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INTERIM REPORT...

MASTER

**ECONOMIC FACTORS
OF
MFP THERMOELECTRIC
GENERATORS**

CONTRACT AT(30-1)2605
UNITED STATES
ATOMIC ENERGY COMMISSION

GENERAL INSTRUMENT CORP. -- THERMOELECTRIC DIVISION

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NY00-9701
UC-23, Isotopes-Industrial Technology
A.E.C. Research and Development Report

THE THERMOELECTRIC DIVISION
OF THE
GENERAL INSTRUMENT CORPORATION

INTERIM REPORT
ECONOMIC FACTORS OF MFP
THERMOELECTRIC GENERATORS

Prepared by

M. Barmat

CONTRACT AT(30-1) 2605
U. S. ATOMIC ENERGY COMMISSION

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INTERIM REPORT ON THE
ECONOMICS OF MIXED FISSION PRODUCT SYSTEMS

1

I. INTRODUCTION

The importance of electrical power in remote locations for long term operation has become more apparent to us all in recent years. It is particularly evident to personnel directly involved in the nation's defense capability in this special area. While much of the attention and most of the glamour in remote power supplies is in space usages, many important requirements remain on the ground. One of these important requirements is for an underwater electrical power supply which is long-lasting, reliable, economical and easy to locate in its place of use.

One of the power supplies proposed for this mission is a radio-isotope heated thermoelectric generator, in which a long-lived, static heat source is coupled to a static, energy conversion technique. Several thermoelectric generators utilizing separated fission product radioisotopes have been built for terrestrial missions. While, to date, these devices have met their technical objectives, it does not appear that, even in production, that they will meet the goal of economy. The major reason for this "failure" is the present and future projected cost of the separated radio-isotope and its processing.

Some time ago the General Instrument Corporation suggested the use of "gross" or mixed fission products (MFP) - the unrefined, non-separated nuclear reactor waste product - as the heat source for a thermoelectric generator. A feasibility study⁽¹⁾ was performed under a contract with the U. S. Atomic Energy Commission by General Instrument. As part of this study we surveyed the very large scale development effort towards the solidification and "ultimate storage" of nuclear reactor wastes was being undertaken by the Commission's Division of Reactor Development at many National Laboratories. This effort, coupled with our analytical studies, conclusively demonstrated the feasibility of the MFP thermoelectric generator concept. Thus, the major effort of the current Phase II effort is the design, construction and test of an electrically heated experimental generator. An auxiliary task is the study of the economic, availability and utility factors of MFP generators. This is an interim report on these latter studies.

II SUMMARY

Mixed Fission Products (MFP) for use as a heat source for thermoelectric generators will become increasingly available in the coming years. The Atomic Energy Commission sponsored program on solidification of nuclear wastes is now entering the "hot" bench scale test phase. During this phase approximately 5000 thermal watts of two year old MFP could be produced monthly. Two different types of "hot" calcination pilot plants are planned for installation at the Hanford National Laboratories in the 1964 to 1966 time period. Each of these plants should be able to produce 160,000 thermal watts of two year MFP and 16,000 thermal watts of ten year MFP on a monthly basis. During this phase, MFP costs should be less than \$.15 per thermal watt for two year MFP and \$1.50 for ten year MFP. This cost includes operation of the plant solely to obtain heat sources and sealing the MFP into fuel containers. A full scale plant for a 15,000 Mw (e) nuclear economy is estimated to produce four to five times as much MFP as either of the pilot plants. Costs will be dependent upon AEC policy in effect at the time the plant is operating. If the policy indicates that the full cost be paid by the user, the prices will approximate that obtained from the pilot plant operation.

A conceptual design has been made for MFP fueled generators at several output power levels up to 1000 watts. These are for use at great underwater depths and contain an integral biological shield. A low cost biological shield of high density concrete or cast iron is considered. Economic studies indicate that, in production quantities, a 10 watt generator will cost one tenth an equivalent Strontium-90 generator. Because of the low cost for MFP heat sources, radionuclide generators at the hundred and thousand watt level can be reasonably postulated for the first time. At the kilowatt level costs of \$5 per watt year are achievable while \$50 to \$100 are estimated at the ten watt level.

Currently available ocean-going craft can handle the placement of MFP generators up to the hundreds of watts level. Investigation of other available vessels is continuing.

III. MFP AVAILABILITY

A. Background

There was, at the time of our Phase I study, a large Atomic Energy Commission sponsored program leading toward the fixation of high-level nuclear wastes into solids. This effort is primarily directed at solving the problem of "ultimate" waste disposal in a civilian power economy. However, the Operations Areas concerned with plutonium production have also been extremely interested in this work. The following excerpt from the A.E.C.'s 1961 Annual Report (2) indicates the Commission's interest in and position on this program.

"In recognition of this potential hazard the Commission is promoting research and development along the lines of transforming the wastes to solid form for long-term storage or disposal.

Fixation of high-level wastes in a solid form would not only decrease the bulk volume of the wastes but would also make the radioisotopes relatively immobile, thereby facilitating management of the wastes and decreasing the hazard. Development work is being carried out in one area whereby the wastes would be fixed in solid form and stored in an impervious environment, such as a salt mine, under continuous monitoring.

At the National Reactor Testing Station (NRTS), a 60-gallon-per-hour fluidized bed calciner, designed to demonstrate the feasibility of calcination to dry solids of aqueous aluminum nitrate wastes is undergoing initial tests. Full scale demonstrational studies are expected to commence in 1962. Laboratory studies are also being made to evaluate the applications of the fluidized bed technique to the handling of wastes from reprocessing of plutonium and stainless steel fuels.

Detailed design has been completed at Hanford for a pilot plant of the radiant heat spray calciner developed on a laboratory scale last year. Engineering cold tests and hot cell small-scale experiments will be conducted this year.

Cold laboratory and engineering scale studies are being carried out by ORNL on a pot calcination process for handling power reactor fuel reprocessing wastes. This

work is being done in preparation for a hot pilot demonstration program on the pot and rotary ball kiln calciner which will be initiated at NRTS in 1962. Use of a rotary ball kiln for calcination of zirconium-alloy reprocessing wastes has been under study at Brookhaven National Laboratory with non-radioactive pilot plant tests being run during the past year."

The previously referenced⁽¹⁾ Phase I report gave detailed descriptions of the most important of the fixation processes and they will not be repeated here. These calcination processes are: fluidized bed, radiant spray and "pot."

The fluidized bed calcination "hot" pilot plant at Idaho Falls has been having a considerable amount of equipment and processing difficulties. During this program some of the preliminary development steps were omitted, thus the other process programs are planned to be handled in a more usual development cycle. That is, the following development steps are being planned for both the radiant spray and pot calcination processes:

- a) bench scale - simulated waste
- b) bench scale - "hot" waste
- c) pilot plant - simulated waste
- d) pilot plant - "hot" wastes

B. Status of Calcination Plants

The pilot plant (60 gallons of liquid per hour of throughput) for the fluidized bed calcination process has been in the "cold" checkout phase for over one year at Idaho Falls. Several major difficulties have arisen that give rise to the question of whether the plant will ever be run according to the design specifications. These difficulties include:

- a) control of alpha versus amorphous alumina
- b) control of particle size and density
- c) carry-over of fine particles beyond filters
- d) bypassing of mechanical and rotating seals by fine particles

At the Hanford site the radiant spray calciner process has completed the "cold" bench scale stage. The bench scale equipment (1 gallon of liquid per hour of throughput) has been slightly modified in order to be operated in a hot cell. This modification includes the capability of collecting the

calcined powders in a "pot" and subsequent melt-down to a "clinker" or in to a glassy form by means of a flux. This same equipment setup has also been used as a direct "pot" calciner. At the end of May⁽³⁾ the modified equipment had been checked out in a remote operation mode at the hot processing facility with only minor difficulties. The cell where it is to operate has already been cleared out and decontaminated. A delay in installation has been due to a temporary shortage of electrical workers. These "hot" cell bench scale tests on the radiant spray calciner should be underway in the month of July 1962. Some fifty to one hundred pots are planned to be filled with solids from Purex IWW streams.

A "cold" pilot scale (20 gallons per hour of throughput) radiant spray calciner has been designed by Hanford. Components for the system were largely purchased and on hand when the project had to be temporarily curtailed because of lack of funds. This work will be reactivated with the start of the new fiscal year (FY'63). It is estimated, by Hanford personnel⁽³⁾ that this pilot plant will be operating in the first half of Fiscal Year 1963. The next step in the development cycle - the "hot" operation of the pilot plant stage - is planned for a new Fuel Recycle Pilot Plant at Hanford. This building is now in the Title I engineering phase and initiation of construction is expected in FY'63 with availability planned for August 1964. Thus "hot" pilot plant operation of the radiant spray calciner can be forecast for 1965.

At the Oak Ridge National Laboratory the pot calcination process is receiving primary attention. "Cold" bench scale (.5 to 1.0 gallons of liquid per hour), experiments on the basic process have been completed for some time. Bench scale experiments are continuing, however, on methods of increasing the density of the calcined product as well as incorporation into a glass by means of a flux.

Bench scale tests in a "hot" cell were planned for the spring of 1962⁽⁴⁾. The equipment was prepared and ready, a test plan was worked out - but hot cell availability has pushed these "hot" tests back until the fall of the year⁽⁵⁾.

"Cold" pilot plant scale (20 to 40 gallons of liquid per hour) testing on pot calcining techniques has been underway for almost two years. The work had progressed quite well and planning for a "hot" pilot plant is well underway. A contract was signed⁽⁶⁾ with Lockheed Nuclear Products in Georgia to

construct and install, in one of their hot cells, the "mechanical equipment for demonstration of the pot calciner positioning, connecting and seal procedures." Both the cold pilot plant work and the above mentioned remote mechanical work were going so well that "hot" pilot plant operation at Idaho Falls was optimistically planned for Calendar Year 1963. Due to other factors, it appears that the Idaho Falls Chemical Processing Plant may be shut down in the future. Thus the calcination facility would not have a source of "hot" wastes. It has recently been learned⁽⁵⁾ that the "hot" pot calcination pilot plant is now planned to be installed at Hanford, in the Fuel Recycle Pilot Plant mentioned earlier. Since this facility will not be completed until 1964, the "hot" pot pilot plant could not be expected to be operating until late 1964 or early 1965.

C. Estimate of MFP Availability

Both the pot and radiant spray bench scale "hot" tests will have a throughput of approximately 1 gallon of liquid per hour. For power reactor fuel elements, each gallon of Purex IWW waste has approximately 200 BTU/hr two years after reactor discharge and about 20 BTU/hr ten years after reactor discharge. Thus the hot bench scale tests could theoretically turn out almost 40,000 thermal watts of two year old waste per month on a three shift, seven day, basis (this would be 4,000 watts (t) of 10 year aged waste). But this does not take into account the "pot" changeover time, "pot" sealing time, repairs, and the fact that this is experimental equipment. However, a rate of one fifth to one tenth that mentioned above would probably be reasonably optimistic for these bench-scale tests.

The "hot" pilot plants, as presently designed, should have throughputs of about twenty gallons of liquid waste per hour^(7,8). Furthermore, the systems will undoubtedly be designed with a much higher reliability and thus the actual throughput should be no worse than one fifth the designed rate. Thus 160,000 watts (thermal) of two year waste and 16,000 watts (thermal) of ten year waste should be the monthly capability of these hot pilot plants.

ORNL has undertaken a study to evaluate the economic factors of a full scale pot calcination plant. The result of this study have been published as ORNL monographs (9,10). The hypothetical plant is sized for a 15,000 Mw(e) nuclear economy which is estimated for 1970. It is now felt that this date is somewhat optimistic, although about 4,000 Mw(e) (including

naval reactors) should be operating by 1965. A more realistic date for the 15,000 Mw may be in 1972-1975 period. Table 1 shows how we calculated the capacity of this ORNL projected pot calcination plant and the specific references for the assumptions.

Table 1

ORNL Projected Pot Calcination Plant

Total Heat Output of Plant

Waste volume/yr = 20,300 gal solid/yr (p11, ORNL 3192)

$$= 2,720 \text{ ft}^3 \text{ solid/yr}$$

MFP power density = 3,000 BTU/hr ft³ @ 4 yrs. (p30, Ibid)
(Acid Purex)

$$= 880 \text{ watts/ft}^3$$

$$= 1000 \text{ BTU/hr ft}^3 \text{ @ 10 yrs.}$$

$$= 293 \text{ watts/ft}^3$$

Total thermal watts available = 2,720 ft³/yr. x 880 watts/ft³

$$= 2.4 \times 10^6 \text{ watts @ 4 yrs.}$$

$$= .80 \times 10^6 \text{ watts @ 10 yrs. out of reactor}$$

D. Estimate of MFP Cost

One factor affecting projected system cost cannot be assessed at this time; that is, the cost of the MFP fuel itself. While the MFP itself is a true waste product, obviously, any "special pot" or container would be charged to the user. If a user did not remove the MFP from the processing plant, the processor would have to pay for removal and storage. In contrast, the user pays the separation cost of separated radioisotopes but not for its inherent value. Since the cost of MFP concerns itself with AEC policy, we certainly cannot forecast a decision, but we feel it instructive to indicate the MFP cost if the full plant operating costs were charged the user. Based on the previously mentioned ORNL study of a full scale pot calcination plant, Table 2 shows how and exactly from which source we calculated the incredibly low cost of

\$1.50 per thermal watt, where the thermal watt is being created 10 years after reactor discharge. For a cost comparison to strontium-90, one must consider that it has 154 curies per watt and a 28 year half life. If a five year mission were projected for a strontium-90 heat source, an equivalent cost would have to be less than \$.01 per curie in a packaged form.

Table 2

Cost of MFP From ORNL Projected Plant

Calcining Facility (Operating Cost/yr. 1200 sq. ft. Plant)

= \$650,000 (Table 11, p 27, (ORNL-3192)

Capital Amortization Per-yr. = \$176,000 (Table 9, p25, Ibid)

Tank Farm Storage Operating Cost Per year (Acid&Purex only, 5 yr. interim)

$2/3 \times 150,000 = \$100,000$ (Table 11, p26, ORNL 3128)

Tank farm Capital Cost (5 yr. interim) per year = \$260,000
(Table 12, p26, Ibid)

Total \$1,186,000

Cost per watt (10 years out of reactor) = $\frac{\$1,186,000}{800,000}$

= \$1.48 $\approx$ \$1.50/watt

As noted earlier, the "hot" pilot plants for calcination of MFP are expected to be operating at Hanford in the 1964-66 time period. It would be possible, at the conclusion of calcination experiments, to operate these plants expressly to provide fuel for thermoelectric generators. The full cost for operating these pilot plants would undoubtedly have to be borne by the user. At this stage the costs of MFP should merely be the "hot" cell rental and the operational personnel. Such cost items as equipment amortization and interim liquid storage considered in the full scale plant estimate should not, and are not included here. The cell rental is estimated at \$8,000 per month. The ORNL study⁽¹⁰⁾ estimates a labor rate of \$3.00 per hour and a 50% overhead for cell operators plus a maintenance cost. We have previously suggested three-shift, seven-day weeks. Since two operators will probably be necessary at all times, plus occasional other skills to equal one man, the labor cost is approximated at \$9,500 per month plus \$3,000 for maintenance. These same costs can be applied to operation of "hot" bench scales equipment after tests are completed. Table 3 summarizes MFP cost and availability during the various time periods.

Table 3MFP Cost and Availability Summary

	<u>Monthly Availability</u> <u>(Thermal Watts)</u>		<u>Time Period</u> <u>Available</u>	<u>Cost Estimate</u> <u>\$/Thermal Watt</u>	
	<u>2 yr.</u> <u>Wastes</u>	<u>10 yr.</u> <u>Wastes</u>		<u>2 yr.</u> <u>Waste</u>	<u>10 yr.</u> <u>Waste</u>
<u>Bench Scale "Hot"</u> <u>Tests</u>					
Radiant Spray	5000	500	Fall 1962	\$4.00	\$40.00
Pot	4000	400	Winter 1962-63	5.00	50.00
<u>"Hot" Pilot Plant</u>					
Radiant Spray	160,000	16,000	Spring 1965		
Pot	160,000	16,000	Winter 1964-65	.13	1.30
<u>Hot Full Scale</u> <u>Plant</u>	700,000	70,000	1972-1975	.15	1.50

IV. ECONOMICS

A. Design Concepts and Ground Rules

In order to obtain the comparative costs of an MFP thermoelectric generator, it was necessary to postulate a design. Figure 1 illustrates the conceptual design. The center cylinder in Figure 1 contains the MFP heat source and utilizes the same type of configuration as the "pot" or radiant spray calcination process. In addition, it employs a material (Hastelloy C) that will withstand at least 300 years of salt water corrosion and pressures up to underwater depths of 20,000 ft. Surrounding the heat source is another cylindrical container which contains a heat transfer fluid. This cylinder has a tubular coil in intimate contact with it. This coil, by means of a thermosyphon, transfers the heat created by the MFP to the thermoelectric converter. The converter is mounted on, and is in intimate thermal contact with, the outer pressure vessel of the generator. Note that this cylindrical vessel has dished heads to withstand great pressures. Surrounding the pressure vessel is an integral biological shield, in the case illustrated, of concrete.

The temperature drop through the concrete will be in the range of 10°F - 20°F for the 10 watt level. At higher power levels heat conducting bars or loops would be incorporated into the concrete. An outer shield retainer of steel is shown. An alternative design, not illustrated, would employ a cast iron biological shield as the pressure vessel.

While the cylindrical configuration is simpler to construct and utilizes "pots" similar to these to be employed in future calcination processes, it eventually leads to a more costly and bulkier system. A spherical heat source, within certain size limitations (max. 24" O.D. due to projected calcination plant limitations), would materially decrease some important characteristics by as much as 30%. Specific comparisons will be discussed later.

In order to keep the calculated results of various systems on a comparable basis, we established a set of "ground rules" or boundary conditions. Table 4 lists these boundary conditions. While some of these are achievable now, others (10% overall efficiency, MFP energy density of .13W/cc) are projected for attainment in several years.

		SNAP 7A				TABLE 9					SNAP 7E					10 Watt MFP				
Item	Remarks	Quan Gen	Unit Price Matl.	Fab.	Cost Item	Total Gen. Cost	Quan. Gen.	Unit Price Matl.	Fab.	Cost Item	Total Gen. Cost	Quan. Gen.	Unit Price Matl.	Fab.	Cost Item	Total Gen. Cost	Total Gen. Cost	Concrete	Iron	
I Fuels																				
A Strontium-90	Entire operation done @ ORNL - in Generator supplied	48,255c	\$ .380/c		\$15,300		31,000c	\$38/c		\$12,100										
1-Raw Mat'l																				
2-Conversion & Pelleting				\$ .38/c	15,300				\$ .38/c	12,100										
3-Encapsulation																				
B MFP Fuel						\$30,600					\$24,200									
												200 W(t)	\$1.50/w			\$300	\$300			
II Hardware																				
A Fuel Pot	% Costs calc'd on prices for 3000 lb. min. Quantities of Mastelly "C"	25#	\$3/#		75		25#	\$3/#		75			23 #	\$3/#		\$69				
1-Raw Mat'l														\$12/#		\$276				
2-Fabrication				\$12/#	300				\$12/#	300								\$345	\$345	
						375					375									
B. Containers																				
1-Raw Mat'l	Cast in pressure vessel	275#	\$3/#		825								21#	\$ .85/#		\$18				
2-Fabrication				\$12/#	3,300											\$18			\$18	
						\$4,125														
C Pressure Vessel																				
III Shielding																				
A Depleted Uranium	Inc. pattern & Mach'ng charge for 100 castings	1432#	\$4.40#				54#	\$4.40/#												
1-Raw Mat'l (ingot)																				
2-Cast Mat'l				\$7/#	10,000				7/#		378									
						10,000														
B Mechanite																				
1-Raw Mat'l (ingot)	Inc. pattern & Mach'ng charge for 100 castings						2764 lbs.						12,000#	\$ .19/#				\$2,280		
2-Cast Mat'l									\$0.19/#	525										
											\$ 525									
C Iliminite concrete																				
1-Poured concrete																				
IV Outer Liner																				
TOTAL						\$45,100					\$25,478									
												2080#	\$ .85/#			\$920	\$2,071		2,942	

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	TEMPER			DESCRIPTION			
	DIMENSIONAL TOLERANCES UNLESS OTHERWISE SPECIFIED						
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± 1/64	± .005	± 30'	CHECKED	DATE	DRAWING NUMBER		ISSUE
NEXT ASSY.			APPROVED	DATE	18-A		

Table 4

Technical Boundary Conditions for MFP Systems Study

1. Mission Life	.... 5 years
2. Age of waste at start of life	.... 4 years out of reactor
3. MFP energy density at end of life	..... 0.13 W/cc
4. Fuel capsule shall be a single cylindrical "pot"; rather than a cluster of small pots.	
5. Void volume in fuel capsule	.... 5%
6. Overall generator efficiency	.... compute for 2.5%; 5%; 10%
7. Insulation thickness	.... 4"
8. Thermal conductivity of insulation	.... 0.01 BTU/hrft °F
9. Shielding requirements	.... shield for 10 mr./hour at 1 meter from surface and 200 mr/hr at surface
10. Complete generator shall be inside shield.	
11. Shield materials	.... concrete at 230#/ft ³ (magnetite or iliminite aggregate) and cast iron.
12. Place of installation	.... underwater @ 20,000 ft (9,000 psi)
13. Pressure vessel shall have ellipsoidal domes.	

b. Cost Estimates for MFP Generators

Based upon the previously described design and set of technical boundary conditions, we calculated the costs for 10; 200; and 1,000 watt cylindrical generators. Tables 5, 6 and 7 summarize these calculations. Figure 2 graphically shows the effect of power output, efficiency and shield material on the cost. Figure 3 shows the effect of these same variables on overall weight. The figures and curves really speak for themselves. Incredibly low costs can be forecast for MFP fueled systems. For the first time one can seriously consider, in terms of cost, radioisotope fueled systems to provide power at the kilowatt level. If one considers only the five year mission life and ignores the

MFP GENERATOR OUTPUT

VS.
COST FOR VARIOUS EFFICIENCIES
& SHIELDS

EUGENE DIETZEN CO.
MADE IN U.S.A.

NU. 540-L-1-1ETZ-1 RAP. ...ER
LOGARITHMIC
3 CYCLES X 3 CYCLES

WATTS

LEGEND
25% ———
5% - - -
10% ———

THOUSANDS OF DOLLARS

FIG. 2

MFP GENERATOR OUTPUT VS WEIGHT FOR VARIOUS EFFICIENCIES & SHIELDS

EUGENE DIETZGEN CO
 MADE IN U.S.A.

ETZEL - PAPER
 LOGARITHMIC
 3 CYCLES X 3 CYCLES

FIG. -3

TABLE 5

Weight & Cost Summary - 2.5% Efficiency

Item	Unit Cost\$	10 WATT				200 WATT				1000 WATT			
		Weight #		Cost \$		Weight #		Cost \$		Weight #		Cost \$	
		Conc.	Iron	Conc.	Iron	Conc.	Iron	Conc.	Iron	Conc.	Iron	Conc.	Iron
Fuel	@1.50 watt	14	14	600	600	270	270	12,000	12,000	1,360	1,360	60,000	60,000
Fuel Pot (Hastelloy)	@6-15 #	41	41	615	615	920	920	8,280	8,280	4,120	4,120	24,720	24,720
Heat Tank	@.85 #	33	33	28	28	190	190	161	161	550	550	468	468
Insulation		?	?	50	50	?	?	100	100	?		150	150
Pressure Vessel	@.85	366	366	311	311	1,850	1,850	1,573	1,573	5,900	5,900	5,015	5,015
Shield-Concrete	@.013	31,785	-	413		72,220	-	940		131,790	-	1,713	
Iron	@.19		19,500	-	3,705	-	47,525		9,030	-	99,882	-	18,978
Outer Shield Retainer	@.85	1,397	-	1,187		2,490	-	2,117		3,975	-	3,379	
Sub Total I (S.T.I.)		33,635	19,954	\$3,204	\$5,310	77,940	50,755	\$25,171	\$31,144	147,695	111,812	\$95,445	\$109,331
Thermoelectric converter		(\$20/watt)		200	200	(\$10/watt)		2,000	2,000	(\$5/watt)		5,000	5,000
Sub Total II (S.T.II)				\$3,404	\$5,510			\$27,171	\$33,144			\$100,445	\$114,331
Misc. Cost (10% of S.T.II)				340	551			2,717	3,314			10,045	11,433
Assembly Cost (35% of S.T.II)		(35% of S.T.II)		1,191	1,929	(30% of S.T.II)		8,151	9,943	(25% of S.T.II)		25,111	28,583
Total Cost				\$4,935	\$7,990			\$38,039	\$46,401			\$135,601	\$154,347
Overall Dimensions		Conc.		Iron		Conc.		Iron		Conc.		Iron	
Length		92"		66"		122"		90"		172"		140"	
Diameter		69"		43"		90"		59"		100"		68"	

TABLE 6

Summary 5% Overall Efficiency

Item	Unit Cost\$	10 WATT				200 WATT				1000 WATT			
		Weight #		Cost \$		Weight #		Cost \$		Weight #		Cost \$	
		Conc.	Iron	Conc.	Iron	Conc.	Iron	Conc.	Iron	Conc.	Iron	Conc.	Iron
Fuel	1.50 watt	6.8	6.8	300	300	135	135	\$6,000	6,000	680	680	30,000	30,000
Fuel Pot (Hastelloy)	@6-15	22.8	22.8	342	342	578	578	5,202	5,202	2,460	2,460	14,760	14,760
Heat Tank	@.85	20.7	20.7	18	18	131	131	111	111	350	350	298	298
Insulation		?		50	50	?		100	100	?		150	150
Pressure Vessel	@.85	249	249	212	212	1,296	1,296	1,102	1,102	3,758	3,758	3,194	3,194
Shield -concrete	.013	22,000	-	286	-	51,910		675		86,365		1,123	
- iron	@.19	-	11,930		2,276		30,763		5,845	-	60,343	-	11,465
Outer Shield Retainer	@.85	1,084		921		1,978	-	1,681		2,888		2,455	
Sub Totals I (S.T.I.)		23,383	12,229	\$2,129	\$3,189	56,028	32,903	\$14,871	\$18,360	96,501	67,591	\$51,980	\$59,867
Thermoelectric converter	\$20 watt			200	200	(\$10/watt)		2,000	2,000	(\$5/watt)		5,000	5,000
Subtotal II (S.T.II)				\$2,329	\$3,389			\$16,871	\$20,360			\$56,980	\$64,867
Misc. cost (10% of S.T.II)				233	339			1,687	2,036			5,698	6,487
Assembly cost		(35% of S.T.II)		815	1,186	(30% of S.T.II)		5,061	6,108	(25% of S.T.II)		14,245	16,217
Total cost				\$3,377	\$4,914			\$23,619	\$28,504			\$76,923	\$87,571
Overall Dimensions		Conc.	Iron			Conc.	Iron			Conc.	Iron		
Length		76"	50"			100"	69"			129"	98"		
Diameter		65"	39"			86"	55"			96"	65"		

TABLE 7
Summary 10% Efficiency

Item	Unit Cost\$	10 WATT				200 WATT				1000 WATT			
		Weight #		Cost \$		Weight #		Cost \$		Weight #		Cost \$	
		Conc.	Iron	Conc.	Iron	Conc.	Iron	Conc.	Iron	Conc.	Iron	Conc.	Iron
Fuel	1.50 watt	3	113	150	150	67	67	3,000	3,000	340	340	15,000	15,000
Fuel Pot (Hastelloy)	@6-15	14	14	210	210	313	313	2,817	2,817	1,642	1,642	9,852	9,852
Heat Tank	@.85	13	13	11	11	87	87	74	74	252	252	214	214
Insulation		-		50	50	-		100	100	-		150	150
Pressure Vessel	@.85	192	192	163	163	885	885	752	752	2,700	2,700	2,295	2,295
Shield-concrete	@.013	14,766		192		39,445		513		66,560		865	
-iron		-	8,380		1,592		24,255		4,608		44,270		8,411
Outer Shield Retainer	@.85	833		708		1,640		1,394		2,417		2,054	
Sub Total (S.T.I.)		15,821	8,602	\$1,484	\$2,176	42,437	25,607	\$8,650	\$11,351	73,911	49,204	\$30,430	\$35,922
Thermoelectric converter		(\$20/watt)		200	200	(\$10/watt)		2,000	2,000	(\$5/watt)		5,000	5,000
Sub Total II (S.T.II)				\$1,684	\$2,376			\$10,650	\$13,351			\$35,430	\$40,922
Misc. (10% of S.T.II)				168	238			1,065	1,335			3,543	4,092
Assembly		(35% of S.T.II)		589	832	(30% of S.T.II)		3,195	4,005	(25% of S.T.II)		8,858	10,230
Total Cost				\$2,441	\$3,446			\$14,910	\$18,691			\$47,831	\$55,244
Overall Dimensions		Conc.		Iron		Conc.		Iron		Conc.		Iron	
Length		64"		42"		90"		62"		108"		78"	
Diameter		59"		37"		80"		52"		95"		64"	

fact that these systems will probably provide useful (within 30% of rated power) for an additional 10 years; costs per watt-year are in the range of \$50 to \$100 at the ten watt level and as low as \$10 at the kilowatt (e) level.

In considering costs, we have assumed both a completely developed generator and production tooling. Thus, costs are representative of the twentieth or fiftieth system. The specific bases for the cost of individual items are listed in Table 8. All the material and fabrication costs were obtained for representative parts from legitimate vendors in the past three months. Some explanation should be stated, however, concerning the thermoelectric converter cost estimates. Thermoelectric converter costs are estimated for the time period after 1965 as being about \$20 per watt at the 10 watt level, \$10 per watt at the 100 watt level and \$5 per watt at the Kilowatt level. These low costs are predicated upon the use of completely bonded bismuth telluride couples and the attendant low production and material cost. If a complicated spring loaded, lead telluride converter were used, this cost could go up considerably.

After completing these calculations and after discussions with personnel at the National Laboratories, it was realized that spherical rather than cylindrical heat sources would be both desirable and practical. We, therefore, calculated the effect of the length to diameter ratio of the cylindrical MFP fuel pot configuration on the weight of the cylindrical biological shield. Figure 4 shows the results of these calculations and compares these results with the biological shield weight for a cylindrical shield with rounded corners as well as a completely spherical one. The great savings to be accomplished by a spherical generator are obvious.

The energy density of MFP is an unknown variable, depending upon reactor operation. Although a fairly representative value for power reactors was chosen for the previous computations, it was felt useful to determine the effect of this variable. In order to show the type of trend to be expected, we calculated the overall generator cost and weight for various energy densities. We chose the 200 watt, 5%, spherical generator as the test case. The results are shown in Figures 5 and 6. It is extremely interesting to note that the overall weight

FIG-4
EFFECT OF MEFP FUEL
GEOMETRY ON SHIELD WEIGHT

CONDITIONS
 $\eta = 5\%$
 $P_0 = 200W$
CYLINDRICAL FUEL
FOR
Fe BIOLOGICAL
SHIELD

FIG-6
EFFECT OF MFP ENERGY DENSITY
ON GENERATOR COST

Table 8Specific Bases for Generator Costs

MFP Fuel	\$1.50/watt
Hastelloy Fuel Pot	\$6.00 to 15.00/lb. in finished form depending on size
Steel Heat Tank	\$.85/lb. in finished form
Thermal Insulation	\$1.00/lb.
Steel Pressure Vessel	\$.85/lb. in finished form
Shield-concrete	\$100/cubic yard installed or \$.013/lb.
iron	\$.19/lb. in finished form
Steel Outer Shield Retainer	\$.85/lb. in finished form
Thermoelectric Converter	\$20/watt @ 10 watt level 10/watt @ 100 watt level 5/watt @ 1000 watt level
Misc. (supports, leads, seals, wire)	10% of system cost.
Assembly	35% @ 10 watt level 30% @ 100 watt level 25% @ 1000 watt level

and cost are quite insensitive to MFP energy density. If the MFP energy density is only one tenth that projected, the overall weight is only doubled and the cost goes up by two and a half times. The major cost item for the lower energy density MFP is the Hastelloy C fuel container which also must be a pressure vessel after 300 years of corrosive effects. The dotted curve of Figure 6 shows a substitution of a Hastelloy C clad steel which will meet the same corrosion and pressure criteria as the solid material. In this case the cost differential due to lowering the MFP energy density by a factor of ten is about 50%.

C. Cost Comparison to Strontium - 90 Generators

As part of this economic study, we were asked to compare generators with MFP and Sr-90 heat sources. Table 9 presents a summary of this comparison. We utilized the design of SNAP-7A and SNAP-7E to obtain vendor quotations for mechanical hardware based on production quantities. It was assumed that the thermoelectric portion of the generator would be equal in cost for both generators. It is felt that this is a conservative assumption for the MFP generator since the cost of bismuth telluride will be continuously decreasing due to the economic pressures of the thermoelectric cooling field. A bonded converter will undoubtedly be far less expensive to build in quantities than a machined, hand assembled unit.

The assembly of the generators were also considered to be identical in cost.

Table 9 has a blank in the place for a cost estimate for encapsulation of the Sr-90 pellets, since we have been unable to ascertain a realistic price.

In comparing the three generators, several factors become immediately apparent. First, the major cost factor of the SNAP-7 generators is their fuel while this is a minor factor in the MFP unit.

It is probable that even if the Sr-90 fuel were without cost, the pelletizing and encapsulation would cost at least ten times that for the completely sealed MFP source. Secondly, the SNAP-7A has extremely costly container and shield materials, probably far beyond those needed. Thirdly, in the final analysis, any low cost design

features incorporated into an MFP generator could also be incorporated into a Sr-90 generator and only the relative fuel and shielding costs remain to be compared. It seems unlikely that even under the most optimistic conditions that Sr-90 will cost less than \$.10 per curie. Presently the cost of the raw separated material is \$0.38 per curie. Again, most optimistically, it appears that conversion, pelletizing and encapsulation of Sr-90 will never cost less than \$.05 per curie. Thus, on a wattage basis the MFP heat source will cost 15 times less than on equivalent Sr-90 heat source. The shielding factors, however, favor the Sr-90 generator. Because of gamma contributors in the MFP, the shielding for a Sr-90 generator is about one fourth that required for an MFP generator. There are, however, low cost shield materials that can be utilized in integral shields. As indicated earlier and shown in Table 9, high density concrete and cast iron act to maintain the large differential cost between Sr-90 and MFP generators.

Since the MFP generator is much heavier than the Sr-90 generator, it was necessary to investigate the transportation costs. The cost of rail transportation from Hanford to Newport News, Virginia is \$5.03 per hundred pounds. Thus for a 5% MFP generator with an iron biological shield, the transportation cost should be about \$600. This cost for a Sr-90 generator would appear to be less. There is a further problem however. It is that large amounts of radioisotopes, such as contained in either generator, require special handling conditions in rail shipment. This special handling entails the use of a special gondola or flat car and less than maximum weight loads. Thus the cost is predominantly for the special car rental rather than on a weight basis. This car rental is approximately \$1640 (4) for an empty carrier, Oak Ridge to Hanford. Since this is the same for either generator, the transportation costs for the two generators are roughly equal.

V. UTILITY OF MFP GENERATORS

The primary goal of the MFP - thermoelectric generator concept has always been the attainment of low cost electricity while retaining all the advantages of nuclear power. As shown in the previous section of this report, this goal appears to be within our grasp.

One of the optimum uses, we feel, of MFP generators will be in bottom-mounted, underwater missions. The specific missions await definition by the many ASW system studies now underway. It is interesting to note that many of the systems being considered are being discarded because of the lack of a suitable electrical power supply that, in large quantities, would not bankrupt the nation.

As was noted earlier (Tables 5, 6 and 7), the use of an integral shield with an MFP generator may not seriously affect its cost, but it certainly affects its weight and size. The overall system size and weight might well affect the ultimate utility. A quick perusal of industrial supply catalogs certainly demonstrates that 50 and 100 ton cranes and booms are not a difficult nor costly items. Thus handling of large items on land will probably not cause any undue difficulty. The seaborne handling may be another matter. We have not yet examined all potential sources of information but that data now available is certainly encouraging. To date we have contacted the Coast Guard and the U. S. Navy Underwater Sound Laboratory (USNUSL) in New London for information.

First, there is no problem of physical dimensions. USNUSL has been handling units as large as 26 feet in diameter and 30 feet long. The U. S. Coast Guard regularly handles buoys that are 8 feet in diameter and 26 feet long on their "Large" Buoy Tenders. The largest unit we contemplate - 1000 watts output at 2.5% efficiency - would be about 8 feet in diameter and 14 feet long.

The problem of weight is more difficult. USNUSL has modified the boom on one of their ships to handle a 15 ton load. They do not see any technical difficulty in being able to handle up to 50 tons (11). There are 53 Coast Guard "Large" Buoy Tenders now in service and these are tested to be capable of handling 30 tons although they regularly only use 20 tons (12). Within these limitations, units up to several hundred watts (see figure 3) could be handled. Furthermore, "Jane's Fighting Ships" (13) lists several U. S. Navy vessels that might be useful in this work, i.e. deck cargo ships outfitted for arctic use, assault cargo ships, salvage vessels, ocean going tugs, seaplane tenders, etc. The Point Barrow, for instance, a deck cargo ship, can carry 8,000 tons of cargo and has "overhead gear for general cargo." A seaplane tender must be capable of lifting a 50 ton aircraft out of the water.

Further inquiry will be made on the capability of these ships.

Another possibility for handling large weights is a "Flying Crane". The Sikorsky S-64 helicopter, which is now operational, has a maximum load carrying of 10 tons. Studies are now being conducted on a helicopter with a 20-ton load capacity. It is "safe to predict there will be a 20-ton heavy lift vehicle available within the next ten years." (14) Sikorsky Aircraft is somewhat more optimistic, forecasting "undoubtedly, a 40 or 50 ton payload helicopter-crane within 10 years."

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