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Date: April 27, 1965

To: Mr. P. I. Perry

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From: J. E. Allen

Subject: Comparison of SNAP-50/SPUR System
with MHD, Brayton, Boiling Reactor
and Thermionic Systems

cc: Messrs.

R. I. Strough
R. M. Meyer
A. I. Chalfant
A. Rice
G. Champagne
R. J. d'Arcy
M. T. Hoey
J. A. Marcello
M. Prendergast
G. C. Sinko
V. Stello

SPECIAL REREVIEW FINAL DETERMINATION Class: <u>U</u>	Reviewer	Class.	Date
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-2-

CNLM-6249

Date: April 27, 1965

TABLE OF CONTENTS

	<u>Page</u>
I. Introduction	4
II. Summary	4,5,6,7,8,9
III. Discussion	10
A. SNAP-50 SPUR	10
1. Description	10
2. Performance	10
3. Advantages and Disadvantages	11
4. Status	11
5. Weight	11,12
B. Boiling Potassium Reactor System (MPRE)	13
1. Description	13
2. Performance	13
3. Advantages and Disadvantages	13
4. Status	13
5. Weight	14,15
C. MID System	16
1. General	16
2. Description	16
3. Performance	16
4. Advantages and Disadvantages	16
5. Status	16
6. Weight	17,18
D. Thermionic System	19
1. General	19
E. Inpile Thermionic System	19
1. Description	19,20
2. Performance	20
3. Advantages and Disadvantages	20
4. Status	20,21
5. Weight	21,22

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-3-

Contract AT(30-1)-2789

CHLM-6249

Date: April 27, 1965

	<u>Page</u>
F. Out-of-Pile Thermionic System	23
1. Description	23
2. Performance	23
3. Advantages and Disadvantages	24
4. Status	24
5. Weight	24,25
G. Brayton Cycle (710 GE Reactor)	26
1. Description	26
2. Performance	26
3. Advantages and Disadvantages	26
4. Status	27
5. Weight	27,28,29

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To: P. I. Perry

-4-

CHLM-6249

Date: April 27, 1965

I. INTRODUCTION

How does SNAP-50/SPUR rank among various space electrical power generating systems? This is a question frequently asked and one which I will attempt to answer in this report. It is hoped that a better perspective of how the SNAP-50/SPUR powerplant weights compare with other powerplant systems can be derived from such discussions. The systems which we shall compare to SNAP-50/SPUR are listed below:

1. Boiling Potassium Reactor (MPRE) Rankine cycle.
2. In-File Thermionics.
3. Out-of-File Thermionics.
4. Magnetohydrodynamics
5. Gas Cooled Reactor Brayton Cycle (GE 710 Reactor)

The characteristics of each of these systems are discussed with particular emphasis on specific weight, maximum operating temperature and cycle efficiency. In addition a description of each system, its performance and present status will be reviewed. Much of the information used in this report for thermaionic and MHD systems was obtained from unpublished notes from A. Chalfant and acknowledgment is hereby given.

II. SUMMARY

In general the powerplant weights for all the systems considered are in a range of 16.6 to 33.2 lb/Kwe. The SNAP-50/SPUR system with a specific weight of 21.5 lb/Kwe is felt to represent the most realistic weight since the greatest amount of developmental effort has been expended on this system. Furthermore, the SNAP-50/SPUR performance is based on moderate temperatures (approximately 2000F) at which materials have been developed.

The two systems which were found to have specific weights lower than SNAP-50/SPUR are the magnetohydrodynamic (MHD) and the boiling potassium reactor systems. These systems have specific weights of 16.6 lbs/Kwe and 21.1 lbs/Kwe respectively as compared to 21.5 lbs/Kwe for SNAP-50/SPUR. However, the specific weight of the MHD system is based on a generator efficiency of 68.6 percent. The highest efficiencies which have been obtained from MHD tests are approximately 50 percent. In addition, higher liquid metal temperatures are used (2500F) which requires material development work. The two-phase flow problems and corrosion problems associated with the generator are also felt to be severe and will require a considerable extension of present state-of-the-art.

The system which is felt to be the most competitive with SNAP-50/SPUR is the boiling potassium reactor system (MPRE). This concept is similar to the SNAP-50/SPUR with the primarily lithium circuit and boiler replaced by a boiling potassium reactor. The big question mark for this system however is the ability to boil potassium in the reactor under zero gravity conditions without burning out fuel pins within a reasonable sized reactor package.

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To: P. I. Ferry

-5-

CHLM-6249

Date: April 27, 1965

The other systems such as in-pile and out-of-pile thermionics and gas cooled reactor Brayton cycle system all require high operating temperatures. This means a considerable extension of present material capabilities. Even if suitable materials for these systems are developed, the SNAP-50/SPUR has a lower specific weight.

One of the major advantages expressed by the proponents of the MHD, and thermionic systems, is that no rotating parts are required. However, the 10,000-hour non-nuclear test recently completed at CAMEL has shown that rotating machinery is capable of high temperature, long time operation. The problems associated with the higher operating temperatures of these systems to achieve comparable weights may offset all apparent advantages of eliminating rotating parts.

Table I and II summarizes the results of this study. Table I lists typical maximum reactor and liquid metal exit temperature, cycle efficiency, specific weight and the advantages and disadvantages of each of the systems. Table II shows typical weight breakdowns for each system. The weights were obtained from various external publications. We felt that many of the component weights were overly optimistic and where necessary made new estimates more consistent with those obtained from SNAP-50/SPUR component design studies. These are denoted in the Tables by (CAMEL).

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-6-

Contract AT(30-1)-2789
CNIM-6249
April 27, 1965

TABLE I

	<u>SNAP-50/SPUR</u>	<u>Boiling Potassium Reactor System (MPRE)</u>	<u>Brayton Cycle (T10-GE Reactor)</u>	<u>Thermionic Out-of-Pile</u>	<u>Thermionic In-Pile</u>	<u>MID</u>
Reactor Coolant Temp. F	2000F	1850F	3500F gas exit temp. 563F gas inlet temp.	2600F	2000F	2500F
Max. Fuel Cladding Temp.	2200F	2200F*	3900F*	2800F*	3500F*	2700F*
Cycle Efficiency	15%	15%	12-18%	5-7%	8-12%	5-7%
Heat Rej. Temp.	1200F	1200F	750-1000F	1250F-2600F	1300-1800F	1400F
Specific Weight	21.50 lbs/Kwe	21.1 lbs/Kwe	27.1 lbs/Kwe	33.2 lbs/Kwe	30.6 lbs/Kwe	16.5 lbs/Kwe
Description	Rankine Cycle Boiler, Turbo-alternator, & condensing radiator	Same as SNAP-50/SPUR except for Boiling K reactor	Gas cooled reactor used with Brayton cycle	Thermionic converters used in radiator or heat exchanger	Thermionic converters used in reactor	Magnetohydrodynamic generator system
Advantages	1) High Cycle Efficiency 2) State-of-the-Art well advanced 3) Low Specific Wt. 4) Small reactor size	1) High Cycle Efficiency 2) Low specific weight 3) Fewer number of components than SNAP-50/SPUR	1) Single phase fluid eliminating turbine erosion problems 2) No corrosion problems 3) Minimum number of components 4) Simple and predictable start-up and control	1) No rotating machinery 2) Permits redundancy of thermionic generators 3) Simplicity	1) No rotating machinery 2) Permits redundancy of thermionic generators 3) Low radiator area	1) No rotating machinery

*Estimated

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-7-

TABLE I (cont'd.)

	<u>SNAP-50/SPUR</u>	<u>Boiling Potassium Reactor System (MPRE)</u>	<u>Brayton Cycle (710-GE Reactor)</u>	<u>Thermionic Out-of-File</u>	<u>Thermionic In-File</u>	<u>MHD</u>
Disadvantages	1) Large number of components 2) Control of liquid vapor interfaces during startup	1) May require more shielding due to activation of liquid metal 2) Unknown behavior of boiling LM reactors in space	1) Requires gas bearing & seal development 2) Requires high temp. reactor 3) High reactor wt. 4) High radiator area 5) Heavy structures for containing high pressure gas.	1) Low efficiency 2) Heavy reactor and shield 3) DC power conditioning difficult	1) Low efficiency 2) High temp. technology required 3) Heavy reactor and shield 4) DC power conditioning difficult 5) Fission gas venting in reactor required	1) Low cycle efficiency 2) Corrosion and erosion of insulators and metal ceramic joints 3) Heavier reactor and shield due to low cycle efficiency.

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-8-

Contract AT(30-1)-2789

CHIM-6249

April 27, 1965

TABLE II

POWERPLANT WEIGHTS

1. SNAP-50/SPUR WEIGHT BREAKDOWN
(Direct System)
(CAMEL Estimate)2. MPRE (Boiling Potassium/ORNL)
(CAMEL Estimate)
Reference-CHIM-6206

Max. Liquid Metal Outlet Temp. 2000F

Max. Liquid Metal Outlet Temp. 1850F

<u>1200 Kwe System</u>		<u>300 Kwe System</u>	
Reactor	4200	Reactor	1500
Primary System	1440	Power Conv. System	420
Power Conv. System	5540	Main Radiator	1385
Heat Rejection System	11,670	Aux. Radiator Structure,	2240
Structure Controls & Subsystems	2900	Controls & Subsystems	900
Total	25,750 lbs	Total	6445 lbs
Specific Wt.	21.50 $\frac{\text{lbs}}{\text{Kwe}}$	Specific Wt.	21.5 $\frac{\text{lbs}}{\text{Kwe}}$

<u>300 Kwe System</u>	
Reactor	1500
Power Conv. System	1870
Main Radiator	1652
Aux. Radiator Structure,	
Controls & Subsystems	900
Total	6334 lbs
Specific Wt.	21.10 $\frac{\text{lbs}}{\text{Kwe}}$

3. 1 Mwe MID POWERPLANT
Weight Estimate (East Hartford)
(SA-62, SA-40)

Max. Liquid Metal Outlet Temp. 2500F

Reactor	4200 lbs (CAMEL)
Power Conversion System	2680 (E.H.)
Heat Rejection System	6780 (CAMEL)
Structures, Controls, Subsystems	2900 (CAMEL)

Total Weight 16,560 lbs
Specific Weight 16.56 lbs/Kwe-Looks optimistically low!

MID Generator Efficiency = 68.6%

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CHLM-6249

April 27, 1965

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-9-

TABLE II (cont'd.)

POWERPLANT WEIGHTS

4. INPILE THERMIONIC SYSTEM
(GE - MSD Estimate)
(GE-64-SD-700)

Maximum Fuel Clad Temperature - 3450F

1 Mwe System

Reactor & Primary System	4500 (CANEL)
Power Conditioning System	6540 (GE)
Heat Exchangers	530 (GE)
Primary Radiators	14,536 (GE)
Secondary Radiators	1644 (GE)
Structures & Subsystems	2900 (CANEL)

Total	30,650 lbs
Specific Weight	30.65 lbs/Kwe

5. OUT-OF-PILE THERMIONICS SYSTEM
CONVERTERS IN HEAT EXCHANGERS
(APR 1046) (PUNA-East Hartford Est.)

Maximum Liquid Metal Outlet Temp.-2500F

1 Mwe System

Reactor	4200 lbs (CANEL)
Primary System	6757 (E.H.)
Heat Rejection System	7780 (E.H.)
Power Conditioning	4064 (4 lbs/Kwe E.H.)
Structures & Controls	2900 (CANEL)

Total Weight	25,700
Specific Weight	25.7 lbs/Kwe

6. BRAYTON CYCLE

(APM-1206) (PUNA-East Hartford Est.)

Maximum Gas Outlet Temperature - 3000F

1 Mwe System

Reactor	5900 lbs (CANEL Estimate)
Power Conversion System	7850 (E.H.)
Radiator	6860 (E.H.)
Auxiliary Radiator	260 (E.H.)
Low Temperature Radiator	400 (E.H.)
Structure & Subsystems	5840 (E.H.)

Total	27,110
Specific Weight	27.11 lbs/Kwe

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-10-

III. DISCUSSION

A. SNAP-50/SPUR

1. Description

The SNAP-50/SPUR powerplant consists of a Rankine cycle power conversion system with a nuclear heat source and space radiator heat rejection system. Both direct and indirect systems are being considered. The indirect powerplant system consists of four major systems: a lithium power generation system, a potassium power conversion system, a NaK main heat rejection system, and a NaK auxiliary heat rejection system. Columbium alloys are used in the power generation system and power conversion system. Stainless steel is used in the main and auxiliary heat rejection systems. Lithium is circulated through the reactor and transfers the reactor heat to the boiler. Potassium enters the boiler, vaporizes to 100 percent quality or to a slightly superheated condition and is delivered to the turbine where the energy of potassium vapor is converted to mechanical power to drive the alternator. After leaving the turbine the potassium is condensed and sub-cooled in the condensers. The heat of condensation is transferred to the main radiator loop coolant (NaK) which is circulated through the radiator where the condenser heat is rejected to space. The auxiliary coolant, NaK, is pumped to the individual electrical component heat exchangers where it absorbs the waste heat of the components, maintaining them at their required operating temperatures. This heat is then rejected to space by radiation from the auxiliary radiators. In the direct system the fluid leaving the turbine is condensed directly in the radiator and is circulated to the boiler. It should be noted that the use of stainless steel in the direct system may present corrosion and mass transfer problems. These problems are being evaluated by ORNL in a two-phase corrosion loop mock-up of the direct condensing system. If results show the use of stainless steel to be unsatisfactory, columbium alloy radiator tubes or liners can be used.

2. Performance

The SNAP-50/SPUR reactor is designed for 2000F liquid metal temperature operation. The potassium in the boiler enters the turbine at 1850F and 94 psia and exits at 1274F (7.5 psia). The radiator operates at a temperature of approximately 1168F (average) for the indirect system and 1200F (average) for the direct system. These low temperatures permit the use of conventional materials. The cycle efficiency is 15 percent.

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-11-

CHIM-6249

April 27, 1965

3. Advantages and Disadvantages

The major advantages of the SNAP-50/SFUR Rankine cycle powerplant system is the high cycle efficiency, small reactor size, output power in a favorable form for use in electric propulsion and the relatively low temperatures compared to other systems. The major disadvantage is the relatively large number of components with the attendant system complexity. It should be noted that the direct system uses fewer components than the indirect system and is more advantageous from this viewpoint. Another apparent disadvantage is that the system requires operation of rotating machinery with liquid metal bearings for long periods of time. However it has been demonstrated by recent tests at CANEL that rotating machinery is capable of operation for extended periods of time. Liquid metal corrosion of containing materials has been mentioned as a feasibility problem in some discussions of the cycle but tests have demonstrated that potassium and lithium do not corrode or mass transfer to the refractory alloy containment material when adequate control of purity is maintained.

4. Status

The present status of the SNAP-50/SFUR program is a concentrated effort of testing key components for feasibility demonstration. Several subsystem components are presently being tested such as bearings, pump components, fuel pins and reactor pressure vessels. A full-scale prototype boiler test is scheduled for 1968, a reactor test in 1970, and non-nuclear systems test in 1972.

5. Weight

Fig 1 presents a weight breakdown of four typical SNAP-50/SFUR turboelectric systems: 1) 1200 Kwe indirect system 2) 1200 Kwe direct system 3) 300 Kwe indirect system 4) 300 Kwe direct system. As can be seen the specific weights vary from 21.5 lbs/Kwe to 25 lbs/Kwe. These estimates are from CANEL studies and are typical of turboelectric systems. The last column shows a weight breakdown of a 1 Mwe turboelectric system as reported in GE-64SD-700. This estimate was included to give some insight as to the type of estimates published by other organizations. A specific weight of 17 lbs/Kwe was obtained. As can be seen the major differences are in the reactor and primary system, the radiator and the shield. The GE radiator estimate is based on using beryllium as a radiator material. Our radiator estimates are based on stainless steel-copper construction. The GE estimates for the reactor and primary system and shield are felt to be optimistic.

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-12-

CHIN-6249

April 27, 1965

FIG 1

SEAP-50/SPUR WEIGHT BREAKDOWN FOR 300 KWE AND 1200 KWE
DIRECT AND INDIRECT SYSTEM

	<u>300 Kwe</u>		<u>1200 Kwe</u>		
	<u>Indirect System</u>	<u>Direct System</u>	<u>Indirect System</u>	<u>Direct System</u>	<u>G.E. Estimate</u>
Reactor	1500	1500	4200	4200)	2350
Primary System	420	420	1440	1440)	
Power Conversion System	1855	1385	7300	5540	5900
Heat Rejection System	2785	2240	13,130	11,670	9460
Structure, Controls, & Subsystems	925	900	3000	2900	3000
Total Weight - lb	7485	6445	29,070	25,750	20,710
Specific Weight - lb/Kwe	25	21.5	24.2	21.5	17.0
Shield: 10^{13} NVT, 10^7 RAD	1650		6000		*3400
5 x 10^{11} NVT, 10^7 RAD	3300		11,000		

* 10^{11} NVT, 10^6 RAD

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B. Boiling Potassium Reactor System (MPRE)

1. Description

A variation of the SNAP-50/SPUR system can be made by replacing the primary lithium system and boiler system by a boiling reactor. This system is presently being developed by ORNL and is known as the MPRE (Medium Power Reactor Experiment). The MPRE is a Rankine cycle boiling reactor using potassium as a working fluid. The fuel is UO_2 in stainless steel capsules. The system employs a free turbine driven feed pump and plans to employ a turbo-generator developed for the SNAP-50/SPUR program. The containment vessel of stainless steel encloses the separator which directs the liquid back to recirculating jet pumps and the vapor down stream to the turbine. The working fluid is then condensed in a direct condensing radiator and pumped back to the reactor. An auxiliary radiator is also employed in the system for electrical component and bearing cooling.

2. Performance

The reference design power level is 1-Mw thermal (140 Kwe). The reactor exit temperature is 1540F and the condensing temperature is 1040F. The MPRE can however be designed for power levels as low as 30 Kwe and by changing to refractory metals it can be designed for power levels up to 300 Kwe without increasing the size of the reactor core, the radiator or the turbine.

3. Advantages and Disadvantages

The major advantage of a boiling potassium reactor system is the elimination of the boiler and the accompanying components required in the SNAP-50/SPUR system. Proponents of the direct cycle also have claimed the advantage that the system may employ iron or nickel base alloys throughout instead of refractory alloys. The feasibility of using iron or nickel base alloys has not been conclusively demonstrated by corrosion tests, however, one likely disadvantage is the possibility of having to add additional shielding around power conversion components due to liquid metal activation. The major problem affecting feasibility is the unknown dynamic behavior of boiling liquid metal reactors in space.

4. Status

To date 7-rod and 91-rod boilers have been operated with water and work is in progress with these tests using potassium. The present objectives include a full scale 241-rod boiler electrically heated mock-up in FY-66, an MPRE hot critical experiment in FY-66, startup of MPRE in FY-68 as well as concurrent component performance and endurance tests and fuel element impile tests. The design of the test facility is continuing and a contract has been awarded for the containment shell and vacuum system.

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-14-

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5. Weight

The MPRE system and SNAP-50/SPUR system weights have been previously compared in a CANEL study. Results of this study are summarized in CNLM-6206 and are shown in Fig 2. As can be seen from Fig 2 the ORNL specific weight estimate for a 300 Kwe powerplant system differs by a factor of approximately 3 from the Pratt & Whitney-CANEL estimate. These weight differences are attributed to CANEL results being based on detailed component and vehicle design studies. The ORNL estimates are typical of early SNAP-50 studies before detailed studies were performed. The exclusion of some powerplant and vehicle components in the ORNL estimate also accounts for some of this difference.

The CANEL weight estimate is based on scaling up the basic 140 Kwe MPRE reactor to satisfy requirements of a 300 Kwe system. The power conversion system is based on that of the 300 Kwe SNAP-50/SPUR reference design using direct condensing radiators. The reactor circuit and boiler of the SNAP-50/SPUR powerplant are replaced by a boiling potassium reactor. In addition, 1) a regenerative heat exchanger was included in the system to reduce thermal stress levels in the reactor, 2) the SNAP-50/SPUR pump weight was increased by 30 percent to account for the increased head rise, and 3) a piping length of 80 inches from the reactor to the turboalternator and 80 inches from the regenerative heat exchanger to the turboalternator was assumed. Power conversion system component weights as presented in Fig 2 are a result of the most recent design study (FWAC-651).

A potassium vapor temperature of 1850F was used for compatibility with the SNAP-50/SPUR power conversion system, however, the ORNL estimate is based on 2000F potassium leaving the reactor. This imposes a weight penalty on the radiator since a higher heat rejection temperature results in a reduction of radiator area and weight. For example, a difference of approximately 1.5 lb/Kwe is obtained by increasing the radiator temperature from SNAP-50/SPUR design conditions to 1350F (ORNL design estimate for 300 Kwe system). However, increased component temperatures require additional structural support which would tend to effect the radiator weight advantage of a higher temperature system. Furthermore this weight difference is almost insignificant compared to the large total weight differences existing between CANEL and ORNL estimates.

The reactor weight is based on an estimate obtained from CNLM-6178. Although this estimate is based on a scale up to a temperature of 2000F, it is felt to be representative of a boiling potassium reactor at the 1850F SNAP-50/SPUR design conditions.

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-15-

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CHLM-6249

Date: April 27, 1965

FIG 2

MPRE WEIGHT ESTIMATE

	<u>300 Kwe System</u>		<u>140 Kwe System</u>
	<u>CAMEL</u> <u>Estimates</u>	<u>ORNL</u> <u>Estimates</u> <u>(ORNL 3748)</u>	<u>Estimates</u> <u>(ORNL 3748)</u>
Reactor	1500	850	750
Turboalternator	808	500	300
Frequency Converter	37	-	
Transformers	65	-	
Potassium Pump	150	50	30
Jet Pump	10	-	
Regenerative Feed Heater	40	40	20
Accumulator	40	-	
Valves and Actuators	100	-	
Piping	410	120	70
Potassium Inventory	210	50	50
Main Radiator	1652	950	1080
Auxiliary Radiator	412	60	30
Low Temperature Cooling Radiator	84	-	
Structures	623	-	
Controls	200	-	250
Electrical Distribution (400 cps)	220	-	
Total:	6561 lbs	2720 lbs	2580
Specific Weight:	20.25 lbs/Kwe	9.06 lbs/Kwe	18.42 lbs/Kwe

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-16-

C. MHD System

1. General

Exploratory research and theoretical analysis have been carried out on a number of "closed cycle MHD" systems which could, in principal, be applied to produce power in space. This method of conversion requires that a fluid media be made very hot and conductive. By accelerating and passing the fluid media through a strong magnetic field an EMF is produced. Direct current can be extracted from the system by placing electrodes in the fluid stream. The use of both ionized gases and vapors (single phase MHD) and liquid metal (two-phase MHD) as a fluid media has been studied. Only in the case of the two-phase approach has the technology advanced to the point where a definite space power system can be proposed.

2. Description

There have been many variations of this system proposed, however, a typical two-phase system consists of two flow circuits. The primary circuit in which the reactor is located heats a fluid such as lithium to a high temperature. This fluid enters a two phase nozzle as a saturated liquid. A fraction of the lithium working fluid vaporizes and expands in a nozzle. Part of the vapor leaving the nozzle is separated and diffused to low velocities. This vapor is then condensed and pumped back to the reactor. The remaining mixture is diffused to the liquid state where its high velocity is converted into electrical energy in the MHD generator and returned to the reactor.

3. Performance

A typical reactor outlet temperature for this system is approximately 2500F. A typical space radiator temperature is approximately 1400F. A net efficiency of 5-7 percent can be obtained from this system.

4. Advantages and Disadvantages

The primary advantage of this system is the elimination of all rotating machinery. The principal disadvantage is its low efficiency due to losses in the separator and nozzle as well as the MHD generator. Heavier reactors and shields are required for this cycle due to the low cycle efficiency. Problems of liquid metal erosion and corrosion of insulators and metal ceramic joints are prevalent. Liquid level control is difficult.

5. Status

The two-phase system with separator is being investigated in a research and development program at JPL. Preliminary experiments on the liquid slug type of converter are being conducted at BNL.

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-17-

6. Weights

The unshielded specific weight for the MHD system as reported in Pratt & Whitney memos SA-62 and SA-40 and shown in Figure 3 is 11 lbs/Kwe. Since there was no reactor weight presented for this system, the SNAP-50/SPUR reactor weight was used. It should be noted that the reactor outlet temperature on which the MHD system is based is 2500F, whereas the SNAP-50/SPUR reactor outlet temperature is designed for 2000F. Therefore the reactor weight should be greater both due to the higher temperatures and lower cycle efficiency. The efficiencies of the EM pumps and MHD generators for the system seem to be overly optimistic. The pump and generator efficiencies assumed were 50 and 68 percent respectively. So far, the highest generator efficiency which has been obtained in actual tests is 50 percent. The pump weights of the MHD heat rejection system were increased to partially account for the high values of the component efficiencies assumed.

The MHD heat rejection system weights are quite low and were scaled to agree with the design weights of the analogous SNAP-50/SPUR components.

Structure, controls and subsystem weights given for the MHD system are much smaller than for the 1 Mwe SNAP-50/SPUR system, and it is not unreasonable to expect these weights to be compatible. For this reason the structures, controls and subsystem weights were increased.

Incorporating the weights and weight changes discussed above and shown in Figure 3, the MHD unshielded system specific weight has been increased to approximately 17 lbs/Kwe. It should be pointed out that this system was not based on a detailed design study and weight increases are anticipated.

~~CONFIDENTIAL~~

To: P. I. Perry

-18-

Contract AT(30-1)-2789

CHIM-6249

Date: April 27, 1965

FIG 3

1 MWE MID POWERPLANT (L1)

SA-62 & SA-40

Reactor*	4200	
Power Conversion System	2680	
Two phase nozzle	360	
Separator	180	
Vapor Diffuser	550	
Liquid Diffuser	190	
MID Generator	1200	
EM Pump	200	
Heat Rejection System	2290	
Heat Exchanger Condenser	220	800**
EM Pump	740	1480**
Radiator	1330	4500**
Structures, Controls, Subsystems	1810	2900**
Total	10,980 lbs	16,560 lbs
Specific Weight	11 lbs/Kwe	16.56 lbs/Kwe
Shield* 10^{11} to 10^{13} nvt-l	11,000 to 6000	

*Same as SNAP-50/SPUR 1-Megawatt System
**CAMEL estimate

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To: P. I. Perry

-19-

CHIM-6249

Date: April 27, 1965

D. Thermionic Systems

1. General

Thermionic power conversion systems directly convert thermal to electrical energy. The system works like a radio tube or gas discharge tube. Electrons are boiled off a hot metal surface called the cathode. These electrons have enough energy to move through an intervening space to a cooled electron collector called the anode. The driving potential so created can be used to cause a current to flow in an external load. Although several types of converters are being considered, the most promising appears to be the cesium cell. The cell consists of an emitter (cathode) which operates at a temperature sufficiently high to permit electron emission rates of approximately 10 amp/cm², a collector (anode) which accepts the electrons; a space between the emitter and collector which is permeated with cesium vapor, a cesium reservoir which is maintained at a temperature corresponding to the desired cesium vapor pressure; a container which houses the cesium vapor and prevents contamination of the plasma space by air or other undesirable substances; and hot and cold electrical leads from the emitter and collector. The ionized cesium vapor is used to neutralize the space charge which would otherwise be built up near the cathode by emitted electrons. The flow of electrons is from the emitter through the cold lead to the load, through the hot lead, and back to the emitter.

For space power these cells can be coupled with a reactor system. The heat generated from the reactor is used to heat the cathode. The anode is cooled by circulating a liquid metal coolant around it and rejecting this waste heat from a radiator. The cells can be located within the reactor or within a radiator or heat exchanger system. The former is called an "inpile system" the latter an "out-of-pile system."

E. Inpile Thermionic System

1. Description

A typical inpile thermionic fuel element as described in FWA-2319 is presented below:

Each cesium converter consists of a thin-walled cylindrical tungsten-25 rhenium cathode cladding a UC-ZrC fuel pellet, a cylindrical Cb-1 Zr anode around the cathode, and a tungsten-25 rhenium cathode support which separates the fission gases from the cesium vapor. The fuel elements are connected in pairs to form a dual element. Each dual element contains a tubular lead housed in the element and enclosures. The leads electrically connect the anode of one fuel element with the cathode of the adjoining element. The tubular lead is coated with high density, high purity BeO insulation to prevent arcing from the high voltage electrical lead through the cesium vapor to ground. Dual elements are assembled to form a hexagonally-shaped fuel assembly. The dual elements are welded at their upper end stems to a small plenum which supports the assembly by a single support

OFFICIAL USE ONLY

To: P. I. Ferry

-20-

Contract AT(30-1)-2789

CHLM-6249

Date: April 27, 1965

stem. Housed in the upper tip of the support stem is the cesium reservoir which supplies cesium to all of the elements in an assembly. The lower ends of the elements are contained in a single enclosure through which passes an electrical lead which allows the electrical current generated in each assembly to be conducted to a collector bus bar located in the lower plenum of the reactor. Fission gas as generated in the fuel contained within each assembly are vented to space through the electrical bus bars and their enclosures.

2. Performance

Inpile converter designs employ high power densities to minimize the reactor core size. The power density will be typically 5-10 watts/cm² cathode surface, requiring cathode temperatures in the range of 3000-3500F. Fuel centerline temperatures typically run 3200 to 3800F in normal operation. When a converter cell becomes open circuited and loses the electron cooling effect, its temperature will increase several hundred degrees higher than during normal operation. Fission gases cannot be contained by the fuel matrix or cladding at these high temperatures and must be vented to space. The performance of thermionic converters is only slightly affected by coolant temperature over a wide range; thus a high coolant temperature such as 1800F may be selected to minimize radiator area. If beryllium radiators are available the lowest weights are probably obtained when the coolant temperature corresponds to the maximum usable with beryllium fins or about 1300F. The power conversion efficiency of the converters will typically be in the range of 8-12 percent.

3. Advantages and Disadvantages

Advantages of this system include fewer components and greater simplicity than other systems (excluding the complexity of the reactor itself), a smaller radiator area than other systems and multi-element reliability in the power conversion device. Also no mechanical rotating parts are required as the pumps can be of the dc Bd type. Disadvantages include a large reactor size which would require a greater amount of shielding, the necessity of providing fission gas venting, the requirement of high temperature, and low cycle efficiency. System weights are sensitive to the form in which the power is used for propulsion. If it is used as high voltage dc in an ion thruster, a weight penalty is involved in conversion of the low voltage dc to high voltage. If a plasma type thruster could be used the weight penalty would be low.

4. Status

A few inpile tests have demonstrated cell lives exceeding one thousand hours. These tests have not gone to the fuel burnups required to demonstrate fission gas venting of the fuel over a reactor lifetime. Owing to the fact that they were conducted in thermal reactors they have exposed the insulating materials to far lower integrated fast fluxes than they would encounter in

OFFICIAL USE ONLY

To: P. I. Perry

-21-

CHIM-6249

Date: April 27, 1965

the fast spectrum thermionic reactor. Thus the ability of the fuel to vent and the ability of the insulators to withstand fast neutron flux are two outstanding problems. Furthermore the reactor must contain cesium supply ducts, fission gas vent ducts, and electrical leads in addition to the complex fuel-converter assemblies. The difficulty of maintaining tolerances, leak tightness and purity in such a complex assembly is so great that it must be regarded as a feasibility problem. Large performance penalties are involved if the power is not reasonably flat throughout the core and it is difficult to devise control methods which do not perturb the power distribution. To date only simplified analyses of this difficult problem have been published. The stability and control of the reactor is another problem area.

5. Weight

Fig 4 presents a weight breakdown for a 1-Mwe inpile thermionic system. This estimate was based on a preliminary design study as reported in GE-64SD-700 and is felt to be representative of typical inpile systems.

Contract AT(30-1)-2789

To: P. I. Perry

-22-

CHLM-6249

Date: April 27, 1965

FIG 4

1-MWE THERMIONIC POWERPLANT

GE REPORT 64 SD 700

<u>System</u>	<u>Weight, lbs</u>
Reactor and Primary System	4000
Power Conditioning System	5770
Bus Bars	770
Heat Exchangers	530
Primary Radiators	14,536
Secondary Radiators	<u>1,644</u>
Total	27,250
Specific Weight	27.3 lbs/Kwe
Shield 10^{11} nvt, 10^6 rad	10,000 lbs

OFFICIAL USE ONLY

To: P. I. Perry

-23-

CHLM-6249

Date: April 27, 1965

F. Out-of-Pile Thermionic System

1. Description

This system differs from the inpile thermionic system as the cells are located in the heat rejection system. Other concepts such as the location of the cells in an intermediate heat exchanger which lowers the vulnerable radiator area and therefore radiator armor requirements have been proposed. The thermionic converter for both systems are similar. The converter consists of:

- 1) An inner columbium tube containing the hot reactor lithium coolant.
- 2) Thermionic cells consisting of tungsten-rhenium cathodes and columbium alloy anodes.
- 3) An outer tube which, in the radiator system, is a thin liner inside the meteoroid barrier. In the heat exchanger system a columbium jacket provides the heat transfer surface for waste heat removal by the shell side coolant.
- 4) Beryllium oxide insulation to isolate the cathode and anode electrically from the tubes and coolant.

Heat from the reactor coolant (lithium) is conducted radially to the cathode. The intervening thermal resistances are those of the lithium film, the tube wall, and the electrical insulation, the latter being the largest. The net result is a cathode temperature significantly lower than the reactor coolant outlet temperature. Transfer of heat energy not converted to electrical energy takes place within the thermionic converters by radiation across the cesium gap from cathode to anode, by conduction through the cesium plasma, and by conduction through and radiation from the cathode-to-anode electrical leads and support structure. The lead material is tantalum, with the geometry optimized for maximum converter efficiency. Cesium vapor is supplied to the converters from reservoirs which may be common to one or more converters.

2. Performance

A typical maximum liquid metal temperature is 2500F and a typical cathode temperature 2400F. Anode temperatures may be selected for optimum space radiator temperature, typically 1250F. At these temperature conditions the efficiency of the converter cells will be typically 5-7 percent and power density of 1-2 watts/cm².

To: P. I. Perry

-24-

CHUM-6249

Date: April 27, 1965

3. Advantages and Disadvantages

Advantages of the out-of-pile thermionic system include the absence of mechanical components (since dc EM pumps can be used), and the ability to test the power conversion device for performance and reliability as a small low power module. The primary disadvantage is the low power conversion efficiency.

4. Status

Adequate endurance of out-of-pile thermionic converters at the required high temperatures have been demonstrated in several tests. Outstanding technical problems include the development of liquid metal systems capable of providing temperatures of 2500F and above, and the development of insulators which are not excessive thermal barriers. The endurance of converters remain to be demonstrated at high voltages in which several hundred cells are connected in series. Until about two years ago the endurance of converters was in question; corrosion grain growth and other affects being possible life limiting processes. Several organizations have recently demonstrated thousands of hours life of such converters.

5. Weight

The component and subsystem weights of a typical 1-Mwe out-of-pile thermionic system (reported in AFR-1046) is presented in Fig 5. In order to make this consistent with results of the inpile system several adjustments were made. 1) The reactor weight was increased to 4200 pounds which is consistent with SNAP-50/SPUR estimates. 2) The power conditioning equipment was increased to 4 lbs/Kwe which is consistent with later East Hartford reports (FWA-2351). 3) The radiator was scaled to SNAP-50/SPUR type systems and was increased by approximately 7.5 lbs/Kwe. 4) The shield weight and structures and control system were assumed equal to the SNAP-50/SPUR system. Taking all of these changes into consideration a powerplant specific weight of 33.2 lbs/Kwe is obtained. This is consistent with other studies which have shown the inpile system to have an inherent weight advantage over out-of-pile systems.

To: P. I. Perry

-25-

Contract AT(30-1)-2789

CNLM-6249

Date: April 27, 1965

FIG 5

OUT-OF-PILE THERMIONIC 1-KWe SYSTEM WEIGHT BREAKDOWN

	<u>Multiloop in Heat Exchangers</u>	<u>CANAL Estimate</u>
<u>Reactor</u>	1007	4200
<u>Primary System</u>		
Heat Exchanger	6400	
Primary & Secondary Pumps	357	
<u>Heat Rejection</u>		
Radiator & Meteoroid Protection	6200	13,700
Piping & Meteoroid Protection	1580	
<u>Power Conditioning System</u>		
Power Conditioning Equipment	1500	4000
Bus Bars	64	
<u>Structures & Controls</u>	-	2900
Total	17,108 lbs	33,201 lbs
Specific Weight	17.11 lbs/Kwe	33.2 lbs/Kwe
<u>Shield</u>	272**lbs	6000** lbs, 11,000***lbs

*dose level not clear only damage threshold to transistors
16,500 hours, no scatter considerations

** 10^{13} NVT; 10^7 RAD

*** 10^{11} NVT; 10^7 RAD

OFFICIAL USE ONLY

To: P. I. Perry

-26-

CHLM-6249

Date: April 27, 1965

G. Brayton Cycle (710 Gas Cooled Reactor)

1. Description

The Brayton cycle uses a gas cooled fast spectrum reactor as a heat source and a regenerative gas turbine for power conversion. A reactor for this system is presently being developed by General Electric Company and is known as the GE-710 experimental reactor. The 710 Experimental Reactor is a fast spectrum gas cooled UO_2 fueled refractory metal reactor. The primary objective of the program is the development of the reactor for a wide range of future possible applications in the general areas of propulsion and mobile power generation systems. The program of technology development is scheduled to culminate in a reactor experiment in 1968. To attain a reasonable cycle efficiency and a reasonable size space radiator high gas temperatures of the order of 3000F are necessary. Gas cycle pressures tend to be high (500 to 1000 psia) to improve heat transfer and minimize component volumes. The gas leaving the reactor expands through a gas generator turbine and then through an alternator drive turbine. Cooled turbine blades are required to produce turbines with reasonable numbers of stages. The turbine exhaust gas passes through the hot side of a gas-to-gas regenerator and then to a space radiator. The minimum radiator temperature is typically .25 to .35 of reactor outlet temperature and thus the radiator required will be larger than that required by the Rankine cycle. The typical thermodynamic efficiency for the cycle is in the range of 12-18 percent. In the 710 reactor the fuel element is a UO_2 tungsten matrix, clad with tantalum, the pressure vessel is inconel, the forward reflector is stainless steel, the radial reflectors and control drum structure are beryllium.

2. Performance

The design specifications for the 710 experimental reactor experiment in a closed loop arrangement are a power level of 10.7 Mw, gas (Neon-10% He) exit temperature of 3500F, a gas flow rate of 12.67 pounds per second, and a total coolant pressure drop of 34.8 psi.

3. Advantages and Disadvantages

The outstanding advantages of the Brayton cycle are a minimum number of components and simple and predictable startup and control processes owing to the absence of the liquid phase. Disadvantages include a large radiator surface, large and heavy ducting, and a heavy reactor owing to the use of tungsten and gas cooling. Feasibility problems are involved in the nuclear fuel elements which must operate at extreme temperatures and the fabrication of complex cooled turbine blades from refractory alloy materials. The gas bearings also present a difficult development problem.

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To: P. I. Perry

-27-

CNIM-6249

Date: April 27, 1965

4. Status

The significant accomplishments in the program to date are largely in the area of fuel element technology. A 710-type partial-length fuel element has been compatibility tested at 3900F in helium for 100 hours without degradation of fuel element or cladding leaks. Laboratory fuel element samples have performed successfully in excess of 1000 hours at 4000F in helium. Cycle tests from 3900F to 500F in helium on partial length 710-type fuel elements indicate that the fuel elements are able to withstand the thermal stresses and thermally induced strains of high temperature operation. Thermal strain tests of single-hole fuel element samples at 3900F show no deterioration or loss of bonding. Some inpile tests to relatively low burn-up have been completed. Work is in progress to determine test equipment and facilities required to test the 710.

Further work on fuel elements includes more extensive thermal cycle testing to demonstrate reliability and reproducibility. Additional work is required to determine vibrational response characteristics of the fuel element and the influence of test atmosphere, pressure and longitudinal and transverse temperature profiles within the fuel element. Additional tests are required to demonstrate a life capability far beyond intended test duration and cycling.

Much work remains to be done on the other components including completion of a mechanical and thermodynamic design adequately supported by development and proof testing of actual hardware. These tests on control drum and drive assemblies, mixing devices, pressure vessel discontinuities, joints and seals and static structures will verify design assumptions and provide performance assurance prior to operation of the experimental reactor.

5. Weight

Figure 6 presents a weight breakdown of a 1 Mwe Brayton Cycle space powerplant. The unshielded weight of 22.2 lbs/Kwe makes this system competitive with other nuclear-electric systems.

The reactor weight of 1000 pounds does not seem too realistic in comparison to the 710 reactor weight, which coupled with a Brayton Cycle delivers a nominal 1-Mwe of user power. The core and pressure vessel weight of the 710 reactor is approximately 4750 pounds, which should remain relatively constant for either ground or space applications. Assuming that the relative weights of the core and pressure vessel to the control drives, reflector and accessories of a space oriented 710 reactor is the same as that of SNAP-50/SPUR, the 710 reactor for space application would weigh approximately 5900 pounds. This would increase the unshielded specific weight of Figure 6 to 27.1 lbs/Kwe.

OFFICIAL USE ONLY

To: P. I. Ferry

-28-

CHLM-6249

Date: April 27, 1965

The net efficiency of the 1 Mwe powerplant described in Figure 6 is 19.8 percent. This efficiency appears to be quite optimistic and any decrease would lead to a higher system specific weight.

The radiator concept incorporated in this design is a deployable planar radiator. The development of a reliable deployment mechanism which operates in the 1000 psia range would appear to be quite difficult and would add an additional weight penalty to the system. In GE Report 63SD886, the folding radiator concept was found to be approximately 10 percent heavier than the fixed cylindrical radiator. This weight penalty is for a low pressure liquid metal system, and the penalty for a high pressure gas system would be appreciably higher.

Thus, it appears that the weight breakdown given for the 1-Mwe Brayton Cycle with the inclusion of the T10 reactor is overly optimistic and a true specific weight of the system would be well over the 27.1 lbs/Kwe level.

J. E. Allen

JEA:gfd

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Contract AT(30-1)-2789

To: P. I. Ferry

-29-

CHDM-6249

Date: April 27, 1965

FIGURE 6

1-MWE BRAYTON CYCLE SPACE POWERPLANT (APM-1206)

<u>Component</u>	<u>Weight, lbs</u>	<u>CANEL Estimate</u>
Reactor	1000	5900 lbs
Radiator	6860	-
Regenerator	3400	-
Piping	2300	-
Turbo-Compressor	1350	-
Powerplant Meteoroid Barrier	800	-
Auxiliary Radiator	260	-
Low Temperature Radiator	400	-
Electrical Equipment	2040	-
Structure	3800	-
Total	22,210 lbs	27,100 lbs
Specific Weight	22.2 lbs/kwe	27.1 lbs/kwe
Shield 10^{13} NVT - 10^7 RAD gamma	2140 lbs	6000 lbs
1011 NVT - 10^7 RAD gamma		11,000 lbs

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