in power-to-weight ratios. This improvement over silicon cells is important for space applications. Thin films are two to three orders of magnitude more radiation resistant than their single crystal counterparts. It is conceivable that such devices in very large area films (10,000 ft^2) could supply power in the tens-of-kilowatt range and compete strongly on a cost, weight, and time available basis with a nuclear power system. The large areas in such a solar cell system would require some ingenious unfurling technique since it is not possible to be launched while open. Hopefully, the flexible cell would allow for a neat launch package.

3.7 Array Considerations[17]

The principal advantages of high-powered solar arrays are that no major development problems must be solved for the construction of such arrays, and the lifetime and reliability of solar arrays have been proved to be good. It is difficult to predict whether solar array systems will use single crystal or film type cells. Single crystal silicon cell arrays are being made lighter in weight, lower in cost, larger in area and more radiation resistant (e.g., the use of the lithium cell could save 90% of the shield weight). Such arrays would represent a moving target for the thin film cells and it will be difficult to catch up. For example, the Mariner solar cell system produced about 680 watts at about 9 watts/lb. Conceivably with improvements in the areas mentioned above, 30 to 50 watts/lb may be a possible goal. In comparison, thin film cells have already been made to yield over 100 watts/lb for the cell alone. However, the supporting structure, the electrical leads and other structural detail will increase the weight and it may be that a figure of about 50 watts/lb will be optimum for the film cell as well as the single crystal cell array. In any event, a factor of two improvement for film arrays over crystal arrays may be the most one can expect in power/weight ratio of large power systems. When one also considers efficiency and reliability, where the single Si crystal will excel, one can conclude that the major factor that will determine which type cell is used will be economics. The thin film CdS array will have to be substantially lower in cost than the silicon cell arrays if it is to be used in future large space power systems.

There are three basic designs of deployable solar arrays now being developed. They are: drum rollout, flat foldout, and flat rollout. A detailed review of these three basic designs and their characteristics can be found in reference 24.

The most advanced, but still earthbound, development exploiting lightweight solar cell technology is a rigid-panel array that uses beryllium structures and 8-mil cells plus 3-mil covers. The array weighs about 2000 lb and is designed to produce 50 kw. A large orbiting manned space station can use 50 kw or more of power but the array area, about 5000 ft^2, can cause sufficient drag at low earth orbit so as to compromise the life of the space station propulsion system.[15]

3.8 Recommendations for University Research

- The upper maximum theoretical efficiency limit for silicon (Si) is thought to be 24 percent. Currently Si cells have an efficiency of only 10 percent. The loss in efficiency is attributed in great part to impurities in the Si and damage due to present production techniques. What is needed then are new methods for growing high purity silicon in sheet form to the required thickness of approximately 5 mils.[13]

- A significant contribution to silicon cell development would be a new cell cover material that could accomplish the following functions simultaneously:[13]

  (a) be transparent to light

  (b) serve as the current collector thus eliminating the need for "fingers"

  (c) offer protection to radiation damage

  (d) increase emissivity of the cell to keep operating temperatures down

  (e) be anti-reflective coated

- Since the theoretical efficiency limit for Si is 24 percent, this places a definite upper bound on the usefulness of this type of device. For power levels greater than 50 kwe higher efficiencies and lower weight and costs are necessary. A promising alternate approach to solar conversion involves an entirely different category of materials, namely, organic compounds.[25, 26, 27]

The state-of-the-art of organic semiconductors is still in an early stage. Basically what is needed are organic compound systems that do not depend upon charge mobilities and conductivities, two parameters that help to set a limit on the theoretical efficiency of a single crystal structural material such as Si. So far, the actual mechanism of charge formation and transfer in organic semiconductors are still not well understood.[28] However, the major promise of organic systems is that they are not limited by theoretical efficiency and they could be produced in large quantities at a greatly reduced weight and cost.

- A qualitative investigation into the intrinsic degradation mechanisms that are responsible for the gradual reduced electrical output of Cadmium sulfide thin film cells over long periods of time (up to a few years).[7]
- The lithium-doped silicon cell has proved its ability to repair radiation damage, but the mechanism on which it relies is not fully understood.[7]
- Develop means of using available solar cell surface area more efficiently, possibly by the use of concentrators to increase the incident solar energy flux density.[29]

IV NUCLEAR SPACE POWER SYSTEMS

4.1 Introduction[30]

To date, spacecraft electrical power systems have been supplied primarily by batteries, fuel cells, and solar cells. The power levels have ranged from a few watts up to a few kilowatts (i.e., Apollo hydrogen-oxygen fuel cells).

For electrical power loads greater than a few kilowatts that will be required for missions lasting longer than a few weeks, only solar and nuclear systems can be realistically considered. Batteries and other chemical systems can be ruled out because of the large weights associated with these systems.

A graphical presentation of the power levels associated with the various power systems and the period of time over which the systems may operate was presented earlier in Chapter 1, Figure 1.4.

At power levels of the order of a few kilowatts,the various solar and nuclear radioisotope systems offer their own specific advantages and disadvantages. Generally speaking, the nuclear system excels over the solar system with regard to ruggedness, power per unit area, no collector deployment or orientation, continuous power, and minimum power storage requirements.

As power requirements are increased into the tens of kilowatts range, nuclear reactor systems have an increasingly favorable weight, size, and cost advantage over any of the presently envisioned solar power systems. So far, 50 kilowatts is probably an upper limit for solar systems.

For power levels in the hundreds of kilowatts and above a nuclear reactor system is the only one which appears feasible.

The Atomic Energy Commission (AEC) in 1956 recognized the future need for nuclear space power systems. To meet this need, the AEC initiated the System for Nuclear Auxiliary Power (SNAP) program to study the unique energy density advantage of nuclear sources. A primary goal of the SNAP program is to provide solutions to the problems of supplying nuclear power for the exploration of space.

In the following chapters the major nuclear space power systems presently under development in this country (under the sponsorship of the AEC and/or NASA) will be described. Little will be said about the fuel portion of nuclear space power systems since development in this area is under the firm control of the AEC. However, the development of energy conversion systems, under the direction of the AEC and/or NASA is reported here.

First, in section 4.2, the SNAP programs--past and present--will be summarized and a few highlights pointed out. Next, section 4.3 is an outline of future trends.

In the remaining chapters will follow a description of the three basic nuclear space power systems presently receiving the greatest attention, namely: Thermoelectric, Thermionic, and Turboelectric systems. The description of the Turboelectric system is based upon the Brayton and the Rankine energy conversion cycle.

4.2 Status of the SNAP Programs[30]

The SNAP program consists of two primary parts, a nuclear reactor system program and a nuclear radioisotope system program. The reactor systems are identified by even numbers and the radioisotope systems are designated by odd numbers.

-- SNAP Reactor Programs

Past SNAP reactor system development programs are summarized in Table 4.1 below, and the continuing technology programs are listed in the following Table 4.2.

Table 4.1 SNAP Reactor System Development Programs[30]

	SNAP 10A	SNAP 2	NASA SNAP 8	SPUR SNAP 50
POWER (kwe)	0.5	5	35 TO 50	350
REACTOR POWER (kwt)	30	55	600	2500
EFFICIENCY (%)	1.6	9	8	14
REACTOR OUTLET TEMPERATURE (°F)	1000	1200	1300	~2000
REACTOR	U-ZrH$_x$ THERMAL	U-ZrH$_x$ THERMAL	U-ZrH$_x$ THERMAL	UC FAST
PRIMARY COOLANT	NaK-78	NaK-78	NaK-78	LITHIUM
POWER CONVERSION	Ge-Si THERMOELECTRIC	Hg RANKINE	Hg RANKINE	K RANKINE
BOILING TEMPERATURE (°F)	–	930	1070	—
TURBINE INLET TEMPERATURE (°F)	–	1150	1250	1950
CONDENSING TEMPERATURE (°F)	–	600	700	1300 TO 1400
HOT JUNCTION TEMPERATURE (°F)	930	–	–	—
COLD JUNCTION TEMPERATURE (°F)	615	–	–	—
RADIATOR TEMPERATURE (°F)	615	600	580	1300 TO 1400
RADIATOR AREA (ft^2)	62.5	120	1800	700
(ft^2/kwe)	125	40	45	2
SYSTEM UNSHIELDED WEIGHT (lb)	650	1200	10,000	6000 (EST)
(lb/kwe)	1300	240	300	10 TO 20
AVAILABLE	1965		1972	
DEVELOPMENT AGENCY	AEC	AEC	AEC/NASA	AEC/AF
FLIGHT TEST AGENCY	AEC (AF)	*	*	*
SYSTEM CONTRACTOR	ATOMICS INTERNATIONAL	ATOMICS INTERNATIONAL	AEROJET GENERAL	PRATT AND WHITNEY
POWER CONVERSION CONTRACTOR	RADIO CORP OF AMERICA	THOMPSON RAMO WOOLDRIDGE	AEROJET GENERAL	AIRESEARCH
REACTOR CONTRACTOR	ATOMICS INTERNATIONAL	ATOMICS INTERNATIONAL	ATOMICS INTERNATIONAL	PRATT AND WHITNEY
FLIGHT TEST CONTRACTOR	LOCKHEED			
STATUS	COMPLETE	CANCELLED	CANCELLED	CANCELLED

*FLIGHT TEST PLANS CURRENTLY UNDEFINED

Table 4.2 Continuing SNAP Reactor Programs[30]

REACTOR TYPE	PROGRAM DESIGNATION	ELECTRICAL POWER RANGE	APPLICABLE POWER CONVERSION	REACTOR OUTLET TEMP	FUEL MATERIAL	FUEL CLAD MATERIAL	COOLANT
Zirconium Hydride Thermal		1-100 kwe	PbTe TE SiGe TE Organic Rankine Hg Rankine Brayton	1200°F	$(U-Zr)H_x$	Hastelloy N	NaK-78
Advanced High Temperature Fast	Liquid Metal Cooled	0.1-10Mwe	Potassium Rankine Brayton	~2000°F	UN	Refractory Alloy	Lithium
	Thermionic	0.1-10Mwe	Thermionic	3-4000°F	Open	Tungsten	Sodium, Lithium

Up until 1970, SNAP-8 was the only active reactor power system program. SNAP-8, a joint AEC/NASA program to develop a 35 kwe system, based on a Sodium-potassium (Nak) working fluid reactor and a mercury working fluid Rankine cycle power conversion system, was initiated in May 1960. The SNAP-8 system is designed to operate up to 5 years at thermoelectric and mercury-Rankine temperatures of 1000 to 1100°F. Recently, it was decided to modify the SNAP-8 system by replacing the Rankine cycle power conversion system with a Brayton cycle system instead (see Section 7.4).

So far only SNAP-10A, 500 watt system initiated in December 1960, has progressed through the complete developmental cycle from concept identification to flight demonstration in orbit, in the April of 1965 (see Section 5.4).

--SNAP Radioisotope Systems

The SNAP radioisotope system programs, past and present, are summarized in Table 4.3.

Designation	Application	Output (watts)	Design Life (yr)	Isotope Fuel	Status
SNAP-3A	Transit 4A Navigation Satellite	2.7	5	Pu^{238}	Launched June 1961. Operating at an undetermined lower power level
SNAP-3A	Transit 4B	2.7	5	Pu^{238}	Launched Nov. 1961. Shut down by power system failure in June 1962
SNAP-9A	Navigation Satellite	25	5	Pu^{238}	Launched Sept. 1963. Operating at an undisclosed lower power level.
SNAP-9A	Navigation Satellite	25	5	Pu^{238}	Launched April 1964. Burned up in reentry.
SNAP-11	Lunar Surface Use	25	0.3	Cm^{242}	Tested at ORNL in 1966.
SNAP-17A	Developmental	30	3-5	Sr^{90}	Work now limited to thermoelectric module testing, results to be applied to future SNAP generators.
SNAP-17B	Developmental	30	3-5	Sr^{90}	
SNAP-19	Nimbus-III Weather Satellite	25	1	Pu^{238}	Launched May 1969.
SNAP-27	Apollo Lunar Surface Exp. Pkg. (ALSEP)	63.5	1	Pu^{238}	Placed on lunar surface by Apollo 12 astronaut Nov. 1969. Two more have since been placed on the moon.
SNAP-29	Developmental	400	0.25	Po^{210}	Terminated
LRHS*	Manned Space Missions	5-10 kwe	5	Pu^{238}	2000° F heat source to be used with Brayton cycle power conversion. Capsule program completed.
Pioneer (F&G)	Jupiter Flyby	120	3	Pu^{238}	Four modified SNAP-19s, launch date 1972-73.
Viking	Mars Soft Landing	70	1	Pu^{238}	Two modified SNAP-19s, launch date 1975.

* Large radioisotope heat source

Table 4.3 SNAP Radioisotope Systems[30,31]

The SNAP-3 system using polonium (Po^{210}) and lead telluride (PbTe) was started in 1959, and achieved the first demonstration of an integral nuclear space power unit in 1960.

Modified SNAP-3A units fueled with Plutonium (Pu^{238}) were flown in June and November of 1961.

The larger 25 watt SNAP-9A development started in 1961, and three units were flown in navigation satellites in the 1963-1964 time period.

In 1968, two 25 watt SNAP-19 units were integrated into the Nimbus-III weather satellite. The first flight was aborted but a later flight was successfully flown in April 1969.

The first 50 watt SNAP-27 unit designed for lunar surface application was placed on the lunar surface in November 1969 by the Apollo Astronaut Alan Bean. To date, it continues to produce in excess of 70 watts of electrical power.

SNAP-29 incorporated a new thermoelectric element loading design and employed advanced thermoelectric elements called TAGS (tellurium, antimony-germanium-silver) in place of PbTe (see section 5.5).

Up until a few years ago before it was cancelled, the Manned Orbiting Research Laboratory (MORL) program specified a Large Radioisotope Heat Source (LRHS) for use with a Brayton cycle to provide 5 to 10 kw of electrical power. The LRHS Capsule Program has since been completed.

For the planned Pioneer and Viking programs, the SNAP-19 design that was flown on Nimbus-III, will be upgraded to include two new primary modifications. One is to include improved thermoelectric material for increased power output. The second modification is to include a higher temperature fuel capsule to enhance reentry and impact safety characteristics.

4.3 Future Space Power Trends[31]

The trends envisioned in future space activities will carry spacecraft farther from the earth, including operations on the planetary and lunar surfaces, and they will involve larger payloads with increased power requirements. These trends are ones in which the advantages of nuclear power will become increasingly valuable and, in fact, will be indispensable for a variety of missions. Table 4.4 lists some of the likely U.S. space activities anticipated in 1970.

Table 4.4 U.S. Space Program Trends[31]

1. Likely New Mission Trends of Early-to-Mid 1970's	Power System Requirements	Missions Selecting Nuclear Power
Automated Missions		
Planetary Probes	100's of watts-operation of several years, distant from sun	Pioneer Jupiter Flyby
Lunar & Planetary Landers	10's - 100's of watts	Viking Mars Lander
Military Satellites	10's - 100's of watts-long life;insensitive to radiation	Transit Navigational Satellite
Manned Missions		
Earth-Orbiting Space Station	10's of kilowatts- long life	Space Station (Reactor prime candidate)
2. Possible Longer Term Trends-Late 1970's & 1980's		
Increased payloads to planets Electric Propulsion Large Com-Sat	Spectrum of power levels thru the 100's of kw	
Lunar Base Space Base		Space Base (Reactor power specified)

Since 1969, two NASA missions have selected radioisotope thermoelectric generators as their sole power sources: the Pioneer missions of 1972 and 1973 to send scientific probes to the vicinity of Jupiter and the Viking automated Mars lander now scheduled for 1975.

Power supply requirements for space missions vary over a broad range of power levels and must meet widely differing spacecraft and mission environments. The nuclear space power program as it stands now, is attempting to provide the technology for a minimum number of systems which can serve as the building blocks to provide the power necessary to meet all the expected requirements. These building blocks, or categories, are listed in Table 4.5.

Category	System Characteristics	Potential Missions	FY 1971 Program Emphasis
0-100W	Radiosotope Thermoelectric Generator (RTG)	TRANSIT* PIONEER* VIKING*	Isotec Generator Development Modified SNAP-19 Modified SNAP-19
100-1000W	Modular Isotope & Thermoelectric Reusable Fuel or High Efficiency Power Conversion	Grand Tour LRV NIMBUS F&G	Multi-Hundred Watt Generator Development
1-10kw			
a. Recoverable Fuel	Modular, Reusable Isotope & High Efficiency Power Conversion	Satellite Experiments for Space Station/Base	High-Temperature Capsule Technology
b. Unrecoverable Fuel	Modular Low-Cost Isotope	DOD Applications	-----------
Unmanned	Partly Shielded Reactor	Comsats	
10-100 kw	Reactor - Thermoelectric 10-35kw Reactor-Dynamic 35-100kw	Space Station Space Base	ZrH Reactor & Compact Thermoelectrics
100kw & Above	Reactor-Thermionic or Reactor-Dynamic	Space Base Electric Propulsion	Thermionic Fuel Element

*Firm Commitments

Table 4.5 Categories of Nuclear Systems and Technology[31]

In the field of reactors for space power, work is aimed primarily at providing systems in both the 10's and 100's of kilowatt power categories. Presently the two most active reactor programs are the uranium-zirconium-hydride program and the thermionic program. The advanced liquid-metal-cooled reactor is also applicable to the higher power category, but there is only a very basic technology effort sponsored by NASA on this concept at this time. The current elements of the reactor power programs within both the AEC and NASA are depicted in Figure 4.1.

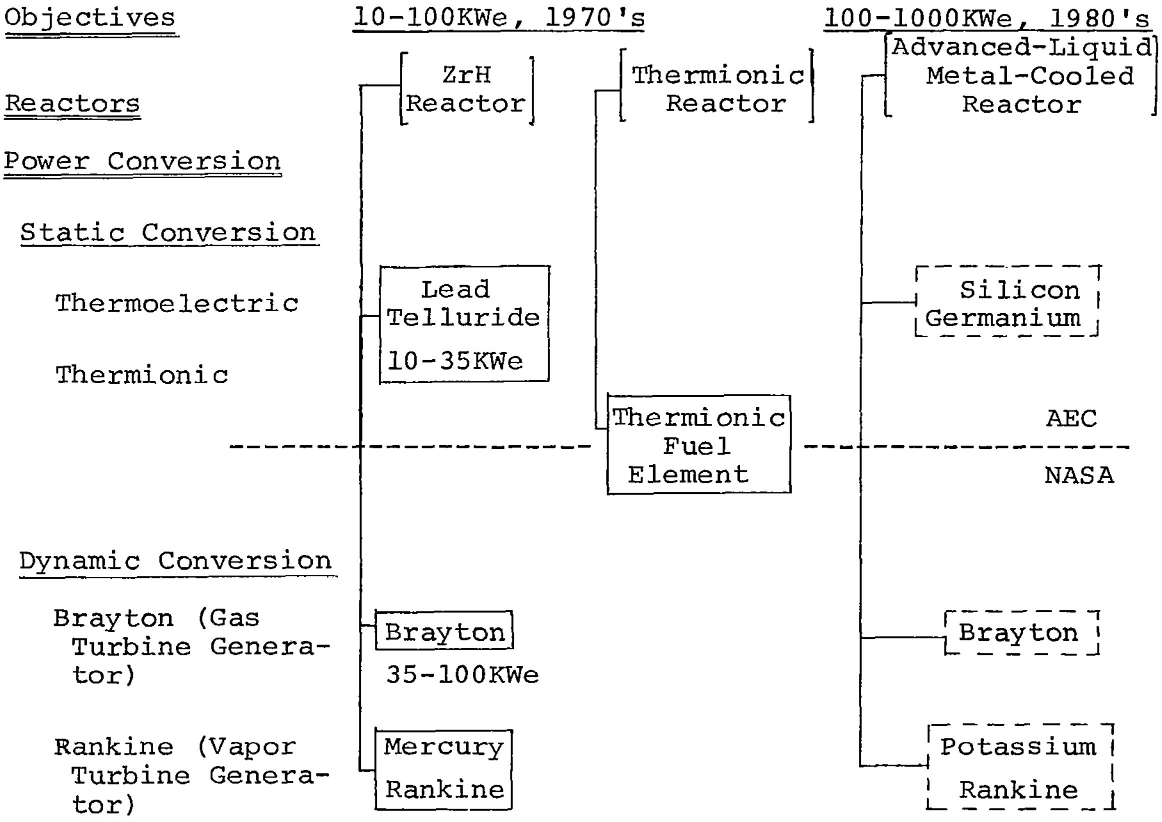


Figure 4.1 Reactor Space Power Program Elements[31]

V THERMOELECTRIC SYSTEMS

5.1 Thermoelectric Power Conversion[32,33]

The direct conversion of heat to electricity by means of the Seebeck (thermoelectric) effect offers advantages of continuous static operation over a long period of time and high reliability potential. However, the temperature limits and the conversion efficiency of current state-of-the-art converter materials limit the usefulness of thermoelectric conversion systems to relatively low power levels; a few kilowatts.

A basic limitation of the thermoelectric device is that it is a heat engine and as such, is limited by the second law of thermodynamics. The second law states that continuous conversion of heat into work by a device which receives heat from a source at a higher temperature T_H is possible only when part of the heat is rejected into a sink at low temperature T_L. Therefore, whenever conversion of energy takes place through the intermediary of heat, a cycle must be devised; the efficiency is lower than 100 percent, even without losses. The maximum attainable efficiency is called the Carnot efficiency, n_C:

$$n_C = \frac{T_H - T_L}{T_H} \tag{5-1}$$

The direct conversion of heat to electricity was first reported by Thomas Seebeck in 1821, when he observed a potential difference in a circuit of two dissimilar conductors when one part of the circuit was heated. It was not until over 100 years later, in the 1930's, before any practical significance was given this discovery because of the low efficiency of known materials. Up to this time the only use of the thermoelectric effect was in the measurement of temperatures by thermocouples. The development of semiconductors in the late 1950's changed this and consequently, many practical applications have resulted. One of the most useful applications has been the thermoelectric converter.

The basic elements of an ideal thermoelectric converter are illustrated in Figure 5.1 below.

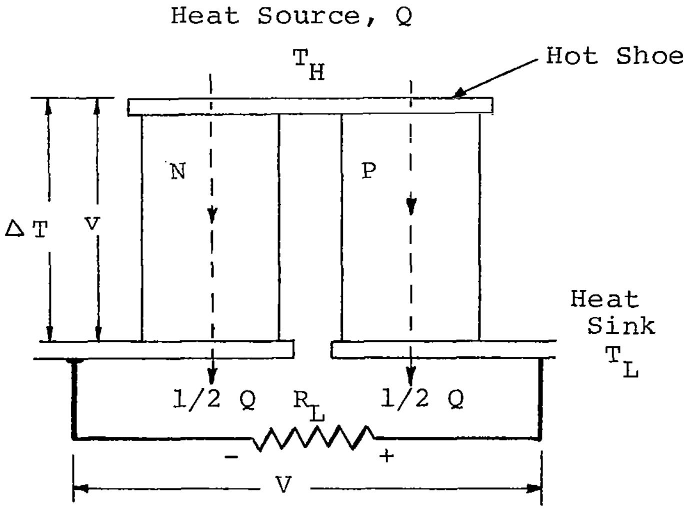


Figure 5.1 Ideal Thermocouple [33]

Heat flows from a source at a temperature T_H through two pieces of thermoelectric material to a sink at a lower temperature T_L. The resulting temperature difference across a thermoelectric material induces a voltage difference between the hot and cold ends, $v = S (T_H - T_L)$. S is the Seebeck coefficient in volts/°C.

The two pieces of thermoelectric material are called a couple and are doped N and P such that the Seebeck voltage across one piece is positive and the other is negative. This allows series electrical connection of the two thermoelectric elements in series to give an open circuit voltage of twice the Seebeck voltage, $V = 2S (T_H - T_L)$.

The efficiency of the thermoelectric element n_D to convert heat to electricity is a function of the thermoelectric material's figure of merit, Z. Both n_D and Z are defined below:

$$n_D = 1/4 \ (Z \ T_H) \qquad (5\text{-}2)$$

$$Z = \frac{S^2 \ \sigma}{k} \ ; \quad (1/^{\circ}C) \qquad (5\text{-}3)$$

where: S = Seebeck coefficient (volts/°C)
σ = electrical conductivity (1/ohm-cm)
k = thermal conductivity (watts/cm - °C)
T_H = source temperature (°C)

Thus, aside from temperature difference between junctions, the device efficiency n_D and in turn, the figure of merit Z, are functions of device material properties only. Notice, however, that the characteristics necessary for good operating performance, namely, low thermal conductivity k and high electrical conductivity σ (i.e., low resistance), are conflicting traits for most materials. Since all the primary properties of thermoelectric materials, in some manner are measures of the concentration and mobility of electron charge carriers, it can be seen from Figure 5.2 below why the major materials used today are semiconductors.

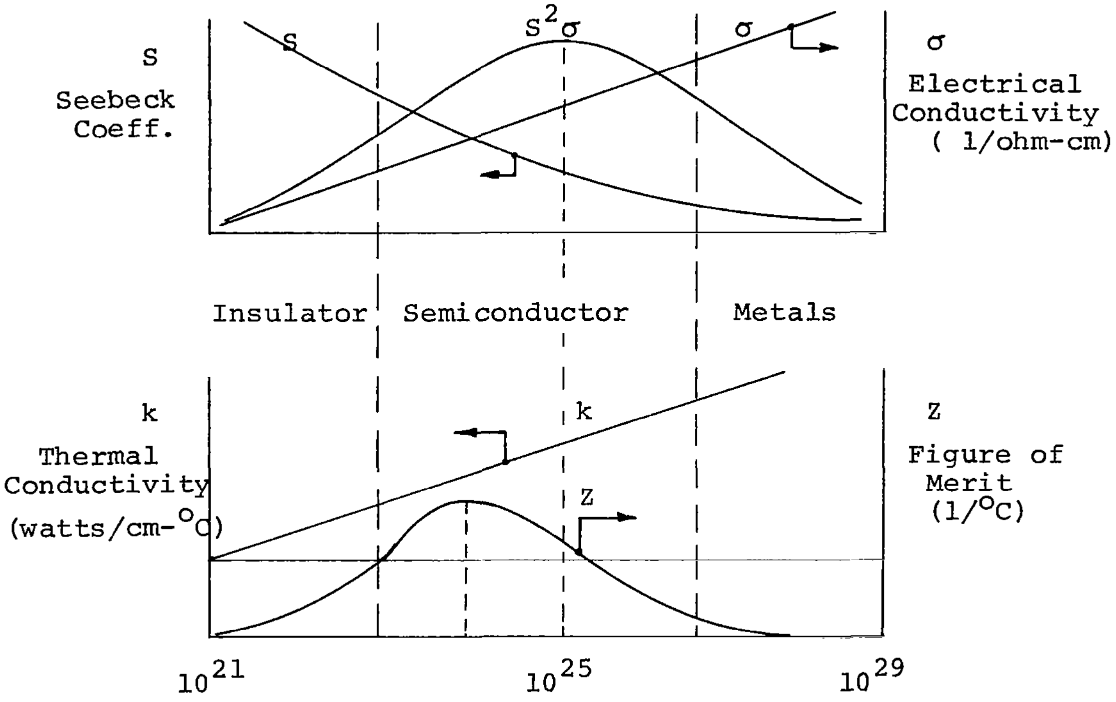


Figure 5.2 Dependence of factors entering into figure of merit on carrier concentration (logarithm scales).[32]

It is in semiconductors that the resistivity can be controlled by the addition of impurities so that it is not too large. Figure 5.3 to the right, shows the temperature dependence of metals, semiconductors and "doped" semiconductors. Of the three thermoelectric properties, thermal conductivity is the least amenable to theoretical prediction and experimental verification.

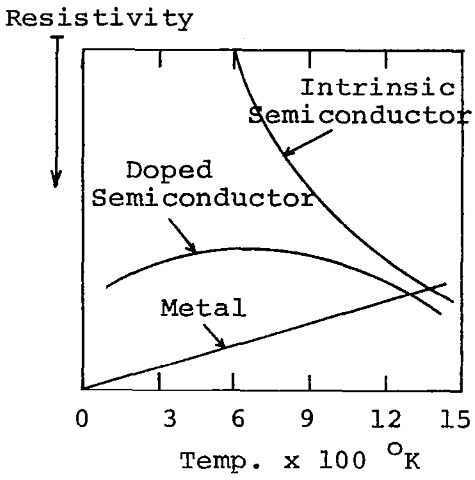


Figure 5.3 Temperature dependence for metals, semiconductors, and doped semiconductors.[32]

A thermoelectric material should possess a very low conductivity and Figure 5.4 to the right, illustrates again why semiconductors are preferred.

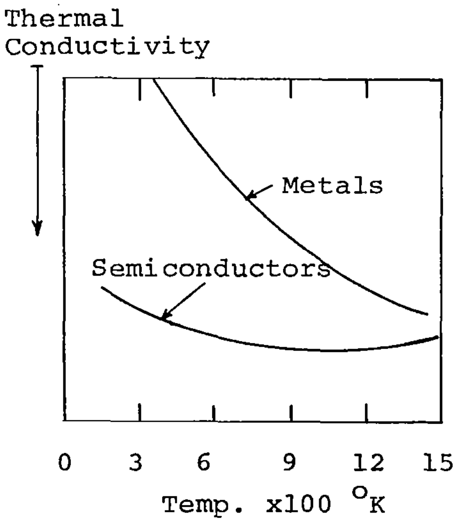


Figure 5.4 Temperature dependence of thermal conductivity.[32]

The thermoelectric generator's efficiency can be expressed by the product of the device efficiency n_D and the Carnot cycle efficiency n_C:

$$n = n_D \, n_C \qquad (5\text{-}4)$$

In large thermoelectric systems the influence of Z and temperature T_H on the radiator area and thus, system weight, is more important than the efficiency n. The reason for this is that if one assumes a constant device efficiency n_D, the power to the load per unit radiator area is proportional to the fourth power of the maximum hot temperature that the thermoelectric material can withstand as determined by metallurgical stability, sublimation, strength, etc. Power to the load per unit radiator area can be expressed as follows:

$$P/A \propto n_D \, T_H^{\,4} \qquad (5-5)$$

Therefore, variations in n_D can be readily overcome by the $T_H^{\,4}$ part of the dependence of P/A if the materials are capable of higher temperature operation.

5.2 Thermoelectric Materials [34]

Table 5.1 below, gives values of the thermoelectric parameters at room temperature for a number of semiconductors. The materials listed are chosen to illustrate the points made in the previous section. From Equation 5-2, stated earlier and repeated here, $n_D = 1/4\ (Z\ T_H)$, the efficiency of the thermoelectric element is dependent upon the product of the figure of merit Z and the maximum allowable temperature T_H. Thus, a maximum value for n_D for the materials listed in Table 5.1 means a value of unity or greater for the product $Z\ T_H$.

Table 5.1 Thermoelectric Properties of Semiconductors [34]

	Melting Point °C	Type	$S^2\sigma$ x10^{-5}	k w/cm-°C	Z max. x10^{-3}	T_H °C	ZT_H
Bi_2Te_3	575	n or p	4	.02	2	175	.35
Bi_2Te_2Se	-	n	3.6	.016	2.3	325	.75
PbTe	904	n or p	2.6	.023	1.2	625	.75
GeTe(+Bi)*	725	p	3.2	.022	1.6	625	1.0
GeSi **	-	n	3	.036	.9	925	.83
		p	2		.6		.56

* data temp. 525°C, ** data temp. 625°C, all others 25°C

All the materials listed in Table 5.1 are tellurides or selenides and have relatively low melting points and energy gaps. They are useful because of the low values of "k" associated with the fairly high atomic weight of tellurium and selenium. For operation above 600°C more refractory semiconductors - higher melting point, lower vapor pressure, higher energy gap - are necessary. So far germanium-silicon, Ge-Si, alloys are the best materials for use in the temperature range above 600°C and up to 900°C, thus the current interest in these materials.

The variation in the figure of merit Z with temperature for some of the best materials to date is shown in Figure 5.5 together with the locus for $ZT_H = 1$ and $ZT_H = 2$. It is clear that the higher the temperature at which a material can be operated, the lower is its maximum value of Z. Thus, the highest values of ZT_H so far obtained are only slightly greater than unity, whatever the hot-junction temperature.

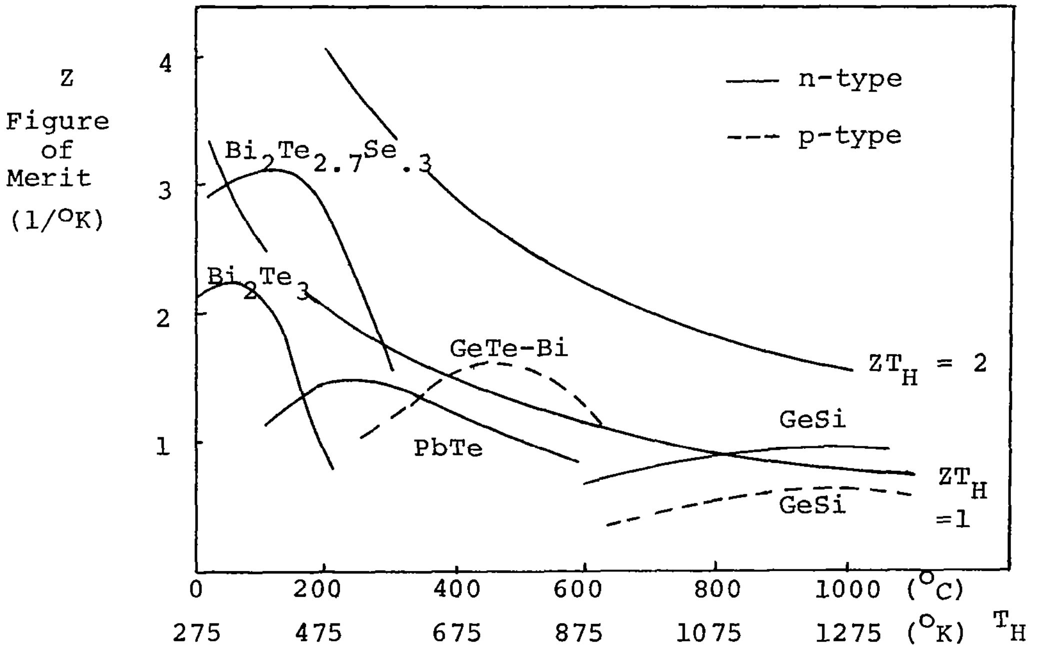


Figure 5.5 Figure-of-Merit Of Some Of The "Best" Materials[34]

Since Z and the product ZT_H does not appear to improve with temperature the use of GeSi in place of PbTe can be questioned. The explanation is that GeSi has a wider temperature range of application at a higher temperature level. A higher temperature level means an increase in net generator efficiency resulting from overall total materials efficiency. There also exists at the higher temperature levels the potential for greater stability than that presently experienced with PbTe.

To date, there appears to be no reason why a material should not exist in the intermediate temperature range of from 200 to 600°C and having the following characteristics: [34]

$$
\begin{aligned}
S^2\sigma &= 4\times10^{-5}\ (v^2/{}^\circ C^2\text{-ohm-cm}) \qquad (5\text{-}6)\\
k &= .013\ \ (\text{watt/cm-}{}^\circ C)\\
Z &= 3\times10^{-3}\ (1/{}^\circ C)\\
ZT_H &= 1.5
\end{aligned}
$$

While no such material has been discovered so far, the possibility exists. Such a material would have a marked effect on the range of application of thermoelectric generators, especially in increased interest in their use in-pile in nuclear reactors.

If higher-temperature operation is desirable--as is indicated by current development trends--an alternative to refractory materials might be to use high mean atomic weight compounds above their melting points. Although some of these compounds--so-called liquid semiconductors--become metallic in the liquid state, there remain some which do not. Those compounds that do not are yet to be thoroughly studied.

5.3 Thermoelectric Converters [33]

The design of a practical thermoelectric converter must provide the following:

1) The individual thermocouples must be electrically isolated to allow series connection for higher output voltages.
2) There must be minimal thermal impedance in series with the thermoelectric material since any loss of available temperature drop directly diminishes the converter efficiency.
3) All interconnection and contact junction resistance in series with the thermoelectric material must be minimal because of I^2R losses.
4) All shunt heat transfer from source to radiator must be minimal.

The physical and metallurgical properties of the thermoelectric material also have an influence on converter design and efficiency. For example:

1) The extraneous converter resistance is strongly influenced by the ability to make metallurgically stable electrical contacts of minimal resistance to the thermoelectrical material.
2) Any requirement for a coating or barrier on the thermoelectric material to suppress sublimating also provides a shunt path.
3) The physical strength of the thermoelectric material can determine structural or thermal stress limitations.

5.4 Reactor Thermoelectric Systems[1, 33]

As a result of practical engineering limitations, the only materials that have found use as space power supplies are PbTe, Pb-Sn-Te, and Si-Ge alloys. The basic PbTe material has a theoretical conversion efficiency of about 15% of Carnot and is limited to a peak hot-junction temperature of about 800°F (400°C) by sublimation. Through converter design the upper temperature limit can be extended somewhat by use of an encapsulant to suppress sublimation. The Si-Ge alloys have a lower conversion efficiency, about 10 to 15% of Carnot, but are not as limited in operating temperature.

Other practical engineering considerations such as thermal impedances and electrical contact resistance limit net efficiency of practical devices to about 10% of Carnot. This means that for present PbTe converters efficiencies of the order of 4 or 5 percent are typical.

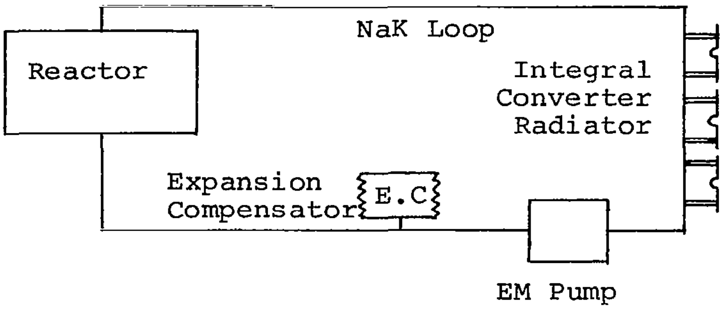
Although there is considerable research under way to improve these materials, the efficiencies will probably not increase above 6 percent. If two thermoelectric materials are segmented together so that maximum efficiency can be maintained over a wider temperature range, then a combined converter efficiency of perhaps 7 or 8 percent may be obtained.

Segmented thermoelectric elements containing Si-Ge for higher temperature use and PbTe for use in the lower temperature region are currently under study with promising results.

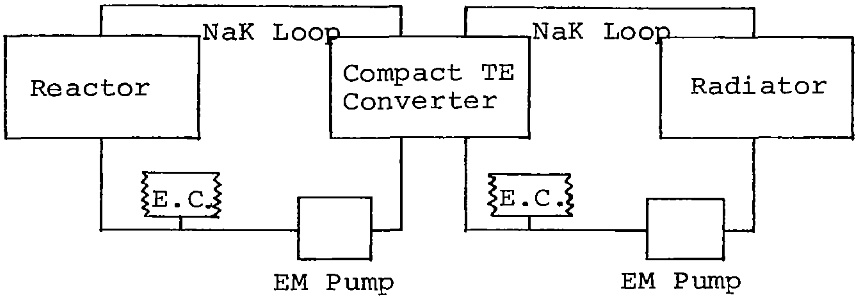
The desirability of such low efficient power conversion systems is due largely to the advantage of a system having no moving parts. This is practical because of the large energy content of a reactor heat source. Naturally, this inefficiency penalty is acceptable only for applications where the electrical power requirements are low. This is particularly true at this time since isotope materials are scarce and expensive to manufacture. Also, there is a point where further increase in physical size alone results in a greater percentage gain in weight than in power, and efficiency then becomes of greater concern.

The most appropriate thermoelectric system configurations are shown in Figure 5.6 below. The converter of Figure 5.6A is referred to as the direct radiating converter and employs a single liquid metal heat transfer loop for coupling to the reactor heat source. This configuration has already been successfully flown in space. It is the concept of SNAP 10A, a thermal reactor power supply, and it is described further in this section.

The converter of Figure 5.6B is referred to as a compact converter and requires two heat transfer loops: one coupled to the heat source and the second coupled to a remote radiator. The principle advantage of this approach is the vehicle design and integration flexibility afforded by the remote radiator.



A) Direct Radiating Converter System



B) Compact Converter System

Figure 5.6 Reactor-Thermoelectric System Schematics[35]

-- SNAP 10A[31,33,36]

SNAP 10A is the first reactor-powered electrical system to have been flight tested in earth orbit. It was designed to produce 500 electrical watts for a period of 1 year in a space environment. The SNAP 10A flight system was launched on April 3, 1965 and was operational for 43 days. On May 16 the system was shut down due to what is believed to be a malfunction in the command electronics.

By today's standards, the power level of the SNAP 10A is considered low for reactor thermoelectric systems. Thus the probability is reduced that this system will see future mission use.

However, the technology acquired from this flight will serve to develop larger systems.

SNAP 10A employs a Zirconium hydride (ZrH) thermal reactor coupled to an integral Ge-Si thermoelectric converter-radiator which converts NaK-transported fission heat to electrical power. Figure 5.7 below illustrates the construction of the thermoelectric module.

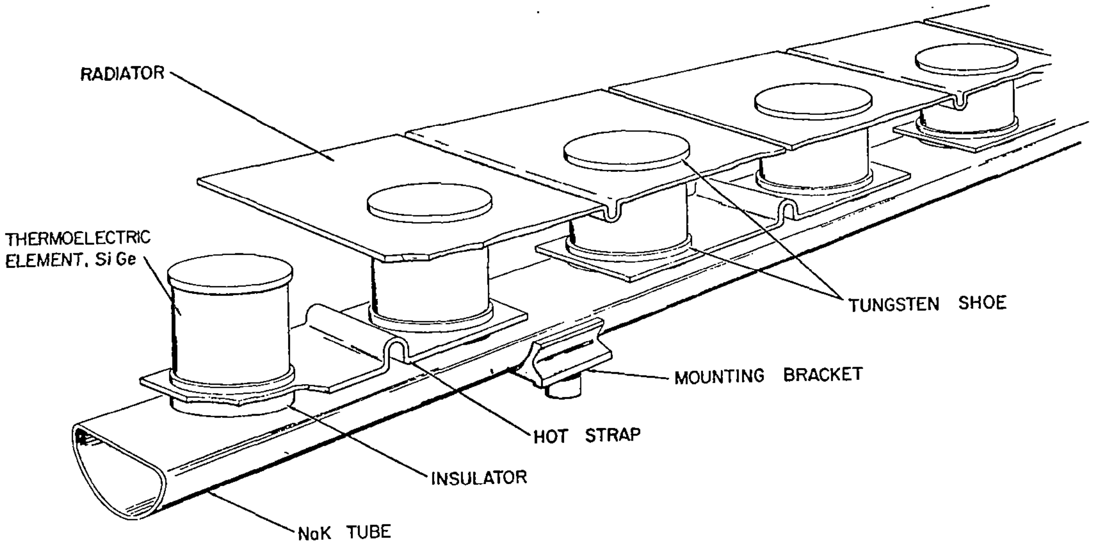


Figure 5.7 SNAP 10A Thermoelectric Converter Module[33]

The SNAP 10A system is nearly conical in configuration with a base diameter of 5 ft and an overall height of 11 ft. The system weighs approximately 950 lbs including shield weight.

The reactor core consists of 37 fuel elements of 1-1/4 inch diameter by 13 inch long located within a 9 inch diameter core vessel. Each fuel element consists of a mixture of uranium metal and ZrH. The NaK coolant flows axially through the core and passing between the fuel elements. The reactor control elements are four half-cylindrical reflector sections surrounding the cylindrical core vessel. Rotation of these sections changes proximity to the core and provides reactor control by leakage variation. The sketch below is a simplified layout of the reactor core.

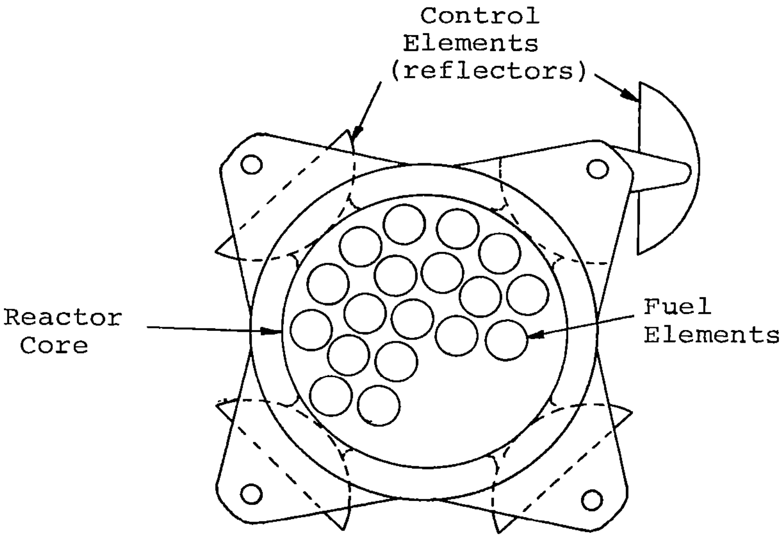


Figure 5.8 Simplified Sketch of Reactor Core[33]

Since the flight of SNAP-10A, the technology base for reactor thermoelectric systems has grown. Besides converters, extensive design, fabrication, and test experience has been accumulated on nuclear radiation shields, radiators and NaK components in general. More than 10,000 hours of successful endurance testing has been demonstrated on all key components. Most important SNAP-10A, as well as the SNAP-2 and -8 programs (see section 7.3), has provided a substantial familiarity with the liquid metal, NaK.

-- Compact Converter [35]

Beside the "direct-radiating" Ge-Si thermoelectric converters used in SNAP-10A, a PbTe "compact converter" has also been developed and tested. Figure 5.9 below shows a cross section of a typical compact converter tubular module.

● INNER DIAMETER (in.)	0.75
● OUTER DIAMETER (in.)	1.50
● ACTIVE LENGTH (in.)	15.07

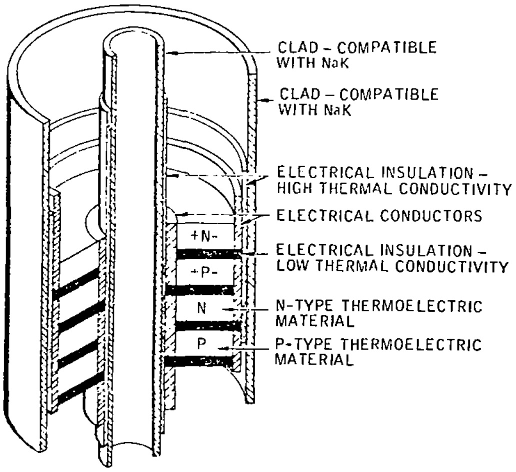


Figure 5.9 PbTe Compact Tubular Thermoelectric Module [35]

The module consists of inner and outer clad, thermoelectric material, electrical insulation, conductor rings, and end fittings. The inner clad serves as the flow channel for the hot NaK. The heat is conducted radially out through the thermoelectric material to the outer clad, where it is transferred to cold NaK which flows around the outer clad. Each PbTe element is separated by a thin mica washer which serves as electrical insulation. Conductor rings connect elements together to provide a series electrical connection for all the elements in the tubular module.

At an average hot clad temperature of 1125°F (600°C) and a cold clad temperature of 570°F (300°C), each module produces 262 watts (e) at an efficiency of 4.7 percent.

A big advantage of the converter tubular design is that it makes for a smaller converter design. The converter modules can now be stacked much like reactor fuel elements.

-- Space Station[37]

Based upon the results of a joint study between the AEC, NASA and Atomic International, a reference 25 kwe nuclear power system design has evolved to meet potential needs for Space Stations to operate in low orbit in the late 1970's, (now more likely in the 1980's). These space stations are part of NASA's post-Apollo space mission plans. Following the space stations will be a more permanent Space Base.

The reactor system design tentatively chosen to meet the reference 25 kwe requirement consists of a zirconium hydride-type reactor coupled to four parallel thermoelectric power conversion sections. Each section is independent of the others and includes a 6.3 kwe thermoelectric converter assembly, a heat rejection loop, and a pump assembly that circulates a liquid metal NaK coolant. Each converter assembly consists of 24 tubular, PbTe modules all like the compact converter modules described earlier.

Since the design and performance characteristics of most space power systems depend strongly on the mission assumptions, constraints, and requirements, it is of interest to note some of these key items upon which the 25 kwe nuclear reactor system described above was chosen. Table 5.2 lists some of the key mission, assumptions, and system requirements.

Table 5.2 Mission Assumptions and Power System Requirements [37]

Initial Launch Date	1975
Launch Mode	Integral with space station on 2-stage Saturn V(unmanned) or separate with Saturn 1B or Titan 3M/Transtage (unmanned)
Operational Mode	Zero "g"
Nominal Orbit	270 n. mi, 50°inclination
Payload Limit (for separate launch)	32,000 lb
Crew Size	6 (9 for short intervals)
Average Power Level	25 kwe (unconditioned)
Voltage	28 vdc (minimum); 42 to 84 vdc desired
Allowable Crew Radiation Dose (Total-Space & Nuclear Power Sym)	80 rem/6 mo; 100 rem/yr
Design Lifetime	2 yr minimum; 5 yr goal
Reliability	Full power 0.96; 75% power 0.98; 20% power 0.990
End-of-Life Reactor Disposal	Orbit boost to 450 n. mi or deboost into ocean

Of the items listed in Table 5.2, crew size accounts for the 25 kwe power requirement. A more detailed breakdown of the 6-man crew electrical requirement is given in Table 5.3

Table 5.3 Estimated Space Station Power Requirements [37]

	Watts
Life Support	5,000 - 7,000
Lighting (general)	1,400
Thermal Control	1,200
Attitude Control	1,000 - 3,500
Instrumentation and Communications	1,000 - 3,000
Maintenance, Checkout, Repair	1,000
Airlock/MDA*	1,000 - 2,000
CSM** (Quiescent) Each	1,000 - 2,000
Experiments (On-Board)	2,000
Docked Remote Modules	1,000 - 3,000
Subtotal	15,600 -26,100
Total (+10% Contingency)	17,200 - 28,700

**CSM -Command and Surface Module
*MDA -Module Docking Apparatus

A few of the major conclusions derived from the joint study are as follows:

a) Reactor-thermoelectric systems can meet the power demands in the 25 to 50 kwe range, based upon current or near term technology.

b) The major areas of uncertainty which must be resolved are the establishment of allowable mission radiation doses and official approval of nuclear safety provisions regarding end of life disposal of the reactor.

5.5 Radioisotope Thermoelectric Systems [39]

Basically the same considerations mentioned for reactor thermoelectric systems apply also to radioisotope thermoelectric systems. The main system difference so far, except for SNAP-29 (described later on in this section), is that no cooling fluid is required. Because of the generally low power levels involved, generator mounted radiating fins are sufficient (see Figure 5.10).

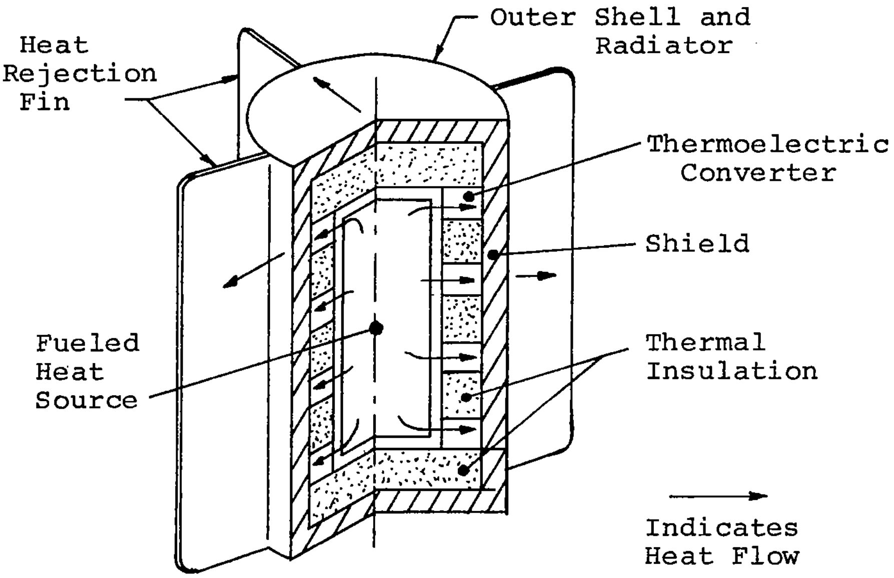


Figure 5.10 Major Components of a Radioisotope Thermoelectric Generator (RTG) [38]

Isotope power systems are particularly attractive for missions in which relative freedom from environment, long life, and compactness are desirable.

Isotope heat sources produce heat by stopping the alpha, beta, or gamma particles emitted by suitable radioactive nuclides.

Because of availability, cost, and safety problems, isotope power will generally be limited to applications of a few kilowatts or less.

Some of the principal advantages and disadvantages of isotopic power are given in Table 5.4.

Table 5.4 Isotopic Power: Advantages/Disadvantages [39]

Advantages	Disadvantages
- independent of environment	- safety requirements
- no power storage requirement	- availability
- flexible in operation	- possible costs
- long operational use	- possible interference with experiments
- highly reliable	
- heat available to maintain equipment thermal balance	

Isotopes need no storage system, and excess heat is available, if needed, to maintain equipment thermal balance and for life support systems. However, isotopes can pose spacecraft integration problems because of the heat and radiation produced. These problems though are believed to be minor and interest in radioisotope heat sources remains high.

A considerable number of isotope-power generators ranging from a few milliwatts to about 70 watts have been built. All of them have been built by the AEC. Section 4.2,Table 4.3 presented earlier listed the space units to date. Five generators of the SNAP-3 and 9 type have been launched into space. Figure 5.11 is an exterior drawing of the SNAP-9A generator and its configuration is typical of all the radioisotope generators so far up to and including the present SNAP-27.

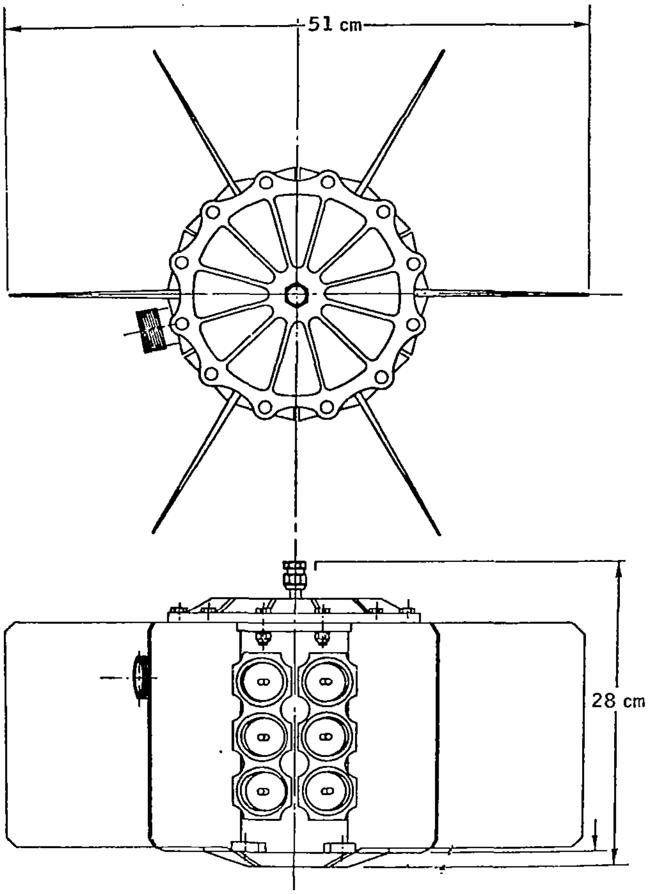


Figure 5.11 Exterior Drawing of the SNAP-9A Generator [40]

The early model generators experienced some power degradation in space because of various problems, such as leakage and increased contact resistance at the hot-junction. Current designs incorporate many technical improvements, such as reduction in number of seals, improved thermoelectric materials and better thermal and mechanical designs. Currently, one of the principal problems is the development of a suitable high-temperature heat capsule. The advantage of going to higher temperatures, of course, is higher efficiency.

-- SNAP-27 [31,41]

SNAP-27 is the most recent thermoelectric generator to be launched into space. It was placed on the moon by Apollo 12 Astronaut Alan Bean, November 1969, as the sole source of electrical power for the Apollo Lunar Surface Experiment Package (ALSEP). SNAP-27 has endured the extreme temperatures of the moon and continues to produce in excess of 70 watts of electricity. A second unit is expected to be placed on the moon in February 1971 by Apollo 14 astronauts.

The SNAP-27 generator consists of three subsystems: the generator and the PU^{238} fuel capsule heat source, a strong cask, and a fuel capsule handling tool which is used for fueling the generator on the lunar surface. Heat generated by decay of the fuel is transferred by radiation to a cylindrical hot frame in the generator. The thermoelectric elements, mounted radially around the hot frame, convert heat directly to electrical power. Waste heat is rejected by a set of radiating fins. The PbTe thermoelectric elements are spring-loaded and sealed in an inert atmosphere. For maximum reliability, the elements are connected in series-parallel ladder arrangement.

-- SNAP-29 [31]

The SNAP-29 generator is the first space isotope-powered generator to have a liquid metal heat transfer loop. The circulating coolant will be NaK and the power output is rated at 400 watts.

SNAP-29 was under development up until June 1969 before it was terminated due to budget constraints. At the time of the termination only two of eight test generators had performed successfully for the total design period of 114 days. Thus, reliable operation was not demonstrated.

An important feature of the SNAP-29 generator involved the new concept of a diaphragm-type pressure vessel applying a load to the thermoelectric elements in place of the conventional springs and pistons. One established cause of failure so far involved leaks in the new diaphragms.

5.6 Recommendations for University Research

- The solubility of doping materials in existing thermoelectrics as a function of temperature and time is unknown. A knowledge of doping material precipitation along the length of the thermoelectric material from the heat source to the heat sink would be helpful to growing improved thermoelectrics.[42]
- The mechanism of sublimation in thermoelectric materials is not clearly understood. What exact role the presence of impure silicon plays in Si-Ge or oxygen impurities (oxides) in thermoelectric materials,in general, with regards to sublimation is not known. It is known, however, that these conditions are undesirable with respect to converter efficiency and lifetime.[42]
- The upper limits on operating temperature and useful operating lifetime, associated with thermoelectrics, are related to the sublimation characteristics of the particular material. Sublimation results in a degradation of thermoelement electrical and thermal impedance. In particular, for Si-Ge operating above 1000°C and Pb-Te operating above 600°C, solutions are needed for sublimation suppression. At the present time mechanical means of material containment such as encapsulation or substructure are employed. What would be desirable instead are methods of surface treatment in order to

retard material evaporation. This approach would have the added feature of avoiding shunt heat losses due to mechanical containers and thereby contributing further to system efficiency.[42]

- The performance of thermocouples would be improved by the use of hot-shoe materials (see Figure 5.1) with higher thermal conductivities and/or lower electrical resistivities than currently obtainable with silicon-molybdenum alloys in the 1000°C-and-above temperature range. These characteristics of hot-shoe materials allow the concentration of heat source thermal flux through the thermocouple. The new materials should also have the ability to bond well with thermoelectric materials (e.g., Si-Ge). (Besides silicon-molybdenum alloys, the materials silicon and graphite are also presently being investigated for operation at temperatures over 900°C).[43]
- Investigate high mean atomic weight compounds above their melting points--so-called liquid semiconductors--for possible use in thermoelectric generators.[34]
- Find a thermoelectric material with $ZT_H = 1.5$ in the temperature vicinity of 200 to 600°C.[34]

VI THERMIONIC SYSTEMS

6.1 Thermionic Power Conversion

-- Description [32,33]

Thomas Edison discovered in 1883 that solids, when heated to a sufficiently high temperature, emit electrons. The thermionic converter then may be pictured as an "electron boiler" that converts heat directly into electrical energy by utilizing this thermionic emission.

A thermionic energy converter consists of an emitter (cathode), a collector (anode), electrical leads, and suitable structure. The cathode is heated to a temperature at which it can emit a large current of electrons. A contact potential difference between the cathode and the anode causes the electrons to flow across the interelectrode space and be collected at the anode. Useful electrical power can then be obtained by connecting a load between two electrodes. Figure 6.1 shown below is a schematic diagram of an ideal thermionic converter.

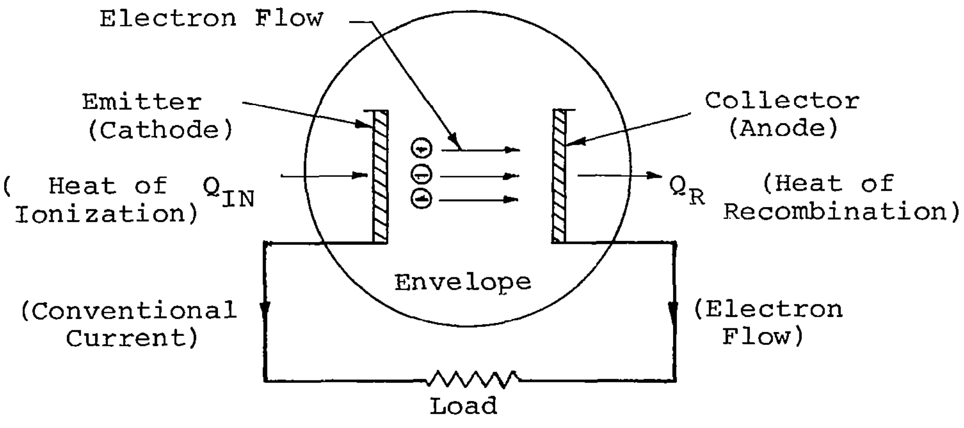


Figure 6.1 Ideal Thermionic Converter[44]

The thermionic converter is an old idea (Schlichter, 1915). In recent years the idea has gained attention because it promises to be a direct conversion device offering very high power density (power to weight ratio of equipment). Since the thermionic converter is a heat engine, its efficiency--as in the case of the thermoelectric converter--is limited by the second law of thermodynamics. Thus, in the ideal case, the efficiency is limited to the Carnot efficiency.

-- Work Function ϕ and Space Charge [32,33]

The conducting electrons in a metal can be looked upon as a gas in the volume of a block of metal. Although they are free to move about within the metal, for an electron to escape from the metal it must overcome an effective potential barrier known as the Fermi energy or Fermi level, at the surface of the metal. This potential barrier is more commonly referred to as the emitter work function, ϕ_e.

Electrons emitted into the interelectrode cavity tend to combine to form a space charge potential at the emitter. This space charge potential reduces the number of the electrons that can reach the collector and thus limit the power output of the device.

Since the collector is also a metallic electrode there is a work function associated with it as well, ϕ_c. Thus, for maximum power output, a high emitter work function, a low collector work function and absence of space charge, are all required.

-- Optimum Emitter Work Function, $\emptyset_{opt}$ [45]

An ideal optimum performance is achieved when the emitter work function ($\emptyset_e$) satisfies the following relation:

$$\emptyset_e \leq \emptyset_{opt} \qquad (6\text{-}1)$$

where $\emptyset_{opt}$, is a function of T_e, the emitter temperature, $\emptyset_c$ the collector work function, and ϵ, the net emissivity of the electrodes in a converter. Primarily, at each emitter temperature there is associated with it an optimum emitter work function.

Since efficiency continues to improve with higher emitter operating temperatures virtually all present-day converters use refractory metal electrodes. Unfortunately, the work function of these materials is much higher than $\emptyset_{opt}$ and thus, must be adjusted. This adjustment is made possible by adding cesium ions to the interelectrode cavity.

-- Two Types of Converters [33,55]

Two types of thermionic converters are possible. Each is characterized by its means of reducing or neutralizing interelectrode space charge. In the first type, the vacuum diode, the electrode spacing is made less than one-thousandth of an inch in order to limit the negative charge buildup between the electrodes. In practice, however, this concept has proven impractical and has been discarded. In the second type, the cesium diode, positive cesium ions are injected into the space between the electrodes in order to neutralize the space charge. This technique has the desirable effect of reducing the electrode spacing requirements.

In addition, cesium vapor is used to make adjustments to the work function of refractory metal electrodes used in present-day converters.

6.2 Cesium Diodes [45,46]

The parameters affecting the volt-ampere characteristics of cesium type thermionic diodes are the emitter temperature, collector temperature, interelectrode spacing and temperature of the cesium reservoir. The temperature of the cesium reservoir in turn controls the cesium pressure. These four parameters are usually interdependent and must be optimized to obtain the best performance. The emitter temperature and the interelectrode spacing are restricted by the particular application, and the output of the converter is a relatively weak function of the collector temperature. Cesium reservoir temperature, however, is not restricted and is an important variable. Thus, the cesium pressure is the first parameter that is optimized.

It is important to optimize the cesium pressure because cesium atoms tend to scatter electrons thus reducing the current. This means lower output power and efficiency.

Typical temperature, efficiency and power density for the cesium diode converter is given in Table 6.1.

Table 6.1 Typical Thermionic Converter Performance[33]

Emitter temperature (°C)	1400-1900
Collector temperature (°C)	600-770
Interelectrode spacing (mils)	2-5
Power density (watts/cm^2)	5-15
Efficiency (%)	6-18

At the present time experiments are being carried out with mixed vapor diodes. By the addition of oxygen or barium to the cesium vapor the necessary cesium vapor pressure can be reduced considerably, thus resulting in a further reduction of the plasma losses (i.e., electron current). One important advantage of this technique is that the diode converter can operate at higher heat rejection temperatures (collector temperature of 700°C or higher) thus, less radiator area is required and higher efficiencies are possible.

As an example of what can be expected in the way of converter performance, Figure 6.2 shows a comparison between several electrode materials that have been or are in the process of being evaluated.

The lowest curve represents the performance of a nominal 100 single crystal fluoride tungsten emitter paired with a niobium (Nb) collector. The middle curve shows a 110 tungsten emitter with a niobium collector and represents the present state-of-the-art as of 1970. The top curve shows the performance of a 110 tungsten emitter plus oxygen additives paired with a molybdenum (Mo) collector and indicates what can be expected in the future.

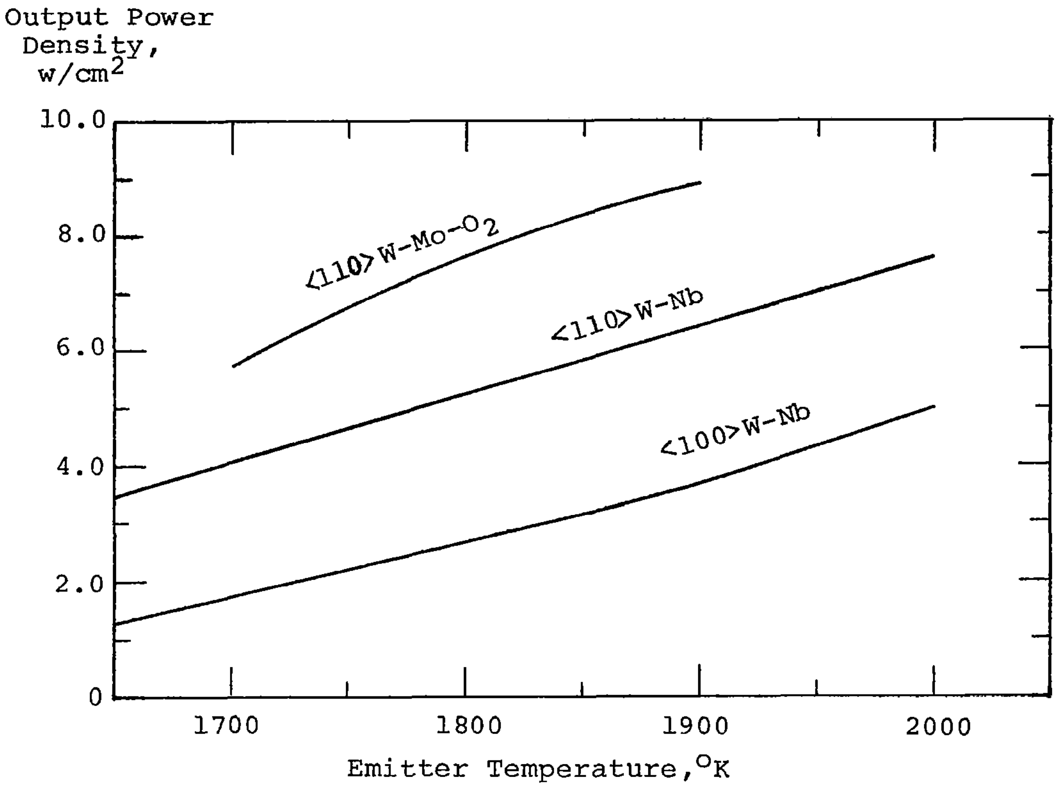


Figure 6.2 Performance Comparison of Several Electrode Materials at an Interelectrode Spacing of 10 mils and a Current Density of 10 amps/cm^2.[47]

6.3 Practical Considerations[32,45]

The primary operational characteristics of thermionic converters are that they produce high direct current, low voltage (typically 3/4 v), and require fine tuning (e.g., the cesium temperature or pressure) for optimum performance. (However, work is under way to reduce the sensitivity to cesium temperature by means of oxygen additives to the emitter electrode.)

Thermionic converters are inherently high temperature heat engines. With present day materials, the optimum emitter temperature is between 1000 and 2200° C and the highest power output is approximately 25 w/cm^2.

One significant feature is that both optimum efficiency and power density increase with increased temperature. An efficiency of 8% has already been achieved and 30% is a future possibility. However, temperature cannot be varied indefinitely because of practical limitations. Emitter temperature, for example, is limited because of material problems which arise from the coupling of the heat source to the emitter. Since the life of a thermionic device depends to a large extent on the evaporation or sputtering rate of the emitter material as well as the electrode insulators, a compromise must be made between the desired efficiency and the life of the converter.

Other limiting factors are the tolerable working stress levels which are a function of temperature, and the creep life of various cathode materials at elevated temperatures. Stress corrosion is another factor. Even in the absence of mechanical loading thermal stresses due to temperature gradients may cause failure of the electrode. Still another problem relates to the electrical resistivity of insulators which decrease with an increase in temperature.

6.4 Applications

To date, feasibility of thermionic conversion has been demonstrated and attention is being directed toward combining thermionic converters with their respective heat sources.

-- Reactor-Thermionic Systems [32,33]

The most promising application of a thermionic energy converter is in the conversion of nuclear energy to electricity. In a nuclear system it is possible to pack 300kw into one cubic foot of volume.

In conventional reactors the fuel element temperature seldom exceeds 1000°C. However, in the thermionic system, it is desirable to have material with a melting point of about 2000°C, the surface of which acts as a good thermionic emitter. What is needed is uranium-bearing material that is also a good conductor of electricity and heat. There are two classes of materials suitable for such an application. One is UCZrC, a cermet with high U/C ratio (nearly 1), the melting point of which is approximately 3500 °C. Another class of material is represented by UO_2 in Mo in cermet form. The U/O ratio of this material is equal to 2, and the melting point is of the order of 2800°C. Both are conductors and both are stable, although corrosion due to cesium might pose some problems.

With present collector materials it has been found that a minimum operating temperature for the collector of about 500°C is sufficient. Conveniently, present coolants in nuclear reactors normally operate at about this temperature range. Thus, the thermionic converter may be conveniently integrated into the design of an atomic reactor to form a compact power supply.

There are presently several alternate approaches to the integration of a reactor heat source and the thermionic power converter. Perhaps the simplest approach is a solid cylindrical reactor with thermionic diodes located on the outer surface of the reactor and an individual radiator fin for each collector. This concept is shown schematically in Figure 6.3 below.

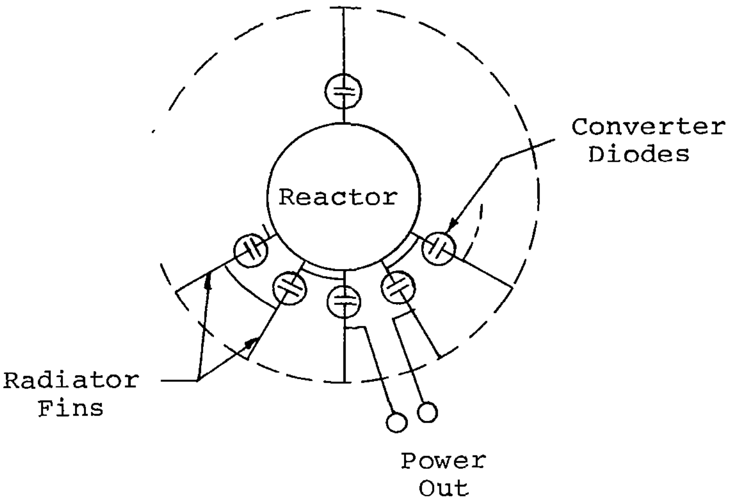
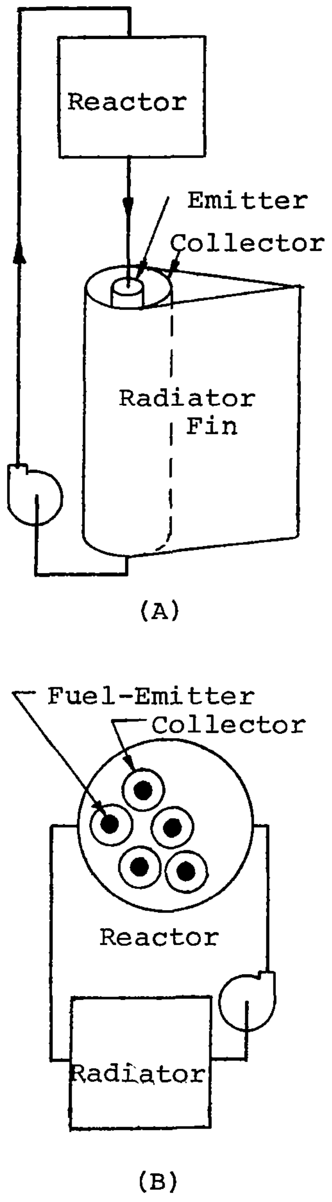


Figure 6.3 Thermionic System Configuration[48]

This concept is inherently limited to small power levels because of the inefficient means of heat transfer to the diode emitter and by the limited radiator area that can be achieved with conductive heat transfer to the extended fins. To make up for the inefficient heat transfer would mean unacceptable higher core temperatures, thus the limit to small power levels.

The core power density limit and the radiator area restrictions mentioned above can be removed by transferring heat from the core by means of a liquid metal coolant loop to converter emitters which are located in an extended array (see Figure 6.4A). The major drawback of this second scheme is that it requires all reactor and coolant loop components to operate at the emitters temperature.

A third and generally favored approach in the U.S. is the fast spectrum "Flashlight" in-pile reactor concept. The reactor core is assembled from a number of long cylindrical tubes, each containing a stack of integral fuel element converters. The nuclear fuel elements would be constructed of a double walled jacket containing the cesium vapor. The inner wall would be the emitter heated by fission reaction in the enclosed fuel, and the outer wall would be the collector cooled by a liquid metal coolant loop (at around 600-700°C) to an external radiator (see Figure 6.4B).



(A)

(B)

Figure 6.4 Thermionic System Configurations[48]

Other thermionic reactor concepts that have been examined in the United States include the following: moderated "Flashlight" reactor; externally fueled, full-length diode reactor; unit cell "Pancake" concept; and out-of-core heat pipe reactor. The many advantages and disadvantages of each of these concepts mentioned here are conveniently summarized in reference[49].

Because of the extremely high cathode (emitter) temperatures required by the above systems the heat source must necessarily be loaded with fissionable fuels. Of the fissionable fuels available only UC and UO_2 have the necessary temperature capability. UC has the advantage of higher uranium density and higher thermal conductivity, and thus smaller reactor size and weight. Not surprising then the most applicable reactor concept for the thermionic systems is the UC fast reactor.

As expected, and based on test information to date, the key life limiting problem at the moment is the problem of fuel swelling due to fission products. In addition, there are potential problems that have been identified dealing primarily with insulation breakdown and leaks in gas seals that are yet to be investigated fully.

-- Isotope Thermionics

The lack of a suitable high temperature fuel has helped delay progress in the development of a practical thermionic-radioisotope space generator. The disadvantage of most proposed systems is the large difference between the required diode operating temperatures and the available radioisotope fuel temperatures. These temperatures are about 1800°C and 1000°C respectively. For this reason the predominent effort in the radioisotope power area continues to be in thermoelectric generators where the temperature requirements are lower (i.e., about 1000°C). Thus, it will be necessary for thermionic generators to achieve efficiencies and specific power densities several times greater than what is presently available from thermoelectric generators in order to justify the expense and uncertainties of developing new systems.[50,51]

The developmental work in isotopic-thermionic power, under the sponsorship of the AEC, has been basically limited to SNAP-13, a thermionic generator designed as a demonstration device. Developed in the early part of the 1960's, SNAP-13 had a power rating of 12 watts electrical, weighed 4 pounds, was fueled by Cm-242 and had a useful lifetime of 90 days. Since SNAP-13 no system of any significance has been developed in the way of high power density while based upon isotope-fueled thermionic diode converters.[52]

One area that has received some attention is in fractional-wattage power supplies. A group of devices known as "atomic batteries" have been developed to provide electric power in the range of 10 microwatts to several watts. Specifically, a miniature radioisotope-fueled low-temperature thermionic converter (ISOMITE) has been developed. In these devices the heat produced by the decay of radioisotopes provides power sources with practical energy densities of 200-200,000 watt-hours per pound. In contrast, energy densities for existing power supplies based on chemical batteries have been limited to approximately 100 watt-hours per pound. Since these batteries are operated at current densities less than 100 milliamperes per square centimeter, the vacuum diode mode of discharge can be used together with cesiated electrodes and achievable electrode spacings. Low work function surfaces can also be employed since operation is now at relatively low temperatures as compared to high power density converters. Lower temperatures in turn allow component life to be extended and permits a much greater choice of construction materials.[53]

-- Solar Thermionics[45]

NASA and the Air Force have supported the development of solar thermionics. These systems use a parabolic mirror to focus solar energy into a cavity formed by the emitters of several thermionic converters clustered together. Since the diode is shorted when cold, it is therefore vibration-resistant during launch. When the emitter is heated to 1700°C, the interelectrode space opens up to 2 mils by thermal expansion. Such converters have been life-tested in the laboratory for periods exceeding 1.5 years. The power-to-weight ratio for the system is 10 watts/lb with a nickel mirror and could be improved by using lighter mirrors. This value, however, is roughly equal to the power-to-weight ratio of silicon solar cells. The disadvantage of the mirror concentrator system as compared to solar cell panels is the need for precision orientation. The advantage for solar thermionic systems appears for solar probe missions where the vehicle must operate at a minimum distance of 0.05 to 0.1 AU(astronomical unit)from the sun, a condition that solar panels cannot tolerate.

6.5 Recommendations for University Research

- The exact determination of the work function of electrode-refractory metals in a pure cesium atmosphere is of great importance for the optimization of diodes. New simple and reliable techniques are needed to make these measurements.[46] (For background material see reference 54.)
- A study of the techniques for achieving the optimum work function ϕ_{opt} of an emitter electrode at lower cesium pressures. This research should lead to a decrease in the number of electron-neutralizing collisions and thus result in higher power output.[55]
- The present attractiveness of thermionic conversion systems could be enhanced with improved converter performance. The improvements could be utilized to increase outputs at the same operating conditions or traded off to reduce operating conditions such as emitter temperature, which, in turn, would ease material design or fabrication problems and increase reliability or lifetime. Presently, such performance gains are anticipated in the following areas:[56]
    - (a) preferred emitter and collector surface orientations (i.e., electrode surface material crystal-structure orientation)
    - (b) reduction of the plasma voltage drop or space charge
    - (c) utilization of plasma additives for space charge neutralization

- Investigate the use of surface additives (e.g., oxygen) with other refractory electrode materials besides tungsten.[55]
- Develop thermodynamic understanding of electrode surface effects in order to establish criteria for better surfaces. This information then may be used to formulate boundary conditions for plasma studies.[55]
- A careful theoretical study of plasma and sheath phenomena in the interelectrode space in order to obtain a better understanding of the mechanisms responsible for losses.[55]
- Study variations in electrode geometry for possible increase in performance.[55,32]
- A major obstacle to the use of thermionics in space is the lack of a qualified 2000°C heat source. So far only the fissionable fuels UC and UO_2 have the necessary temperature capability. The areas that are particularly troublesome and in need of solutions for systems currently under consideration (ref. Figure 6.4B) are as follows:[7,14,34]
  - (a) maintaining compatibility between fuel forms and the capsule liner material
  - (b) fuel swelling and maintaining dimensional stability of the fueled emitter
  - (c) release mechanism for the selective venting of fission products from the fueled capsule (i.e., helium gas).

VII TURBOELECTRIC SYSTEMS

The interest in turboelectric systems is a reflection of the need for more efficient conversion techniques. As the trend for higher power requirements continues to grow, greater efficiency becomes more critical. This is particularly true where scarce isotopes serve as the heat source. Thermoelectric generators, though very promising, have rather low efficiencies of the order of 5 or 6 percent. Thermionic generators promise efficiencies of about 14 percent, but because of the high temperatures required much research and development is still required. Turboelectric conversion systems, however, hopefully will yield cycle efficiencies as high as 25 percent. Besides the promise of higher efficiency, the extensive experience with turbomachinery in this country means working with familiar hardware from the start.

Turboelectric systems implies dynamic power sources wherein heat is converted into electrical energy through an intermediate step that involves mechanical work. Power systems of the turboelectric type include the familiar Rankine and Brayton systems and are of principal interest in the low kilowatt to megawatt level. These two dynamic systems can be used with any energy source that can provide heat at the required temperatures.

In a comparison of the characteristics of these two cycles, it is important to remember that the working fluid of interest in the Rankine cycle systems are liquids, either metal or organic compounds, and involve a phase change. The working fluid in the

Brayton cycle systems, on the other hand, are inert gases and involve no phase change. A brief description of these two cycles is given below.[57]

7.1 Basic Rankine Cycle Power Conversion [33]

The cycle diagram and the schematic arrangement of the Rankine cycle are shown to the right in Figure 7.1. The Rankine cycle is characterized by a working fluid that changes state. In the cycle, the working fluid is compressed as a liquid and heat is added to raise the liquid to the saturation temperature, i.e., 1-2; heat is added at constant pressure and temperature during a phase change from liquid to vapor, i.e., 2-3; the vapor is expanded through a turbine and work is extracted, i.e., 3-4; and the waste heat is rejected at constnat pressure and temperature during a phase change from vapor to liquid, i.e., 4-1.

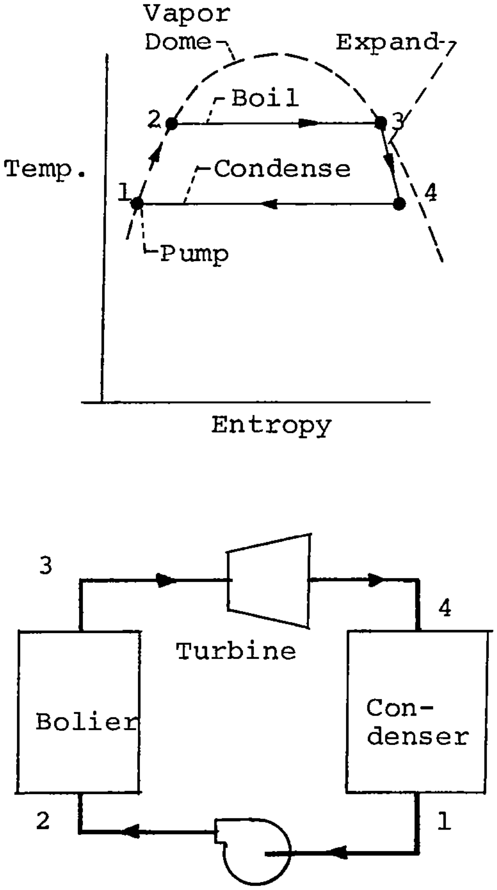


Figure 7.1 Rankine Cycle Thermodynamic Diagram and System Configuration [33,57]

As a result of the boiling and condensing phase change which allows constant temperature heat addition and subtraction, the ideal Rankine cycle efficiency approaches the Carnot cycle efficiency. In addition, very little work is required to compress the working fluid in the liquid state.

The principal advantages of the Rankine cycle are the high cycle efficiency and the isothermal heat rejection which allow minimum radiator areafor a given source temperature.

The principal disadvantages are the inherent corrosion and erosion characteristics of the applicable working fluids.

In the application of a Rankine cycle to space, it is necessary to identify potential working fluids for application in the high temperature range demanded by radiator area considerations.

The vapor pressure of mercury and alkali metals is shown in Figure 7.2 below. One thing of interest is that the available fluids do not provide a continuous coverage of the temperature scale. The thermodynamic properties of all these liquid metals are such that they yield an ideal Rankine cycle efficiency of about 95% of the Carnot efficiency in the range of interest for space applications.

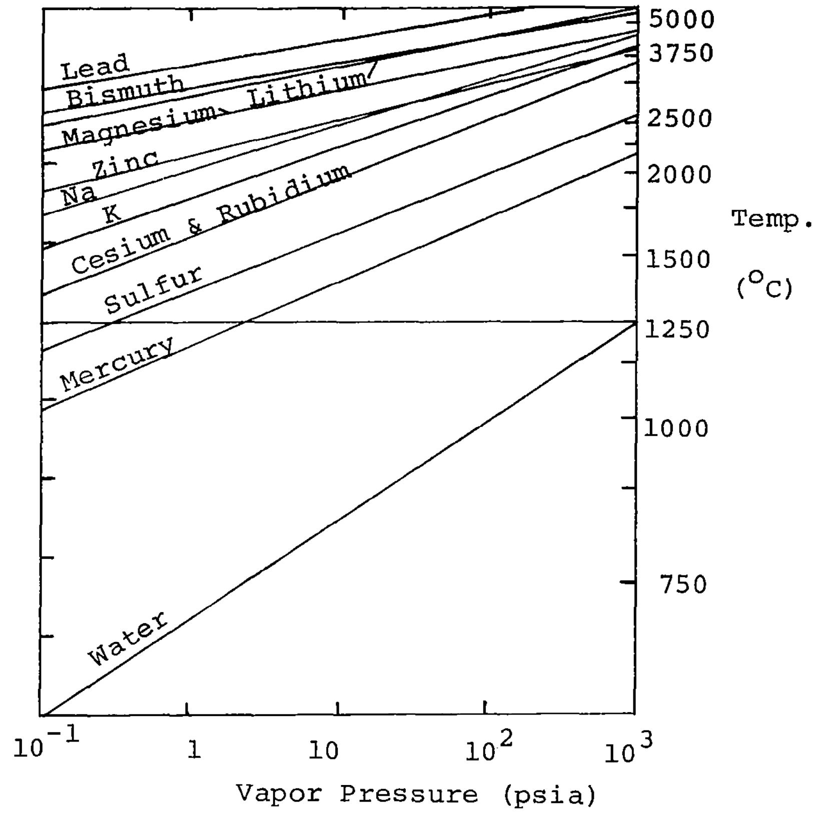


Figure 7.2 Vapor Pressure vs Temperature for Potential Rankine Cycle Working Fluids [33]

The optimum heat rejection temperature for a Rankine cycle is determined by the working fluid selected. As a result of balancing Carnot efficiency against T^4 law for radiation, the optimum radiator or condensing temperature is about 3/4 of the absolute boiling temperature. The relationship between boiling temperature, radiator area, and cycle working fluid is shown in Figure 7.3 below.

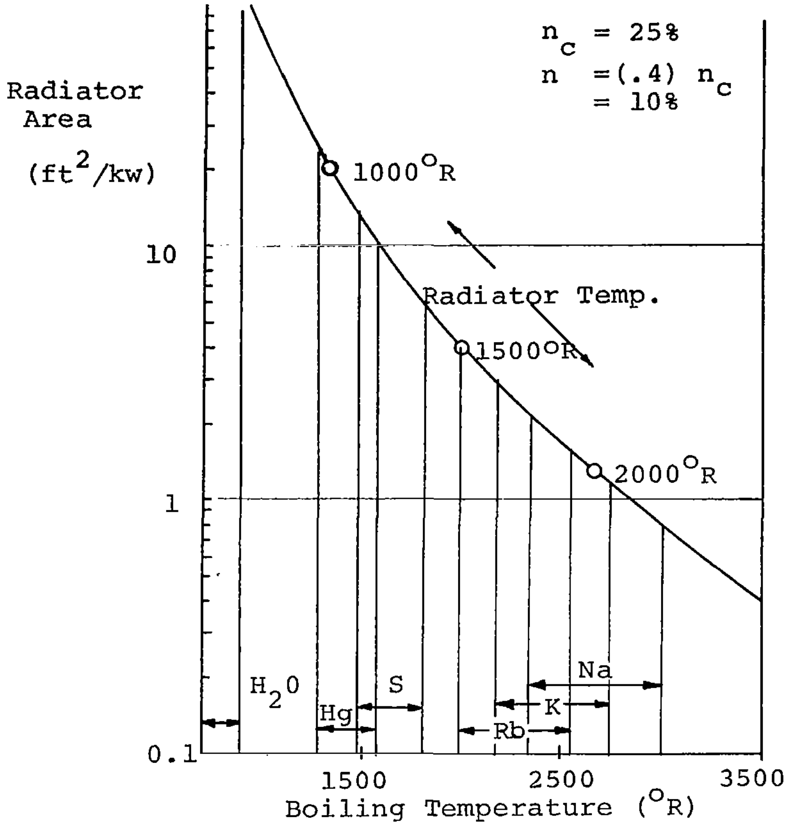


Figure 7.3 Radiator Area per Kilowatt as a Function of Boiling Temperature for Rankine Cycle Working Fluids 33

In Figure 7.3, the radiator area per kilowatt of output is calculated on the basis of an optimum Carnot efficiency of 25% and a conversion efficiency of 40% of Carnot which results in an overall system efficiency of 10%. The boiling pressure range of the working fluids in Figure 7.3 typically fall within a necessary range of 50 to 300 psia and is dependent on system design.

7.2 Basic Brayton Cycle Power Conversion [33]

The cycle diagram and the schematic arrangement of the Brayton cycle are shown in Figure 7.4 below. The Brayton cycle is characterized by a working fluid that remains in a single state.

The working fluid is an inert gas such as helium, neon, argon, etc., or a combination of these gases. In the cycle, the gas is compressed, i.e., 1-2; heat is added at constant pressure, i.e., 2-3; the gas is expanded through a turbine and work is extracted, i.e., 3-4; and waste heat is rejected by a radiator, i.e., 3-4; and waste heat is rejected by a radiator, i.e., 4-1. Because the working fluid is in a single state and absorbs energy at constant pressure through a rise in temperature, the ideal cycle is inherently limited to a relatively small fraction of the Carnot efficiency.

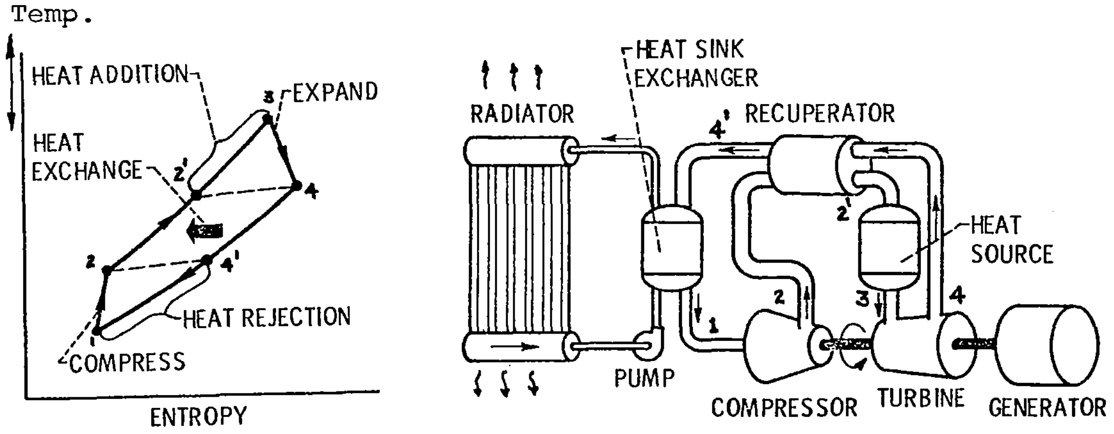


Figure 7.4 Brayton Cycle, Thermodynamic Diagram and Space Power System[57]

However, recent advances in lightweight gas heat exchangers have made it feasible to consider the recuperated Brayton cycle wherein a portion of the otherwise waste heat (4-1) is used in the initial phase of the heat addition (2-3). The recuperated cycle achieves an ideal gas cycle efficiency of about 25% to 30% of Carnot.

Considerable work is expended in the gas compression portion of the cycle (1-2) and a large fraction of the work output (3-4), or nearly 2/3's of the energy produced in the system, is consumed by the compression stage. Thus, the cycle performance is quite dependent upon the turbine and compressor efficiency. Efficiencies of about 85% in the turbine and 75% in the compressor must be demonstrated.

But again, recent advances in the state of the art of high efficiency and high speed turbines and compressors have contributed to the renewed interest in the Brayton cycle.

The major advantages of the Brayton cycle are:

1) Inherent simplicity of a single loop and a single phase working fluid.
2) The noncorrosive properties and the near absence of zero-gravity problems in inert gas working fluid systems.

The disadvantages of the Brayton cycle are:

1) The cycle net performance is heavily dependent upon achieving high component efficiencies.
2) The low ideal gas cycle efficiency must be overcome by going to a high Carnot cycle which results in either extreme source temperature requirements or extremely large radiator area.

This latter consideration is probably the dominant factor in the performance evaluation of the Brayton cycle. Figure 7.5, below, shows the results of a detailed study by AiResearch on a computer optimization of a 35 kwe recuperated Brayton cycle.[58] For comparison, the radiator area-per-kwe for a Rankine cycle of 40% of Carnot efficiency is shown also. It is evident that the minimum area Brayton cycle requires a much larger radiator area than a saturated Rankine cycle operating at the same source temperature. In practise, a minimum weight Brayton cycle would probably require even more radiator area than that shown in Figure 7.5.

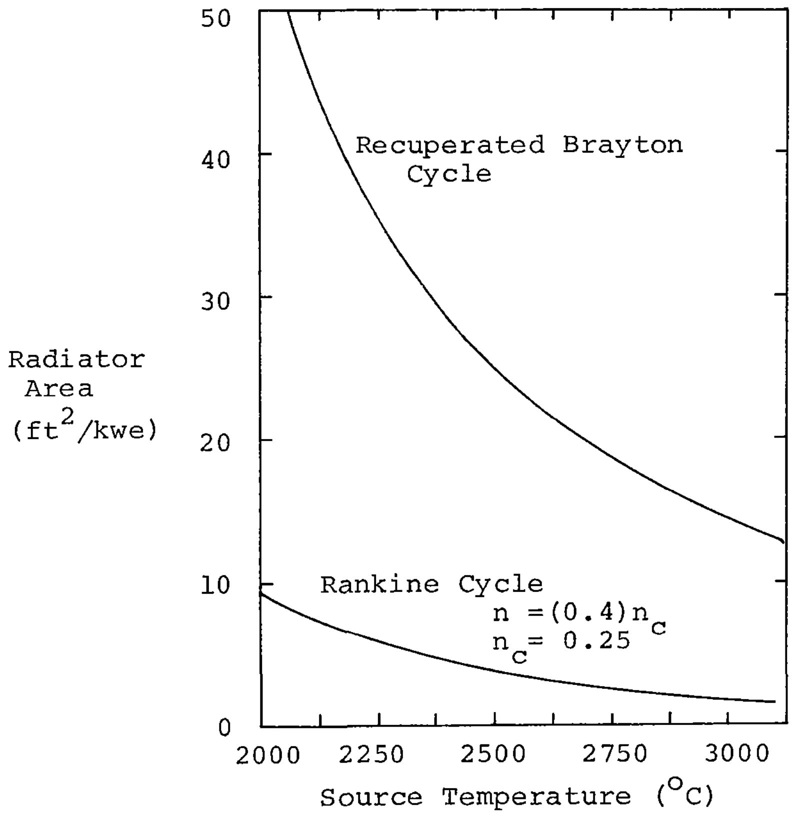


Figure 7.5 Radiator Area and Source Temperature Comparison for Brayton and Rankine Cycles [33,58]

7.3 Reactor-Turboelectric Systems[33]

At high power levels (>> 100 kwe), a turboelectric nuclear power system will probably utilize Rankine cycle power conversion because it offers high conversion efficiency, operates at relatively low source temperatures, and rejects the waste cycle heat at relatively high temperatures.

The Brayton cycle at first glance appears unattractive for space applications because of its lower fraction of Carnot efficiency, higher reactor temperature requirements, and larger radiator area demands. However, because of the extensive experience with gas turbomachinery in this country and also because of the absence of corrosion of zero-gravity problems in inert gas systems, the Brayton cycle is still being developed. In fact, the Large Radioisotope Heat Source (LRHS) Capsule Program has been completed. This program called for the development of a radioisotope heat source to be used with a Brayton cycle power conversion for application on future manned space missions.

There are a number of alternate approaches to the coupling of a reactor heat source, a power converter, and a heat rejection radiator to form a Rankine cycle system. These alternatives are shown in Figure 7.6.

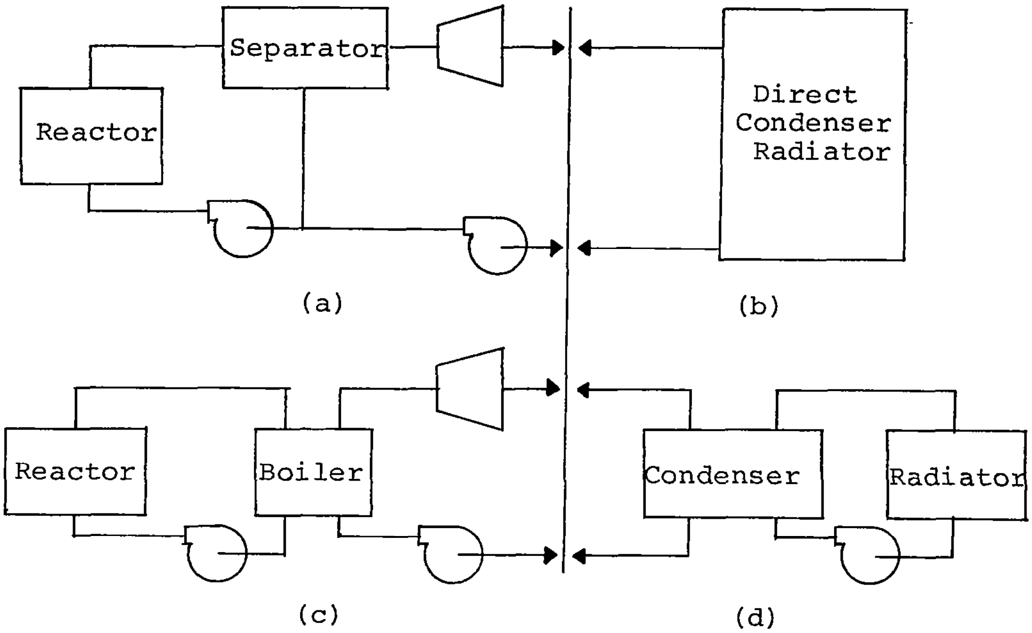


Figure 7.6 Rankine Cycle System Configuration [33]

The most direct approach to a saturated cycle is the combination of a-b which employs direct boiling of the working fluid in the reactor and direct condensing in the radiator. This combination requires a liquid-vapor separator and a recirculation pump so as to minimize moisture content in the turbine. The disadvantages of this system are the nuclear interactions between the working fluid and the reactor.

The more conventional Rankine cycle employs superheat thus eliminating the need for a separator. The combination of c-b form the basic design for two past development programs titleed SNAP-2 and SNAP-50, and were cancelled before completion (see Chapter 4, Table 4.1).

The reactor is coupled to the boiler by a pumped liquid metal heat transfer loop. The working fluid is boiled and superheated in a once-through boiler.

The combination c-d includes an additional loop connecting the condenser to a separate radiator. This combination is the one used in the SNAP-8 program.

The necessary temperature drop in the radiator heat transfer loop has now increased the radiator requirements over that of the direct condenser-radiator approach. However, the third loop does allow greater vehicle integration flexibility which becomes increasingly important at higher power levels.

In Figure 7.3 presented earlier, the heat source temperature requirements for various Rankine cycle working fluids was given.

The reactor heat source thermal power and temperature requirements for Rankine cycle systems are shown in Figure 7.7 below as a function of electrical power output and available radiator area. This survey assumed a constant fraction (50%) of Carnot conversion efficiency and a constant Carnot efficiency of 25% for minimum radiator area.

Generally speaking, the two figures 7.6 and 7.7 point out the fact that lower radiator area (and thus lower radiator weight)is achieved in the higher temperature system.

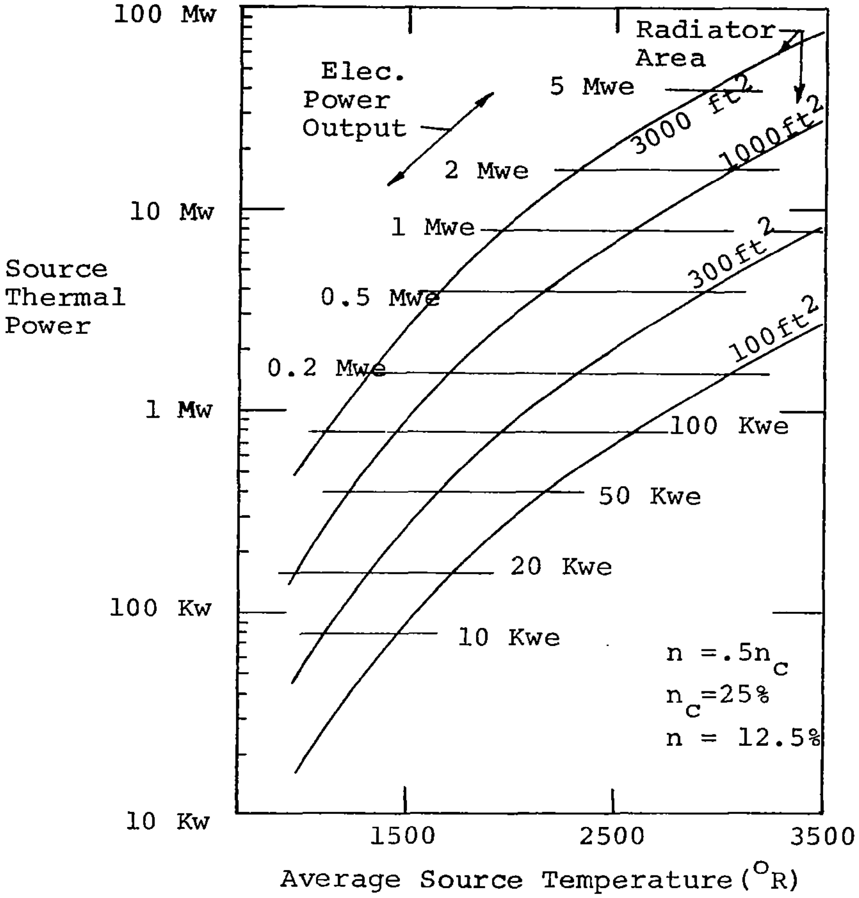


Figure 7.7 Reactor Thermal-Power and Source-Temperature Requirements as a Function of Electrical Power Output and Available Radiator Area for Rankine Turboelectric Systems 33

A higher temperature means increased weight but, more importantly, increased materials problems such as strength, corrosion, sublimation, self-welding, etc. Typically, increased temperature is rarely an easy solution to a problem. However, one cannot rule out a system because of temperature except on the basis of development time.

7.4 SNAP Mercury Rankine Program[33]

Work on a Rankine cycle power conversion system, employing liquid mercury as the working fluid first began with the SNAP-2 program in 1957. SNAP-2, originally planned as a 3-kwe mercury Rankine cycle system with a 1-year life, was later expanded into a technology development program in order to demonstrate the engineering feasibility of larger multi-kilowatt mercury Rankine cycle systems for space. The SNAP-2 demonstrated the feasibility of hermetically-sealed and working-fluid-lubricated rotating machinery for reliable operation of 1 year or longer in space.

A system schematic for a 5-kwe SNAP-2 unit is shown in Figure 7.8. A liquid metal (NaK-78) heat transfer fluid is circulated through the reactor core and the mercury boiler superheated by a thermoelectric pump (TE). In the boiler, reactor heat is transferred to the mercury working fluid of the Rankine power conversion cycle. The superheated mercury vapor is expanded through a turbine. The resulting mechanical power is converted into electrical power by the alternator. The mercury vapor is then condensed in the radiator-condenser (R/C) which may be part of the outer skin of a spacecraft. The condensate is returned to the boiler by way of a feed pump.

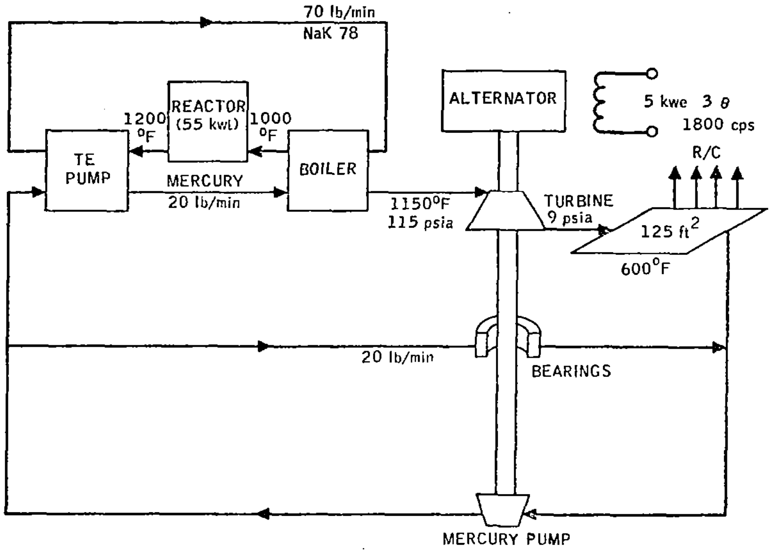


Figure 7.8 5-kWe Mercury Rankine Schematic[33]

-- SNAP-8 Program[59,60,61]

The SNAP-8 is a turboelectric nuclear space power system using a mercury Rankine cycle. It is designed to produce a minimum electrical power of 35 kw, to have high reliability, and to be capable of unattended full-power operation for at least 10,000 hours. Since SNAP-8 was not assigned a specific space mission, the development of the flight radiator assembly and the flight shielding was not part of the SNAP program. The prime objective of the SNAP-8 development effort was to develop components, subsystems and system technology to the point where performance and development uncertainties are understood and resolved, and this was essentially achieved when the program was terminated in 1971.

SNAP-8 was started in 1960. The initial design consisted of two loops and a direct-condensing radiator. Because of development problems a redesign was made in January 1963 to include two additional loops. The four loops or subsystems are: a nuclear system which supplies the thermal power; a power conversion system for converting thermal energy to electrical power; a flight radiator which removes the excess heat from the Rankine cycle; and an organic loop for component cooling and lubrication (see Figure 7.9).

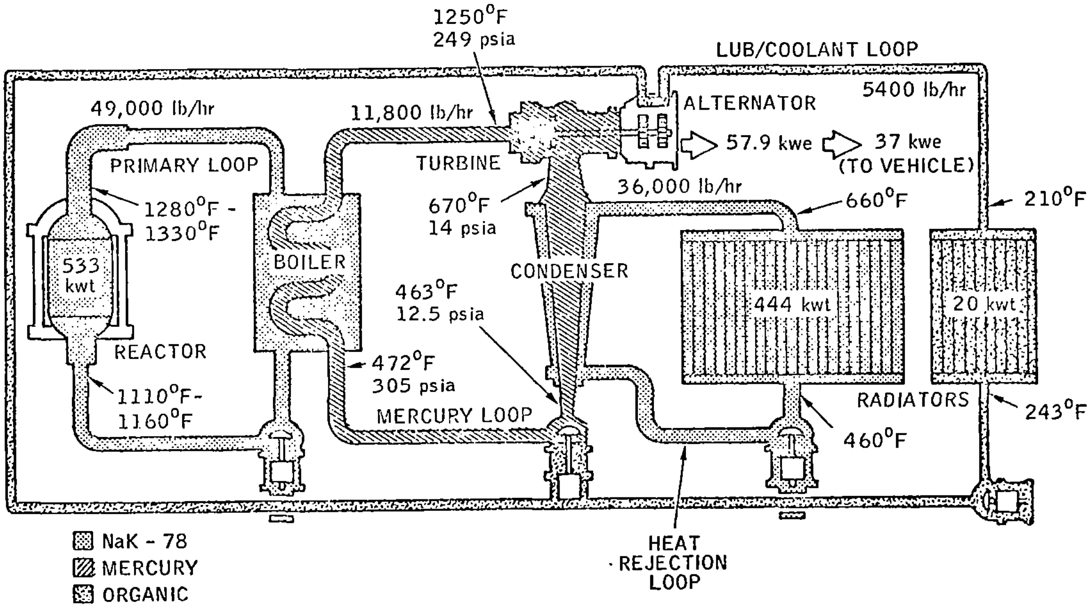


Figure 7.9 SNAP-8 Electric Generating System[33]

It appears at this time that significant progress was made toward solving life-limiting problems of all major system components, namely: turbine alternator assembly, boiler, condenser, and pumps. If continued, the emphasis in future testing would have been the development of complete system reliability and the integration of the nuclear and non-nuclear systems. The recent decision by NASA to terminate development of the 35 kwe mercury Rankine power conversion system (i.e., SNAP-8) in favor of the Brayton approach is attributed to Brayton's greater flexibility to adapt to future mission needs, higher efficiency, and its potential long life capability. The accomplishments from the mercury Rankine program, however, remain significant. They have served to advance the technology of dynamic systems and to provide increased evidence that long life rotating components can be developed.

-- Organic Rankine Cycle Technology (ORC)[15,62,63]

Organic-fluid Rankine cycle power conversion systems are presently being considered for a variety of space applications. The attractiveness of organic fluids lies in the fact that their saturated-vapor entropies decrease with temperature, so that the vapor does not partially condense into a vapor liquid after expansion through the turbine. Because of their tendency to decompose at high temperatures, however, organic fluids limit turbine inlet temperatures to about 700°F. Efficiency must be obtained by a low temperature at the recuperating and condensing end rather than a high temperature at the vapor end of the cycle. With recuperating and condensing temperatures of about 70-260°F, cycle efficiencies may exceed 20 percent. One problem of such low temperature operation is that the corresponding low inlet pressures (0.17 to 0.5 psia) can cause pump cavitation. A recent solution,developed by Aerojet-General,is a 12-kw system that uses a jet spray to condense the working fluid and raise the pump inlet pressure to about 35 psia (see p. 142).

ORC systems appear very attractive for use where long term unattended operation is a requirement. It has the advantage of a high cycle efficiency at a low peak temperature. Low temperature and good material compatibility allow use of state-of-the-art materials and fabrication techniques. An organic system can utilize a variety of heat sources and heat rejection systems, making it extremely versatile.

The AEC is interested in establishing the technology base necessary to successfully develop an ORC power conversion system. The requirement is for long duration operation in a space environment with a nuclear heat source. The specific working fluids being evaluated at the present time are biphenyl and the eutectic mixture of biphenyl and phenyl ether, or what is commonly called "Dowtherm A." The thermal stability, heat transfer characteristics and lubricating qualities of these fluids are under study.

-- Jet Condenser with ORC [64]

A major component in the ORC power conversion system is the jet condenser which allows expansion of the working fluid through the turbine to extremely low back-pressures (0.1psia), unattainable in standard Rankine cycle systems (see Figure 7.10).

Subcooled liquid is introduced into the condenser at a temperature 50 to 75^{o}F below the vapor temperature of the fluid from the turbine outlet. This operation insures single phase flow through the heat rejection equiptment, namely the radiator. Furthermore, the jet condenser is designed to allow considerable fluid pressure recovery because of momentum interchange between the high velocity gas stream and the subcooled liquid stream.

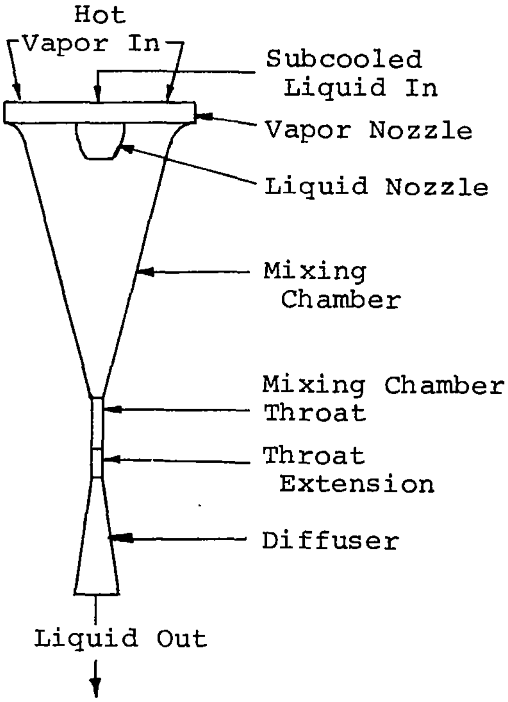


Figure 7.10 Jet Condenser Component Schematic [64]

From a simulated laboratory test in a modified Organic Rankine Cycle Energy(ORACLE) power conversion system it has been demonstrated that with an inlet pressure of 0.2 psia, an overall system efficiency greater than 20 percent can be obtained for a rotating ORC power conversion system. Much development work is continuing at this time with ORC systems and many space as well as terrestrial applications are being given serious consideration.

-- Advanced Rankine Cycle [65]

As part of NASA's responsibility for space power technology a research and technology program has been conducted on other liquid-metal Rankine systems other than the mercury systems mentioned earlier. Specifically, a system where the alkali metal potassium is the working fluid in the energy conversion loop. Potassium has a significantly lower vapor pressure above 1300°F, so that it is more compatible with the lower strength of turbine materials operating within the temperature range of 1700-2400°F.

The basis for system operation of an advanced Rankine potassium cycle is much like that of the SNAP-8 system. The main difference is that the temperatures are higher. For example, the turbine inlet temperature is now about 2100°F whereas for a mercury system it was 1250°F. As expected the higher temperatures bring about a whole new set of design considerations. The implied advantages of a higher temperature system are higher system efficiencies due to a higher heat rejection temperature and lower specific weight because of a corresponding lower radiator weight. The disadvantages all follow a familiar path of component and materials compatibility for high temperature operation. Progress is based heavily on a successful refractory-metal alloy technology program. Considerable effort lies ahead in building and testing initial refractory components typical of advanced Rankine power systems. Components as well as complete system testing will undoubtedly reveal problems presently unknown. Extensive design and testing of these advanced components are planned over most of the 1970's.

At this time, Rankine engines with alkali-metal working fluids are potentially one of the best producers of electric power in the large-space-station range of up to 1000 kw.

7.5 Brayton Cycle Development[66,67,68]

The Brayton power system is being developed by NASA to satisfy the need for long-life, multi-kilowatt power systems for use in space. Interest in the Brayton cycle occurs for many reasons:[57]

a) the extensive technology gained during the last 35 years in the gas turbine field.
b) it has excellent prospects for applications where extended operation is required.
c) it is versatile in that a given system can cover a range of power levels and can be applied to a broad range of heat sources.
d) it has potentially high cycle efficiency (17 to 30%) thus it is attractive for low-power applications where heat sources such as isotope and solar energy are used and energy is at a premium.

NASA started a component technology program in 1963 which centered around demonstration of high-efficiency small-diameter turbomachinery and gas bearings. In 1966 a program was initiated to develop a second-generation Brayton power system to include a complete power conversion unit called the Brayton-B engine. Throughout 1967 and 1968 NASA contracted for all the Brayton-B engine components. These components have since been delivered to NASA and component tests are near completion. System testing will begin in the near future.

Design selection for the new Brayton power conversion system was made such that its rated power output could be adjusted within the range from 2 to 10 kilowatts. In space use it could be coupled to either a solar or radioisotope heat source.

Figure 7.11 shows a schematic diagram of the Brayton-B gas loop with its four major sybsystems shown in phantom. Basically, this system operates as described earlier in section 7.2.

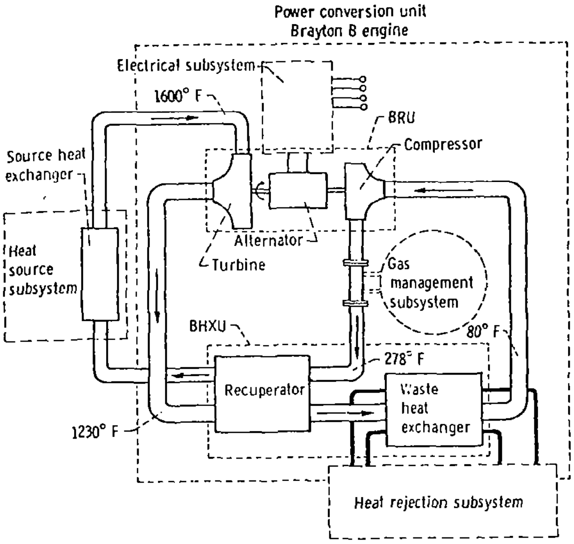


Figure 7.11 Schematic Diagram, Brayton Power System[66]

The electrical subsystem, however, regulates and distributes the power and controls the power system. Output frequency is regulated, and hence, the rotating shaft operates at a constant speed. The gas management subsystem is used mainly to start and stop the power system, It is also used to adjust the working gas inventory.

The rated power output of the closed-cycle Brayton-B system is adjustable. Its range of rated output results primarily from sizing the alternator for the high power, and the ability of the gas bearings to support the shaft at the low power. The power rating may be adjusted by changing the working gas inventory in the power conversion loop. This is done by setting the gas pressure level which fixes the inventory and mass flow rate.

A summary of design conditions and the electrical output characteristics for the new Brayton-B engine is presented in Table 7.1. A description of the engine performance based upon a recent analysis employing recent test data is presented in Table 7.2. Noteworthy is the predicted increase in engine conversion efficiency from 0.17 for 2 kwe to 0.30 in the 10 to 15 kwe power range.

Table 7.1 Brayton-B Engine Design Conditions [66]

Output power range, kWe	2 to 10
Frequency, cps	1200
Voltage, V	208/120
Working gas (mixture)	He and Xe
Gas mixture molecular weight	83.8
Turbine inlet temperature, °F	1600
Compressor inlet temperature, °F	80
Compressor discharge pressure, psia	16 to 41
BRU shaft speed, rpm	36,000

Table 7.2 Brayton-B Engine Performance[66]

	Power output, kWe (0.75 power factor)			
	2	6.5	10	15
Turbine inlet temperature, °F	1600	1600	1600	1600
Compressor inlet temperature, °F	80	80	80	80
Turbine efficiency	0.88	0.90	0.91	0.92
Compressor outlet pressure, psia	16	30	41	57
Compressor efficiency	0.79	0.79	0.79	0.79
Alternator efficiency	0.88	0.91	0.90	0.86
Recuperator effectiveness	0.96	0.27	0.30	0.30

The Brayton gas cycle turbogenerator was selected to be the base power system for the Manned Orbiting Research Laboratory (MORL). In addition, it has been recommended in studies of post-Apollo missions such as space station/space base, interplanetary mission module and advanced lunar explorations.

7.6 Recommendations for University Research

- Since power system efficiencies between 5 and 20% essentially mean that 80 to 95 percent of the heat from the energy source must be dissipated, the development of new workable minimum-weight heat rejection subsystems would greatly enhance the flight readiness of all thermal power systems.[15]
- Ceramic fuels such as UO_2 and PuO_2 are being developed to produce temperatures of 2,000 to 4,000°F to operate in alkali-Rankine and thermionic converters. A problem of ceramic-fueled reactors that remains to be solved is the unpredictability of the interaction of containment materials and the liquid metals and gases used to transport heat.[15]
- Two 1300°F/600kwt Zirconium-hydride reactors have been tested to date. Each reactor has experienced fuel clad-hydrogen barrier cracks which have accelerated the leakage of hydrogen from the reactor thus limiting operating life-time. To achieve extended life requires a solution to this cracking problem.[61]
- Identification and characterization of new fuel forms and structural alloys for use in high temperature reactors operating above 2000°F.[61]
- Identification of more promising reactor concepts for operation above 2000°F. So far, it is believed that such

a reactor must use a fast neutron spectrum for fission.[61]

- In order to benefit from the many performance advantages associated with isotope power, an alternate lower cost, more available isotope fuel is needed to replace Pu^{238}.[61]
- For reasons of cost and availability, exploratory investigations of alternate approaches into the production of Pu^{238} are justified.[61]
- Practical solutions are needed for the problem of reactor power system in orbit repair and replacement.[61]
- Develop gas bearings for turboalternators that are insensitive to magnetic flux imbalance, that are less thermally sensitive, and generally more rugged.[57]

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