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STATE OF THE ART OF RADIOISOTOPE POWER SYSTEMS FOR LUNAR SURFACE VEHICLES

Prepared under Contract No. NAS8-11096 by

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Huntsville, Alabama

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REPORT ON

STATE OF THE ART OF RADIOISOTOPE POWER SYSTEMS FOR LUNAR SURFACE VEHICLES

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For

Astrionics Laboratory

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER

PREFACE

This document by Northrop Space Laboratories, Huntsville Department, is a report to Marshall Space Flight Center on work performed under Task Order N-60, Contract No. NAS8-11096. A nine man week effort beginning on March 1, 1965 and ending on April 30, 1965 was expended on this task.

The NASA Technical Liaison Representative for this Task Order was Mr. E. E. Dungan of Advanced Studies (R-ASTR-A).

The information contained in this document represents an analysis of the state-of-the-art in radioisotope electric power systems applicable to the LSSM or other lunar surface vehicles.

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SECTION 1.0

SUMMARY

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The development status of six radioisotope electric power systems suitable for operation on the lunar surface is investigated and discussed. The six systems considered are a thermoelctric system, a thermionic systems, a Brayton cycle system, a Mercury Rankine system, a Dowtherm-A Rankine System, and a Stirling engine. Applicability of these power systems to various lunar exploration concepts is discussed.

All the systems investigated are sufficiently advanced in technology to permit delivery of flight rated systems within four years. Hence these systems can be made available within the time frame planned for early lunar surface exploration. Information on isotope fuel forms was found to be lacking, and recommendations are made to investigate this area.

Author

SECTION 2.0

INTRODUCTION

The feasibility and applicability of radioisotope electric power systems to a MOLAB type vehicle and to the LSSM have been thoroughly investigated as parts of Task Orders N-45 and N-56 respectively. In these studies it was tacitly assumed that the power systems investigated would be current state-of-the-art systems in the 1970-1975 time period. In order to establish the reasonableness of this assumption, this study on the current state-of-the-art in radioisotope power systems was initiated. Since the lunar exploration system concept has not been finalized, the applicability of radioisotope electric power systems to other candidate concepts such as the MOLEM and SHELAB is investigated.

SECTION 3.0

STATE-OF-THE-ART SUMMARY

3.1 GENERAL

There are at the present time several commercial firms engaged in the design and development of isotopic electric power systems. These design efforts have resulted in several power systems which are sufficiently developed to merit consideration of incorporating these systems into near-future space applications. The candidates are a thermoelectric system, a thermionic system, a Brayton cycle system, a Rankine cycle system, and a Stirling engine system. A brief summary of the status of each system is given below.

3.2 THERMOELECTRIC SYSTEM

The thermoelectric system utilizes the electric current flow between the junction of two dissimilar materials when a temperature difference is established between the junctions. Although the principle of the thermocouple has been known for some time, this phenomena was not a useful energy conversion device until the recent advent of doped semiconductor technology. The state-of-the-art for this type system is among the most advanced of the isotopic power systems. Four thermoelectric generators using PbTe elements are currently in orbit furnishing power to U.S. satellites, and a number of terrestrial based units are in operation. Thus many thousands of actual operating time have been accumulated on these systems. All these units, however, are less than 100 W(e), while many future space applications such as manned Lunar exploration will require one to three kilowatts of electrical power. Because of the limited availability of suitable isotopes, efficiency assumes an even greater importance at these power levels. In order to increase the efficiency of the thermoelectric elements, two or more different elements are thermally connected in series. Such an arrangement is called a segmented or cascaded element, and there are several companies engaged in development of such elements at the present time. Although the thermoelectric system still requires development for use at kilowatt power levels, at least one reputable firm estimates that delivery of a flight-rated kilowatt system can be accomplished within 32 months after initial go ahead.

3.3 THERMIONIC SYSTEM

The thermionic converter or diode is another static device for changing thermal energy into electrical energy. This conversion is accomplished by electron emission from a hot cathode (emitter) and subsequent collection on a cold anode (collector). Such a diode is usually filled with cesium gas in order to neutralize the space charge between the electrodes. (In some of the thermionic diode concepts, the cesium gas is used as a heat transfer fluid through a device called a "heat pipe".) The net efficiencies of the thermionic system (10-13%) compete favorably with those of the dynamic systems, and the lack of bulky and weightly conversion hardware leads to a light weight compact system. Thus the thermionic system combines the desirable features of the dynamic systems and the thermoelectric system, i.e., high efficiency with static conversion.

At present, there is only one thermionic system in the SNAP program, although there are several other thermionic systems being developed with private funds or with funds from government sources other than the NASA or the AEC. The thermionic diode system being developed by Republic Aircraft is particularly appealing because of its ability to use isotopes for periods of time approaching the isotope's half life and because isotopes of low power density can be used. A number of these diodes have been built and tested by rf induction heating and/or electron bombardment of the diodes. The highest power level achieved was 190 watts on a single diode. Several of these diodes have undergone extensive thermal cycling and hot and cold shear tests with satisfactory results.

The state-of-the-art of the thermionic systems is such that flight rated systems could be delivered within 31/2 to 4 years. The major remaining areas of investigation are life testing and environmental testing in order to determine system reliability.

3.4 BRAYTON SYSTEM

The application of Brayton cycle turbo-machinery to commercial uses such as gas turbines in aircraft engines and compressors for cabin pressurization has resulted in design techniques and some hardware items which are directly applicable to the small radial-flow turbomachinery of the isotopic Brayton system.

The key items in achieving good reliability in gas turbines are the bearings which account for 95 percent of the failures in this type of machinery. For long life applications, gas bearings are used. These type bearings are currently being used in a high-speed, continuously operated helium compressor for the Minuteman ICBM weapon system. For these units, the observed mean-time-between-failures is 485,000 hours. Demonstration of satisfactory performance of the gas bearings designed for use in the CRU will still be required. The reliability of other components in the isotopic Brayton system can be predicted from operational data on similar components in other systems. Since the design techniques are known and much of the hardware is already developed, then delivery of a flight-rated isotopic Brayton system could be accomplished within 32 months.

3.5 MERCURY RANKINE SYSTEM

Technology for the isotopic mercury Rankine electric power system is well advanced as a result of the SNAP-2, SNAP-8 and Sunflower programs. As a consequence of these programs, many thousands of hours of power conversion equipment tests have been accumulated. Knowledge gained from these tests have been integrated into present system designs, thereby resulting in a "proven" system design.

Some disagreement exists between competitors in the power conversion field as to the reliable operation of the condenser in a zero gravity environment. Although some short duration (30 seconds) condensing tests at zero gravity in a KC-135 aircraft have been performed with positive results, the dilemma is still unresolved and will have to await longer duration demonstrations. Similar disagreements exist on the question of turbine erosion by the mercury working fluid.

In spite of these points of contention, the delivery of an isotopic mercury Rankine system is estimated to take 36 months.

3.6 DOWTHERM-A RANKINE SYSTEM

Another Rankine system which has received considerable development attention is one using Dowtherm-A or biphenyl as the working fluid. The selection of an organic rather than a liquid metal working fluid eliminates the problem turbine erosion by poor quality entrant vapor due to the fact that superheating of the organic vapor takes place with expansion. Additionally, the system operating temperatures are lower and result in increased component reliability. The penalty for this feature is larger radiator requirements which can be a significant restraint for some applications. Also the problem of maintaining a stable liquid-vaporinterface in the condenser under zero gravity operation is present in this system as it is in all Rankine systems. Thus the development status of the biphenyl system is about the same as that of the mercury system. Estimated delivery time is approximately 33 months for a flight rated system.

3.7 STIRLING ENGINE

The Stirling engine is perhaps the newest entry into the isotopic dynamic power field. Although the engine was designed, built, and operated in the early part of the 19th century, its development in this country has just recently received impetus. The most outstanding feature of this system is its potentially high efficiency.

Development tests to date have revealed that satisfactory sliding seals for the two pistons remain to be developed. Also the satisfactory zero gravity operation of the crankcase oil mist lubrication system remains to be demonstrated. Although good design practices are followed throughout the system, sufficient test data is not available to adequately predict the system's reliability for missions of any length (several days or longer).

Allison Division of General Motors estimates a 42 month program would be necessary to deliver a flight rated system.

A summary of the systems considered is shown in Table 1. Table 2 depicts some of the available test data for the various systems. The table is not complete because some of the references did not include specific test data.

TABLE 1

STATUS OF ISOTOPIC POWER SYSTEMS

SYSTEM	State-of-the-Art Relative to Thermoelectric	Development Areas Requiring Attention	Delivery Time (Months)
Thermoelectric	Current	Segmented Thermocouple	32
Thermionic	1967	Demonstrated Reliability	42
Brayton	1966	Gas Bearings	32
Mercury Rankine	1966	Zero "g" condensing & turbine erosion	36
Dowtherm-A Rankine	1967	Zero "g" condensing & turbine erosion	33
Stirling Engine	1968	Seals and demonstrated reliability	42

TABLE 2

COMPONENT TEST DATA

CONVERSION SYSTEM	MAJOR SUBSYSTEM	Significant Parameter	Objective	Results
Thermo-electric	Heat Source	Centerline temperature	1680°F	1800°F SNAP 1A SNAP 11
		impact resistance	fuel containment at 450 fps	SNAP 11 impact at 1100 fps
	T/E Converter	T/E couple efficiency	10%	9.5% in lab tests
	Heat rejection	radiator area (1500 W(e))	195 ft^2	255 ft^2 with PbTe couples
	System efficiency	-	-	8.55%
Thermionic	Heat Source	Fuel power density	low as possible	inverted diode can use 1.5 W/cc
		containment	-	excellent as there are no coolant or electrical lead through
	T/I diode	power/diode	300 W(e)	192 W(e) with smaller diode
	"Heat pipe"	heat flux	75W/cm^2	70 W/cm^2 @ 1400°K for 1000 hr
	Heat rejection	radiator area per KW	5 ft^2/KW	3 ft^2/KW calculated
	Reliability	λ (failure/hr)	10^{-7}	to be demonstrated
	System Efficiency	-	-	11%

TABLE 2 (CONTINUED)

CONVERSION SYSTEM	MAJOR SUBSYSTEM	Significant Parameter	Objective	Results
Brayton	CRU	shaft speed	45, 000 rpm	achieved
		gas bearing life	10, 000 hr	to be demonstrated
	Heat re-jection	radiator area	120 ft^2	design value
	Pumps	Power/pump	35 W(e)/ pump	Same as Apollo
	System Efficiency	-	-	18% (sensitive to turbine inlet tem-perature)
Mercury Rankine	CRU	Life	10, 000 hr @ 24, 000 rpm	3556 hr @ 40, 000 rpm - Total ac-cumulated time $>$ 20, 000 hr
		Alternator Voltage	-	22 V @ 1200 cps for 4329 hr.
	Pump	-	-	4000 hr @ $390^{\circ}F$
	Boiler	erosion	-	corrosion product generation 125 mg/in^2 @ $1100^{\circ}F$ for 2500 hr
	Radiator Condenser	area	24. 1 ft^2	design value
	System Efficiency	-	-	12. 1%

TABLE 2 (CONTINUED)

CONVERSION SYSTEM	MAJOR SUBSYSTEM	Significant Parameter	Objective	Results
Dowtherm-A Rankine	Turbine	inlet temp	650°F	demonstrated
	Bearings	MTTF	10^6	possible but must be demonstrated
	Heat rejection	radiator area	60 ft^2	design value
	System Efficiency	-	-	14.4%
Stirling	Heat Source	fuel temp (max)	1870°F	1800°F achieved
	Engine	power piston seals	acceptable wear	3 failures in 950 hr of tests
	Heat Rejection	radiator area	120 ft^2	design value
	System Efficiency	-	-	19.3%

SECTION 4.0

COMMENTS

As evidenced by the information presented in Section 2.0, most of the power system development efforts have been in the area of conversion hardware. There are at least two related reasons for this line of development. First, the lack of specific missions precludes the selection of appropriate isotopes for the mission, and second, the lack of definite information on the availability of isotopes restricts the selection of specific missions. Thus, the cycle is closed, and development of fuel forms is limited to a few "common" isotopes. However, since the temperature limits of the isotope determine the operating temperature of the conversion equipment, the selection of the isotope needs to be made as early as possible in the power system design effort. Hence, the need for arriving at a mutually satisfactory matching of desirable missions with potentially available isotopes is evident. An agreement between the NASA and the AEC on the production of certain desirable isotopes is being investigated at the present time.

Once there is a definite commitment on the availability of isotopes and definite missions are planned which can beneficially employ isotopic power systems, then the competing companies can tailor their systems to the particular missions instead of designing to some fictitious mission. This lack of a mission requirement has led to the demise of several space projects and severely restricted others. A lack of definite direction to the development of isotopic space power systems may result in having to fit future missions to the developed hardware rather than developing the system to fit the mission. The next section discusses possible applications of isotopic power systems to future space missions.

SECTION 5.0

APPLICABILITY OF ISOTOPIC POWER TO AES CONCEPTS

5.1 GENERAL

During the execution of contract NAS8-11096, NSL has investigated a number of concepts for extended scientific exploration of the lunar surface. These studies included such concepts as the MOLAB, the LSSM, the MOLEM, and the LEM Shelter. A discussion of the applicability of isotopic power to each of these concepts follows. Table 3 shows the isotopic power unit size for each concept.

5.2 MOLAB

Under a previous Task Order (N-45) the application of isotopic power systems to MOLAB type vehicles was investigated in detail. The results of these studies showed that power system weight savings of 500 to 1000 pounds are achievable by using an integrated fuel cell/isotopic power system rather than an all fuel cell system. Other significant advantages of these "hybrid" systems were investigated and are discussed in the Task Order final report. Of particular interest is the fact that the optimum power system weights occurred for isotopic power levels of 2.25 kw(e) to 2.75 kw(e). These power levels are of interest because they are indicative of the isotopic power system that could be developed in a modular concept applicable to most roving vehicle designs.

5.3 LSSM

Studies on the power system for the Local Scientific Survey Module led to the selection of an isotopic thermionic unit combined with a battery as the power supply. This particular concept was chosen over a fuel cell system or a battery system. The reasoning and criteria on which this choice was based is given in the final report for Task Order N-56.

The LSSM is a much smaller vehicle than the MOLAB (6500 pounds for MOLAB and 800 to 1500 pounds for the LSSM) and consequently the power requirements are much smaller. The optimum thermionic power was determined to be 0.75 kw(e) or 1.00 kw(e) depending on the

LSSM weight class. For this particular application, the weight savings are small (only a few pounds). However, there are several other advantages to an isotopic power supply, and these are discussed fully in the aforementioned Task Order report.

5.4 SHELAB

The SHELAB is a LEM vehicle which has been modified to provide shelter and accommodations to two astronauts for 14 days. The LSSM is used in conjunction with the SHELAB as a means of transporting the astronauts and their scientific equipment. One of the guidelines in the SHELAB studies was that modifications of existing designs were to be held to a minimum. Thus, the existing fuel cell power system was retained as the primary power supply. However, the power requirements for the SHELAB are about 50% of those for the MOLAB, and consequently substantial weight savings could be expected as a result of combining an isotopic power system with the fuel cell system. Based on past experience, an optimum isotopic power level of approximately 1 Kw(e) is expected. Figure 1 shows the power profile for the SHELAB.

5.5 MOLEM

The MOLEM is similar to the SHELAB except that a mobility system has been added to the shelter. Hence, this concept is somewhat similar to the MOLAB in that the shelter itself is mobile. The power requirements (see Figure 2) for the MOLEM approximates that of the MOLAB and therefore the power system trade-off studies for the MOLAB are applicable to the MOLEM. Allowing for the actual differences in the power profiles, an isotopic power system of 1.0 Kw(e) to 1.5 Kw(e) should result in an optimum nuclear/fuel cell power system weight.

5.6 OTHERS

While the above concepts represent excellent application opportunities for isotopic power, there are other concepts and missions which could beneficially employ isotopic power. Such possibilities include Mars Excursion Modules, Manned Mars Fly-By missions, Lunar Orbit missions, Outer Planetary Probes, Earth-Orbit mission and many others. In particular, isotopic systems would be extremely useful in earth orbit missions of extended duration (2 weeks or longer) requiring 1 to 3 kilowatts of electrical power.

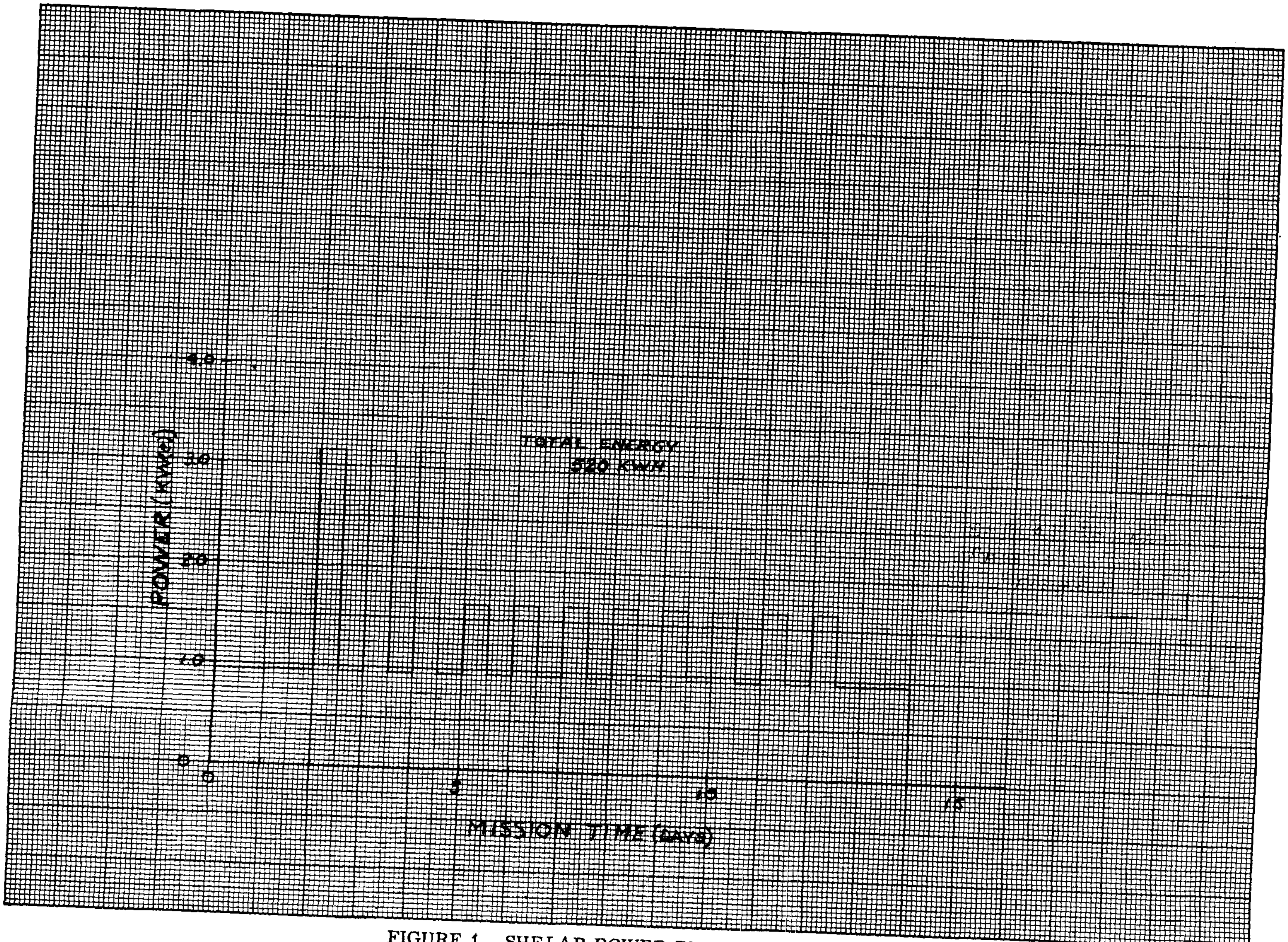

FIGURE 1. SHELAB POWER PROFILE

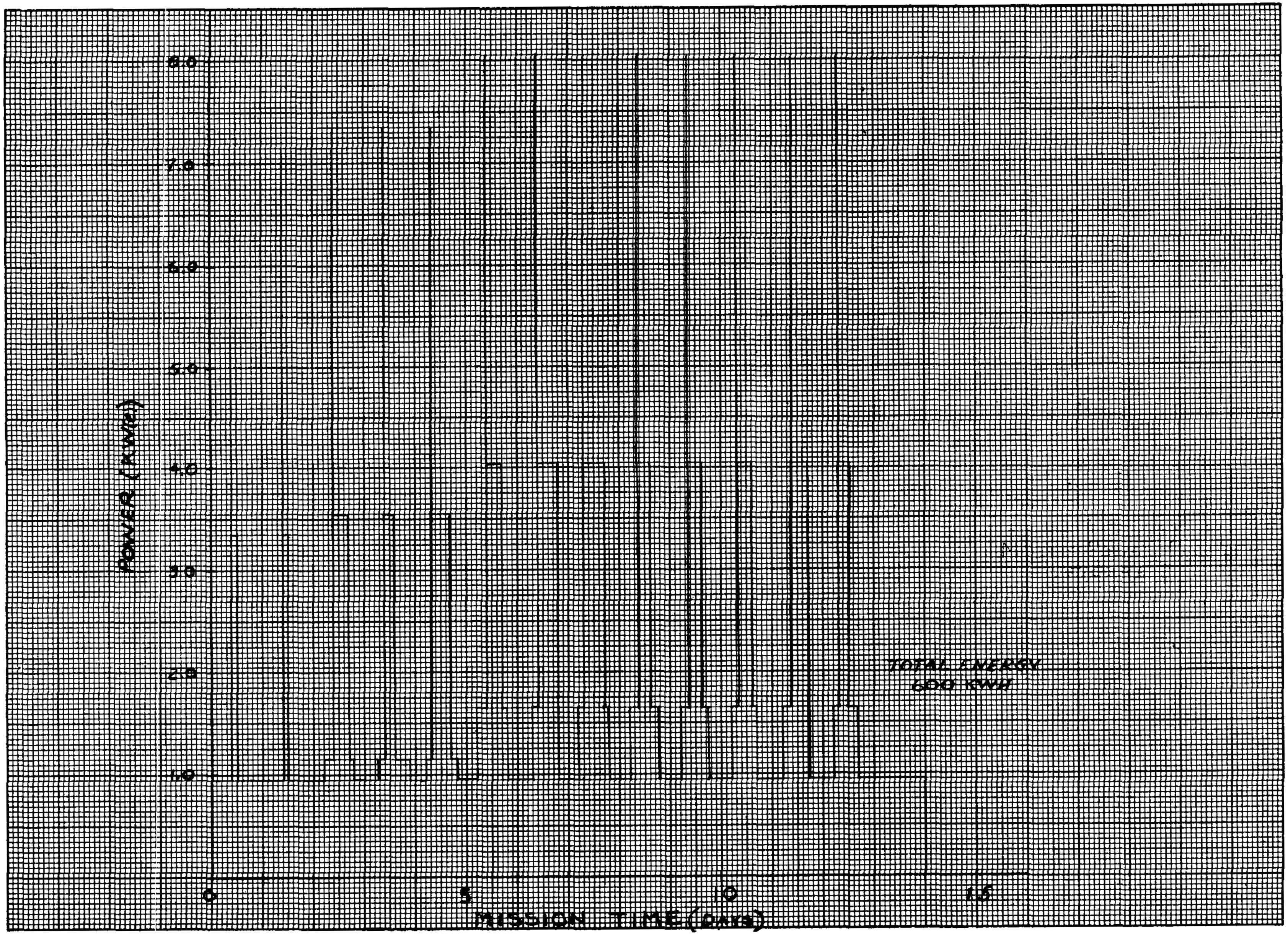

FIGURE 2. MOLEM POWER PROFILE

TABLE 3

ISOTOPIC POWER REQUIREMENTS FOR LUNAR VEHICLES

SYSTEM	ISOTOPIC POWER REQUIRED
MOLAB	2.25 - 2.75 KW(e)*
LSSM	0.75 - 1.00**
MOLEM	1.00 - 1.50*
SHELAB	1.00 - 1.25*

*Value depends on the power system concept, e.g., thermionic or Brayton, etc.

**Value depends on LSSM weight.

SECTION 6.0

CONCLUSIONS AND RECOMMENDATIONS

On the basis of information presented in this document and on the basis of information gathered under other Task Orders to contract NAS8-11096, the conclusion is reached that the technology of conversion hardware is sufficiently advanced to be incorporated into space programs in the 1969 or later time period. Also there are various proposed lunar vehicles and shelters which are excellent concepts in which to incorporate an isotopic power system. Additionally, there are many other missions being planned or proposed which could beneficially employ isotopic power.

Since most development efforts to date have been centered on conversion hardware, it is recommended that an intensive study be established to determine the status of isotopic fuel encapsulation and the associated problem areas. Compatibility of the fuel forms with the electrical generator portion and/or working fluids of the power system will need to be investigated. The study should also include the establishing of guidelines and restraints imposed by the biological hazards of the isotopes during test, assembly, checkout, launch, transit, lunar landing, and manned lunar operations. Such a study would provide the first phases of investigation necessary to establish the guidelines and restraints for a breadboard design of an isotopic system applicable to the LSSM or other lunar surface vehicles.

SECTION 7.0

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