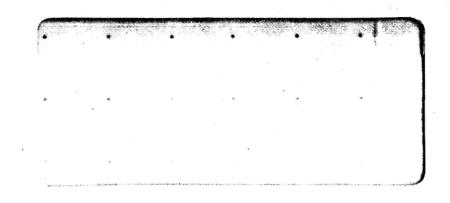N- 104 055

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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

Technical Memorandum No. 33-46

A SURVEY OF ENERGY

CONVERSION SYSTEMS

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Pasadena, California
JUN 2 6 1961

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I. INTRODUCTION

The energy conversion system[1] aboard a spacecraft is that portion of the complete powerplant which converts thermal energy to electrical energy. That is, it receives heat from a source and delivers electrical energy to an electric thrust unit. The application considered here is interplanetary spacecraft, for which some type of nonchemical energy source is assumed.

Conversion systems may be grouped according to type of heat source:

Nuclear (i.e., reactor)

Solar

or according to type of converting elements:

Dynamic (i.e., turbo-generator)

Static:

Electrothermal

Electrochemical

Direct thrust[2]

A brief survey will be made here of the principal types useful for navigation on planetary or space-probe missions; radioisotope-source converters are not considered. The planning of missions and the design of spacecraft to accomplish them requires a familiarity with available and anticipated powerplants. Space exploration, starting from an Earth orbit, requires a powerplant of high

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[1]Variously referred to in the literature as a power conversion system (PCS), energy conversion system, or conversion system: this paper will use the latter term.
[2]Discussed in detail in Ref. 1.

specific impulse, low thrust, and low specific weight; cycle efficiency plays a secondary role.

II. CURRENT PROGRAM

In connection with the responsibility for developing spacecraft for planetary and deep-space exploration, the Jet Propulsion Laboratory is involved in the development of the SNAP-8 conversion system for in-flight propulsion as well as secondary power.

The SNAP-8 system is a nuclear dynamic powerplant for which Aerojet-General Corporation is the prime contractor. Atomics International is developing the reactor, while the conversion system itself is under development by Aerojet-General.

Figure 1 is a cutaway perspective of the SNAP-8 conversion system. The nominal power per unit is 30 kwe; the contractor expects each unit to actually deliver 35 kwe. Two units in tandem, delivering 70 kwe, are needed for a meaningful planetary mission. These two units will operate from a single reactor. In the Figure, the radiator-condenser is shown on the left at reduced scale. Also visible is the mercury boiler and the combined turbine alternator, and mercury pump rotating unit.

Figure 2 shows a flow diagram of SNAP-8. The converter begins with the sodium-potassium (NaK) loop on the left. NaK is pumped through the boiler and back to the reactor. Mercury passes through the boiler in counter-flow and is transformed to slightly superheated vapor. Mercury vapor flows through the two-stage impulse turbine, then to the radiator condenser, then through the

alternator cooling jacket, and from there back to the boiler. The alternator is

a brushless type with a permanent-magnet rotor. The radiator consists of steel

tubes with aluminum armor and fins.

The output of each 35 kwe SNAP-8 unit is as follows:

3-phase (6-phase readily possible)

1000 cycles

43.6/75.6 v ac

20,000 rpm

The SNAP-8 system should be ready for flight in 1965-1966. It will have

an operating life of slightly more than one year.

III. FUTURE CONVERSION SYSTEMS

Table I lists some representative conversion systems, present and

future; it does not claim to be exhaustive. The flight-ready dates are necessar-

ily rough estimates and some specific weights are estimated. Except for the

case of the thermionic systems, specific weight includes the radiator and

assumed shielding (roughly 20% of the conversion system weight), but not the

reactor or the transformation and rectification (or "conditioning") equipment.

Among the dynamic systems, the first is SNAP-2, a 3-kwe system oper-

ating at about 5.7% efficiency and weighing some 300 lb/kwe. Next is the SNAP-8

system discussed in Section II above. A pair of SNAP-8 conversion systems

operating from a single reactor will weigh 45 lb/kwe.

The Air Force SPUR, under development by AiResearch, produces 300 kwe at 12 lb/kwe. The SPUR reactor is not temperature-limited, and can easily supply 1 Mwe of power, at which power level a specific weight of 8 lb/kwe is estimated.

The Aerojet-General Corporation has studied a converter capable of 10 Mwe, weighing 6 lb/kwe in two loops (Li/K) and 5 lb/kwe in the single-loop (K) configuration.

Examining some typical static systems in Table 1, consider first the thermoelectric (thermocouple) type. General Electric has done some developmental work with semiconductor generating elements. The power level is low (5 or less kwe) and a specific weight of about 20 lb/kwe is the best in sight at present. It can be seen in the figure that the thickness of the semiconductor layer is quite important.

The most promising of the static converters--from the standpoint of readily realizable high power and low specific weight--is the thermionic converter. This operates basically as an electronic diode, with heat causing the emission of electrons across a potential difference. The generating elements are incorporated directly in the reactor core, so that reactor and converter are one physical unit; hence, the term "reactor diode." Specific weights for such systems include the reactor. All of the diodes listed are of the cesium-vapor type, the vapor providing a source of ions for neutralization of space charge. General Atomic has studied a 100-kwe system weighing 6 lb/kwe, and a 300 kwe converter at 5 lb/kwe. Marquardt recently proposed a 300 kwe diode system at 3.5 lb/kwe.

Converters of the future--another generation removed--may include types such as the Westinghouse thermionic/thermoelectric combination conver- ter. Thermionic generating pairs characteristically operate at higher tempera- tures than thermoelectric pairs, by their very nature. Westinghouse proposes thermionic elements used in rods in the reactor's hot interior, with thermo- electric pairs used on the reactor's cooler exterior.

Research in another direction has led to proposals for the production of a high-temperature plasma in a reactor, after which the conducting plasma is passed through an electromagnetic field to produce an emf. This has no moving parts, and is known as the plasma-generator converter. It employs the basic magnetohydrodynamic principle. Thompson Ramo Wooldridge has carried out studies on such a converter. Their early model offers considerable promise, and performance data are being evaluated. Other magnetohydrodynamic types are also being evaluated for future reporting.

Those conversion system types offering the greatest promise for high power and low specific weight for space applications have been surveyed. To round out the survey, converters with solar energy sources were also considered. The greatest utility for this type would appear to be nonpropulsive secondary power for communication, attitude control, and trajectory corrections.

The Thompson Ramo Wooldridge Sunflower is a dynamic system, offer- ing 3 kwe at 195 lb/kwe. Sunstrand's converter is a 15 kwe unit of approximately 100 lb/kwe.

Photovoltaic systems convert solar radiation directly to electricity. Here again the thickness of the generating element is very important.

Silicon-cell converters using sheet silicon have been proposed at 1 Mwe and 15 lb/kwe, while film-silicon converters of the same power should drop below 1 lb/kwe. It is not certain whether this last value includes shielding and a solar collector. The great and unwieldy bulk of the required collector is a disadvantage for this type converter--except possibly for Mercury and perhaps Venus missions where the solar constant is much higher than at Mars.

IV. CONCLUSIONS

In summary, large (1-Mwe and up) nuclear dynamic converters should not be much heavier than nuclear thermionic types. The static systems are inherently more reliable, having no moving parts and only a single liquid-metal loop. Also, eventually they should be simpler and cheaper to build. There remain, however, sizeable materials problems of an engineering nature inherent in the thermionic reactor system. Because of these problems, the large dynamic systems appear likely to be ready first. The magnetohydrodynamic types show great promise, but research and development on this type of converter needs much more support.
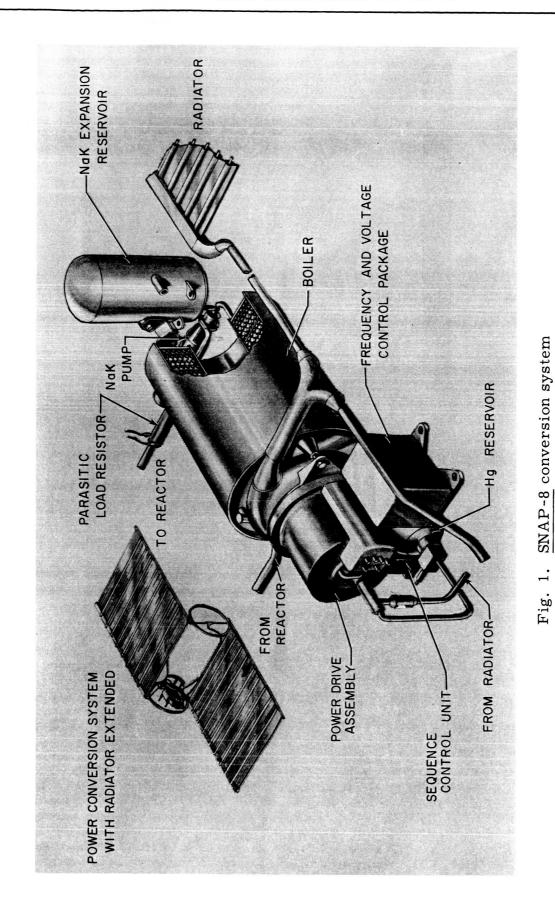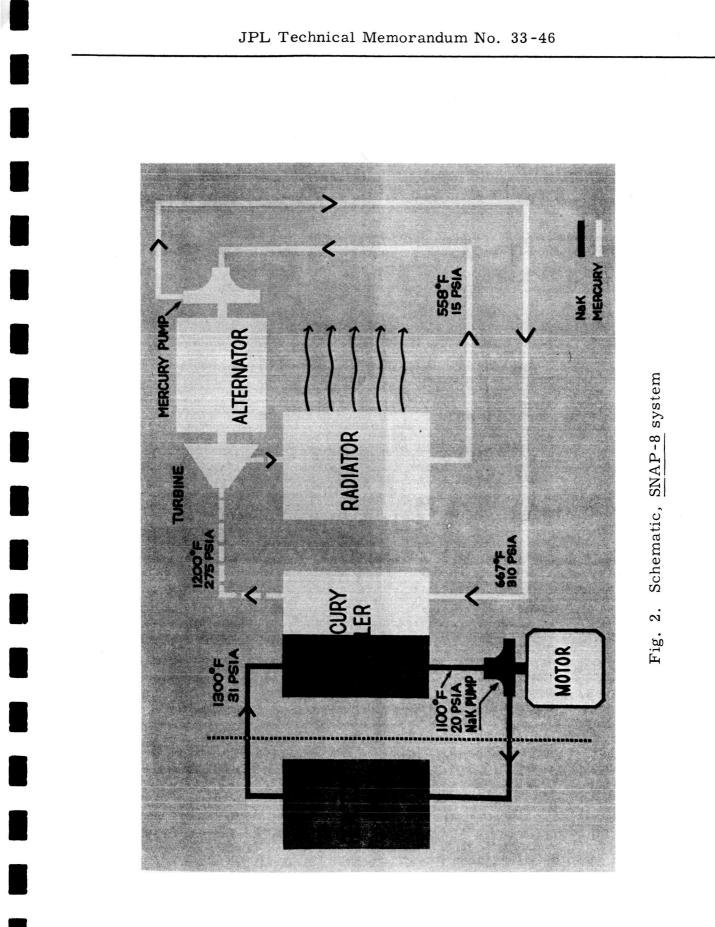
Table 1. Conversion systems summary

Developer, Name	System, Components	Power output, kwe	Specific weight, lb/kwe	Conversion efficiency, η	Radiator temperature, °F	Estimated flight date	Data source (Reference)
				Nuclear Source			
Dynamic Systems (turboelectric)							
TRW, SNAP-2	NaK/Hg	3	300	5.7	600	1963	Ref. 2, 3
Aerojet, SNAP-8	NaK/Hg	70	45	12	700	1966	Ref. 3, 4
AiResearch, SPUR	Li/K	300	12	15	1,050	1967	Ref. 5
WADD, SPUR II	Li/K	1,000	8	16	1,150	1969	Ref. 5
WADD, SPUR III	K	1,000	8	17	-	1971	Ref. 5
Aerojet	Li/K	10,000	6	-	-	-	-
Aerojet	K	10,000	5	-	-	-	-
Static Systems (thermoelectric, thermionic)							
GE	Thermoelectric: Pb-Te sandwich, T_n = 0.1 in.	-	80	1	-	-	Ref. 6
GE	Thermoelectric: Pb-Te sandwich, T_n = 0.1 in.	-	300	4.5	-	-	Ref. 6
GE	Thermoelectric: Pb-Te sandwich, T_n = 0.01 in.	-	20	1	-	-	Ref. 6
General Atomics	Reactor plasma diode, UC/ZrC	0.09	-	10	-	-	Ref. 7
General Atomics	Reactor plasma diode, Li liquid metal	100	6	-	-	-	Ref. 8
General Atomics	Reactor plasma diode, Li liquid metal	300	5	13	1,800	1967	Ref. 8
Marquardt	Reactor plasma diode, liquid metal	300	3.5	-	-	-	Ref. 9
-	Reactor Cs diode, liquid metal loop	1,000	4	18	2,400	1970	JPL int. memo[a]
Westinghouse	Thermionic/thermoelectric[b]	-	-	-	-	-	Ref. 5
WADD	Plasma generator[c]	-	-	-	-	1980	Ref. 5
TRW	MHD generator, gas cooled[d]	-	-	-	-	1980	Ref. 10
				Solar Source			
Dynamic Systems (turboelectric)							
TRW, Sunflower	Hg loop, 1250°F max	3	195	-	600	1963	Ref. 11
Sunstrand	Hg loop	15	100	-	600	-	Ref. 12
Static Systems (photovoltaic)							
GE	Si cells (sheet)	1,000	15	15	-	-	Ref. 13
GE	Si cells (film)	1,000	0.8	10	-	-	Ref. 13
RCA	CdTe cells	-	-	29	-	-	Ref. 13

[a]J. W. Lucas, Engineering Research Section

[b]Internal elements near hot core; cooler elements see space

[c]Hot gases and electric field interact to produce electric potential; no moving parts

[d]Reactor—gas-vortex generator.

Fig. 1. SNAP-8 conversion system

Fig. 2. Schematic, SNAP-8 system

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[*]Presented at ARS Space Power Systems Conference, September 1960, Santa Monica. Many of the papers from this group are published in Vol. 3, Energy Conversion for Space Power, 1961, or Vol. 4, Space Power Systems, of <u>Progress in Astroautics and Rocketry</u> (sponsored by ARS), Academic Press, New York.