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AN EVOLUTIONARY APPROACH FOR A COMPACT-SPLIT-CORE REACTOR

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ABSTRACT

An economical approach for advanced reactor power development is presented, and systems that result from the several stages of this plan are described. The development starts with a highly modularized heat-pipe, radioisotopic design and evolves into a low-specific-weight, high-performance reactor system.

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SUMMARY

A plan for merging several nuclear power developments is presented. The use of heat pipes, modular concepts, a split-core-reactor design, and plutonium fuel provides for an orderly series of nuclear power systems ranging from a 160-watt radioisotope thermoelectric generator to a low-specific-weight, 30-kWe nuclear thermionic design for space power. The general characteristics of these systems are described.

INTRODUCTION

Changes in the direction and in the priorities of the NASA space program have had a major effect on space power. This reevaluation of schedules and systems required coupled with attempts to standardize developments and procurements has resulted in a complete restructuring of the space power program. All nuclear space reactor developments have been stopped and the supporting technology extensively curtailed. Only a modest effort in RTG developments is retained. The merit of this decision to abruptly stop the nuclear reactor space program has been and undoubtedly will be argued at length. But with the present budgetary constraints it is obvious that a space power program based on several reactor designs cannot be conducted in a meaningful fashion.

This paper attempts to examine a possible method of maintaining some effort towards the development of an advanced space reactor as a part of the radioisotopic power system program. Budgetary changes are not presented, but instead a technologically oriented argument for a coordinated research and development is outlined.

THE DEVELOPMENT CONCEPT

The small budget available for nuclear space power requires that any reactor development plan depart drastically from past practice. But nonetheless, an evaluation of some aspects of the recent history of space power as well as an examination of future needs is useful in establishing elements of a new development approach. Some observations are (1) the ratio of nonrecurring-to-recurring costs of reactor development is extremely high; (2) the competitive space power systems have absorbed much of their nonrecurring costs, are improving performance characteristics, and are introducing cost saving procurement procedures, which means the competition to nuclear power is tough to beat; (3) apparently no near future NASA missions require nuclear reactor power, and furthermore the future needs can probably be achieved at powers far less than the 240 + kWe powers projected for nuclear-space-power reactors in the mid 1960's; and (4) uniqueness of a mission capability is demanded for justification of any significant effort and this requires that the system approach does not sacrifice performance potential.

As a result of these observations several premises for the development of an advanced reactor system have been made at the onset:

(1) The design should be adaptable to as broad a market as possible, since NASA needs alone, without possible commercial and DOD applications, may not warrant a reactor development program.

(2) Although not required in the early stages of the development plan, a growth potential to a system of uniquely high performance must be provided.

(3) Since reshuffling of old approaches cannot provide the competitive edge required, new advanced technologies must be used in the development. Also the plan must provide for the orderly incorporation of new possibilities that arise during the development period.

(4) If possible the early stages of the plan should be initiated as a minor perturbation of ongoing programs to provide the experience that may lead to the acceptance of the approach.

(5) The approach should also provide for several decision points where the key elements of the basic design can be evaluated before the commitment of significant funds.

The undertaking described herein was not technically feasible a few years ago, but now several technological advances can be combined to provide an opportunity for a unique reactor development concept. The ingredients are: heat pipes, improved refractory metal alloys, new fabrication methods, new developments in energy conversion systems, and increased availability of improved nuclear fuels.

The advantages of heat-pipe cooled reactors have been alluded to in many recent publications (refs. 1 to 3). For example, the large number of independent heat transfer elements provide redundancy and eliminate the single point failure mode of most liquid-cooled reactors. The many separate heat transfer paths allow a relatively inexpensive statistical evaluation of the reactor coolant system. Single elements and clusters of heat pipes can be tested to provide a modular, scalable design. Heat pipes eliminate conventional pumps. This saves electrical power and is particularly important at reactor startup, idle, and shutdown. Cooling is available for the reactor after-heat that occurs following long periods of nuclear operation. Heat pipes tend to make the core more isothermal thus to reduce stresses, mass transport, and peak temperatures.

Heat pipes also give a great deal of design flexibility. In the proposed system heat pipes are arranged to carry heat out of both ends of the reactor. The reactor is symmetric about the midplane and a split-core reactor results. Control can be achieved by relative motion of the two halves. An extremely large shutdown margin exists at large separation distances. Indeed, the assembly, final machining, fitting, and preflight testing can be conducted on the two independent neutronically noncritical sections. Test costs of the assembly can be significantly reduced by building only half a reactor, designing the system so that it can be tested by heating the core with electrical heaters inserted at the reactor midplane. This will be discussed in more detail later. Finally should launch safety requirements dictate small fuel inventories, the heat-pipe cooled split core permits separate launches of the noncritical halves. The subsequent assembly in orbit appears feasible if the reactor is designed appropriately.

Although heat pipes have the major impact on the capability of providing new reactor design concepts, other recent developments are also important. Recent refractory metal alloys provide high temperature strength and corrosion resistance. New methods such as chemical vapor deposition permit the fabrication of complex shapes with a minimal number of welds.

Also a variety of energy converters have been developed as a part of the space power program that have both space and terrestrial uses. Small Brayton systems are emerging that yield efficiencies greater than 20 percent at powers as low as 500 watts (ref. 4). Silicon, germanium thermoelectric converters maintain quite stable operation at source temperature near 1100° C. These thermoelectric converters can be used in a cascaded form for terrestrial use. Thermionic converters have demonstrated stable operation for over 46 000 hours. Thermionic efficiencies in excess of 10 percent are being observed at temperatures around 1800° K, a temperature level that appears suitable for stable fuel-pin and heat pipe operations. These new energy converters provide the growth potential needed to make reactor systems competitive.

Nuclear fuel technology has advanced to the stage where most of the problem areas have been established so that designs and operating conditions can be selected to provide reasonable life times. The growth of the water reactor program will provide a greater availability of plutonium giving an additional degree of freedom in the selection of fuels.

These developments in themselves could provide for a low cost reactor development, but in an examination of the space-power needs for the next decade it is difficult to justify a major reactor development since radioisotope thermoelectric generators will meet most of the immediate power requirements. But some level of space power reactor research and development appears to be desirable if only to provide some continuity of this technology to the time of its inevitable resurrection.

Obvious questions then arise: Is there a way to blend the on-going developments with space-power-reactor research and development without a major perturbation in budget requirements? Can a logical evolutionary plan be constructed that starts with an advanced RTG that transcends into a reactor development? Of course our answer is yes. The new technological developments do permit an RTG to be the precursor to an advanced reactor concept.

An approach leading to a fast-spectrum, split-core reactor is illustrated in figure 1. The steps include (1) the development of a 160-watt RTG for space or earth use, (2) a 440-watt RTG for earth use, and (3) reactor systems. The first step keeps the amount of plutonium-dioxide fuel (238) used in the RTG less than the smallest critical mass and thus eases some launch safety problems. The second step uses the same fuel in a configuration that meets the needs of a RTG with higher power and that is dimensional identical to half the reactor core used in the final design. And the last step, the reactor phase, uses the 239 isotope (or blends of 238 and 239) of plutonium, again the form of the oxide.

The early development retains the same source temperature and thermoelectric converter design for three options. All three developments include electrical heating prior to commitment to the more expensive fueled tests. Only after successful fueled demonstrations of an RTG or a thermoelectric reactor system would the high-temperature regime of thermionics be entered.

The development starts with the simplest system, a 160-watt RTG shown in figure 2. The basic elements in the RTG are the fuel elements; heat pipes in the housing; the housing; converter heat pipes; the silicon, germanium thermoelectric converter; and radiators.

The steps in the development of the 160-watt RTG include the usual tests of the individual parts, subassemblies, and finally the entire unfueled system. Since the early phases of the plan lead to the thermoelectric reactor, evaluation of the parts include exploratory tests at the reactor conditions. The temperatures are essentially the same for all components but thermal fluxes differ. The most significant change is the reactor testing that is required for the fuel pin in the intermediate stage of the program.

Before any of the somewhat expensive fuel pin tests are started the general feasibility of the design approach can be established by low cost nonnuclear evaluations. The unfueled test of the assembly is achieved by inserting electrically powered radiant heaters into holes normally occupied by the fuel pins. This procedure provides a complete evaluation of the system and also can be extended into life tests of all parts (excluding the fuel pins). After satisfactory system performance is established individual fuel pin tests can be initiated, and if they are satisfactory the pins can be introduced into an assembly that already has a demonstrated performance capability.

The RTG-to-reactor development has stimulated sufficient interest at LeRC to carry the plan from a loosely defined concept to the fabrication of a full scale model. This exercise partially verified our estimates on low costs because of the ease of making and assembling the various cylindrical parts. A series of photographs of the model in figure 3 illustrates the simple design and assembly of this 160-watt RTG. The detailed design of the components and their adaptability to a variety of applications will be discussed in a later section.

Figure 3(a) is a photograph of a full scale model showing the basic parts of the system excluding the hermetic enclosure, insulation, and electrical connections. A molybdenum cylinder that is precision bored to receive the fuel pins and the various heat pipes is the main structural element. The modular elements consist of seven (or six) plutonium dioxide fuel pins, 24 housing heat pipes (sometimes referred to as core heat pipes), four temperature-smoothing heat exchanger heat pipes, three converter heat pipes, and three vapor-chamber- (heat-pipe) cooled thermoelectric modules.

A partial assembly of the RTG is shown in figure 3(b). A clearer understanding of the design and assembly can be achieved by examining the photographs in conjunction with the drawing in figure 2. Three fuel pins, 12 core heat pipes, and four temperature-smoothing-heat pipes have been inserted in the housing.

All of the core heat pipes and fuel pins have been inserted in figure 3(c). The four temperature-smoothing heat pipes are now completely inserted into the rear heat-exchanger portion of the housing. As can be seen in the photograph and the drawing, six core heat pipes surround each fuel pin. These pipes are used to carry the heat to the rear heat-exchanger portion of the housing. The use of a heat exchanger between the converters and the fuel pins minimizes the problem of a propagating failure, provides multiple heat paths, establishes easier thermal matching of the various components, and permits the extensive use of simple reliable cylindrical shapes. This design also lends itself to increased versatility in meeting a variety of power requirements.

Figure 3(d) shows the completely assembled housing with all converter heat pipes in place. The converter heat pipe uses an evaporator that has the same diameter as the fuel pin. This simplifies the housing fabrication, improves heat transfer, and reduces temperature drops. The smaller condenser diameter was selected on the basis of a brief optimization study of the thermoelectric module. From both efficiency and weight considerations high thermal fluxes are desired at the hot leg of the thermoelectric converter.

Finally, figure 3(e) shows the assembled device. The separation distance between the converters and the thermal source is arbitrary, and the design shown represents the closest coupling that appears to be practical. The actual unit will include a container that surrounds the housing and is sealed to the inner face of the thermoelectric elements. The container is insulated on the inside and contains an inert gas to protect the refractory metal components from chemical attack. The outer face of the thermoelectric converters will also be sealed and will have provision for electrical connections.

The unit should develop 162.5 watts at beginning of life (~54 watts per converter) with a 1383-$^{\circ}$K maximum at the interface between the fuel and its clad. This is about 340-$^{\circ}$K lower than that estimated for an RTG of similar power being developed today. The reason for this difference is that the present RTG primarily relies on radiant and gaseous heat transfer. Insufficient data exist to establish whether the combination of high fuel temperatures and simple heat transfer is more reliable than low fuel temperatures and liquid metal heat pipes. The use of heat pipes does, as has been indicated before, provide design flexibility.

Should RTG's with higher power be required another row of fuel pins can be added in a similar but larger molybdenum housing, as is shown schematically in figure 4. The number of fuel pins increases from 7 to 19 and the electrical power grows correspondingly from 162.5 to more than 440 watts.

The power is porportional to the number of fuel pins. The number of converters increases from 3 to 8 and all features of the converters remain the same. However, the length of the heat-pipe adiabatic section between the housing and the converter must be changed to meet layout requirements. Also one converter pipe (located on the centerline) energizes two converters. A symmetric easy assembly results. It is probable that the 19-fuel-pin assembly would be used on earth rather than in space because of the large fuel inventory. The marine and land uses with low temperature rejection capability could incorporate cascaded thermoelectric converters to improve efficiency.

The parts assembly method and appearance and testing procedure for the 19 pin unit are almost identical to those of the 7-pin version. After a 7-pin system is built, tested, and proved acceptable only a minimum effort should be involved to qualify the larger unit.

This similarity continues into the thermoelectric reactor. Two of the 19 fuel pin assemblies form a critical reactor at small separation distances. Only a 5-cm layer of beryllia or molybdenum around the core is required for the radial reflector. Axial neutron reflection is achieved by a minor change to the converter heat pipes as will be discussed later. Reactor control and stability are obtained by methods described in reference 5. The higher power associated with reactor operation probably requires a different electric-heater design in the simulation tests. Heat pipes or electron bombardment could be used.

Specific Characteristics of the System and its Elements

Fuel pins. - The outer diameter of the fuel pin is 3.9 cm and the length, 11.2 cm. Foil-like tungsten disks are sandwiched in the plutonium dioxide to improve the thermal conductivity of the fuel. About 10 percent by volume of the fuel is tungsten. The temperature rise across an average fuel element at a condition corresponding to that of a 5 kWe thermoelectric reactor is about 85° K, approximately one-fourth that of the nontungsten case. About 1 kg of plutonium dioxide is in each fuel pin. The fuel is clad with a metal trilayer consisting of 1 mm of molybdenum bonded between 0.25-mm sheets of iridium. The exposed end is strengthened by increasing the molybdenum layer to 2 mm.

Fuel pin housing. - The two fuel-pin housing designs used in the reactor development plan are shown in figures 2 and 4. The fuel-pin holes, the 1.2-cm-diameter heat-pipe holes in the housing, the converter heat pipe holes, the hole spacings, all lengths and the form of construction are the same for both configurations. The two housings differ only in the number of holes. One additional ring of holes is used for the high-power versions. These two configurations provide for 2.5 isotopic kWt to 300 reactor kWt in convenient steps. The housing is made by stacking 75 precision bored TZM plates that are about 0.25 cm thick. Axial forces are constrained by the 1.2-cm diameter heat pipes and by tie rods. Both the heat pipes and the tie rods are bonded to the housing to improve heat transfer and strength.

Housing heat pipes. - The housing heat pipes are similar for all applications. A radial-groove, artery design made of TZM with lithium fluid is proposed. A heat pipe using these materials has operated at 1773° K for over 10 000 hours. Much longer life times should be attainable with the 1373° K operation for the RTG. Heat pipes designed for cooling a higher-powered split-core reactor (ref. 3) have been tested at axial throughputs in excess of 9.5 kWt/sq cm at 1820° K for over 5000 hours (ref. 6). This flux far exceeds that required in any stage of this development plan. All RTG modes of operation involve axial fluxes that are trivial compared to the reactor conditions. Although thermoelectric reactor operation involves relatively low thermal fluxes, the reduced temperature and lower vapor pressure gives about the same design margin as the higher-temperature thermionic case.

The housing heat pipes are 1.2 cm in diameter and 19 cm long. Those used in the reactors are the same as those in the RTG's except that a molybdenum rod is inserted to form an annular condensing section. The metallic density in the heat exchanger is increased and neutron reflection back into the fuel is improved.

Converter heat pipes. - The converter heat pipes are similar for all applications. Although molybdenum could be used for the wall material, the ductility of tantalum base alloys such as T1-11 appears desirable for most RTG and reactor applications. The converter heat pipe has a 3.8 cm diameter evaporator and is 4.5 cm long. The diameter then reduces to a diameter of 1 to 2 cm in the adiabatic and converter section. The converter heat pipe is the one element that changes with power level since different numbers and types of converters are used at the various power levels. But even though changes are involved this component maintains the same evaporator. The variations in power levels are accommodated by changing the number of heat pipes and the condenser length. The longest heat pipe in the high-power reactor thermoelectric system is about 1 meter long.

The converter heat pipes used in the reactor systems include molybdenum rods in the evaporators that are located in the housing heat exchanger. These rods are sized to provide adequate annular flow areas and a sufficient metallic concentration to assist in the reflection of neutrons back into the fuel. The design of the converter heat-pipe heat exchanger provides compactness and low weight in a configuration considerably simpler than that used in a somewhat similar heat-pipe cooled reactor described in reference 2. In its simplicity this heat exchanger sacrifices some power smoothing, but at the relatively low powers for all phases of this development the simple heat exchanger appears to be the appropriate compromise.

Converters. - The converters for the RTG's and reactor thermoelectric systems are identical. Each module produces about 50 We and consists of five SiGe cylinders segmented into 24 sections. The units are sealed, and the ends are insulated with multifoil material.

A sketch of the thermoelectric converter is shown in figure 5. The design and performance characteristics are based on information contained in reference 7. An efficiency of 6.5 percent is projected for the module used in the RTG. Although this development plan is primarily directed towards space applications the same converter could serve as the first stage of a cascaded thermoelectric generator for terrestrial use. Again the information in reference 7 indicates the terrestrial efficiency is about 13 percent.

Thermionic converters are to be used in the later stages of the reactor development. A cesium diode well suited for this application is described in reference 2. The overall efficiency for the powerplant in an optimized spacecraft using this converter is estimated to be 10 percent.

Other systems such as one based on the Brayton cycle could be used in conjunction with the heat source. The converter heat pipes would then form part of the source heat exchanger.

Radiator. - The radiator for the thermoelectric modules consists of ten, 1.0-cm-diameter stainless-steel, sodium heat pipes arranged to form a flat plate radiator. The designs for the various thermoelectric applications vary only in the length of the heat pipes. High-emissivity coatings are applied to the radiator surfaces in order to improve their effectiveness. The flat plate radiator was selected since it can be arranged to minimize gravitational effects in preflight tests.

Nuclear reactor behavior. - Since each fuel pin contains about 1 kg of plutonium dioxide, two reactor halves will contain about 38 kg. In the conceptual design amount of fuel was estimated from some fairly crude extrapolations of the information contained in reference 8. Specific calculations have now been completed for a core consisting of the parts described above with a 5 cm radial reflector of molybdenum. The hexagonal structure was converted to an equivalent cylinder with a diameter of 20.7 cm. The criticality calculations assumed the use of the 239 isotope of plutonium. The results are tabulated below:

Fuel volume fraction in core	PuO_2 mass, kg	k_{eff}
0.582	43.8	1.1
.524	39.456	1.02

About 1.04 kg of PuO_2 (239) per fuel pin appears to be an adequate fuel inventory. Reference 8 and recent unpublished calculations by E. Lantz indicate that BeO would be a lighter and a more effective reflector than molybdenum. About 5 to 7 cm of BeO would undoubtedly reduce the fuel pin inventory to 1.0 kg or less.

Production grade PuO_2 (238) yields about 400 thermal watts per kilogram so it can be seen that the seven pin RTG has an adequate fuel inventory for the low-power RTG. If the 1.04-kg loading is used only six pins are required to meet the 160-watt output. The center pin could be replaced with a dummy element.

Thus a consistent fuel-pin design can be used for both reactor and RTG, with only a change in the isotope being required. The control and response of this reactor has not been analyzed. But the general behavior should be similar to a larger, fast-spectrum, split-core, heat-pipe cooled reactor described in reference 5. This reference and more recent work indicates stable reliable control can be achieved.

Stubbins and Wolfe (ref. 9) have suggested that a heat-pipe-cooled fast reactor using plutonium 238 can be built for dual operation as an isotopic source and as a reactor. Their reactor is similar in size to the one just described and its general behavior is the same. It is not clear whether the plutonium-239 reactor or the plutonium-238 isotopic operation is preferred for low power. Undoubtedly a detailed cost and reliability analysis is required to establish which approach is the better. But in either case partial power can be obtained effectively by the use of gas controlled heat pipes that, in effect, thermally decouple various parts of the conversion subsystem. This partial-power operation is described in reference 2.

RTG AND REACTOR APPLICATIONS

The development plan is directed towards the final goal of providing a lightweight, high-performance reactor system for electrical propulsion. This objective was not selected because of any established mission. But since this is a potentially unique application for a space power reactor, provision for achieving this demanding performance is part of the plan.

In the process of meeting the electrical-propulsion requirement several other applications appear possible. An illustration of isotopic and reactor space applications are given in figure 6. Included in the figure are tabulated characteristics of the illustrated and related systems. It should be recognized that all performance, size and weight estimates are quite preliminary. First-order designs of the novel elements of the system were conducted, and the characteristics of the remaining parts were established by extracting the required information from the literature. For example it does appear that the thermionic reactor system based on the core design of this development will provide low specific weights down to 30 kWe. This is achieved because using plutonium fuel and the compact heat exchanger described in this report yields a reactor with less than one-third the weight of the one described in reference 2. The design of reference 2 was nominally based on a 40 to 70 kWe, and low specific weights were achieved. Therefore, since the weights of the other parts of system tend to scale with power level (with the exception of the reactor shield) it follows that the present thermionic system should provide the low specific weight required for electrical propulsion.

Although detailed engineering designs have not been completed for terrestrial variations of the isotopic and reactor systems, some first order estimates of size, arrangement of parts, and performance have been made and are presented in figure 7. Since terrestrial use may reduce some of the plutonium 238 handling problems, heavier core loadings are used. Also as indicated in the table of figure 7, the efficiency is improved with the terrestrial rejection temperatures.

CONCLUDING REMARKS

A development plan using a relatively simple energy source has been proposed for producing a variety of nuclear power plants including low power RTG's, nuclear power plants for electric propulsion, and oceanic reactors. The key to this development is the modular, split core reactor that is made possible by the use of heat pipes. The justification for this approach will improve as more experience is accumulated on long-life, high-performance refractory-metal heat pipes. The present generation of larger RTG's uses radiation and conduction to couple the thermal source to the thermoelectric converter. Reliability is achieved through simplicity of this form of heat transfer, but the growth to higher power systems is precluded. The experimental and analytical information available on heat pipes at 1100° C indicates a high probability of success of the present RTG reactor development.

With a reasonable research and development effort on higher-temperature heat pipes ($\sim 1500^{\circ}$ C) and studies directed towards improving thermionic converter efficiencies at lower temperatures the eventual development of a lightweight, high-performance thermionic reactor for electrical propulsion is quite probable.

Plutonium fuel has been proposed in this report because it is now being used as the 238-isotope in RTG's. Shifting to plutonium 239 for the reactor usage appears to be a logical step since the thermal and chemical experience of the fuel pin can be utilized. The alternate approach of using plutonium 238 for isotopic decay and nuclear fission suggested in reference 8 may have merit and should be considered. Should reactor safety problems limit the use of plutonium much of the RTG technology in this reactor development plan could be retained in a uranium-dioxide-fueled reactor. Additional fuel elements are required, and the development is less straightforward than the plan based

based on plutonium fuels. But any of the various development plans would appear to have a simple, low-cost starting point, the 160-watt unfueled RTG.

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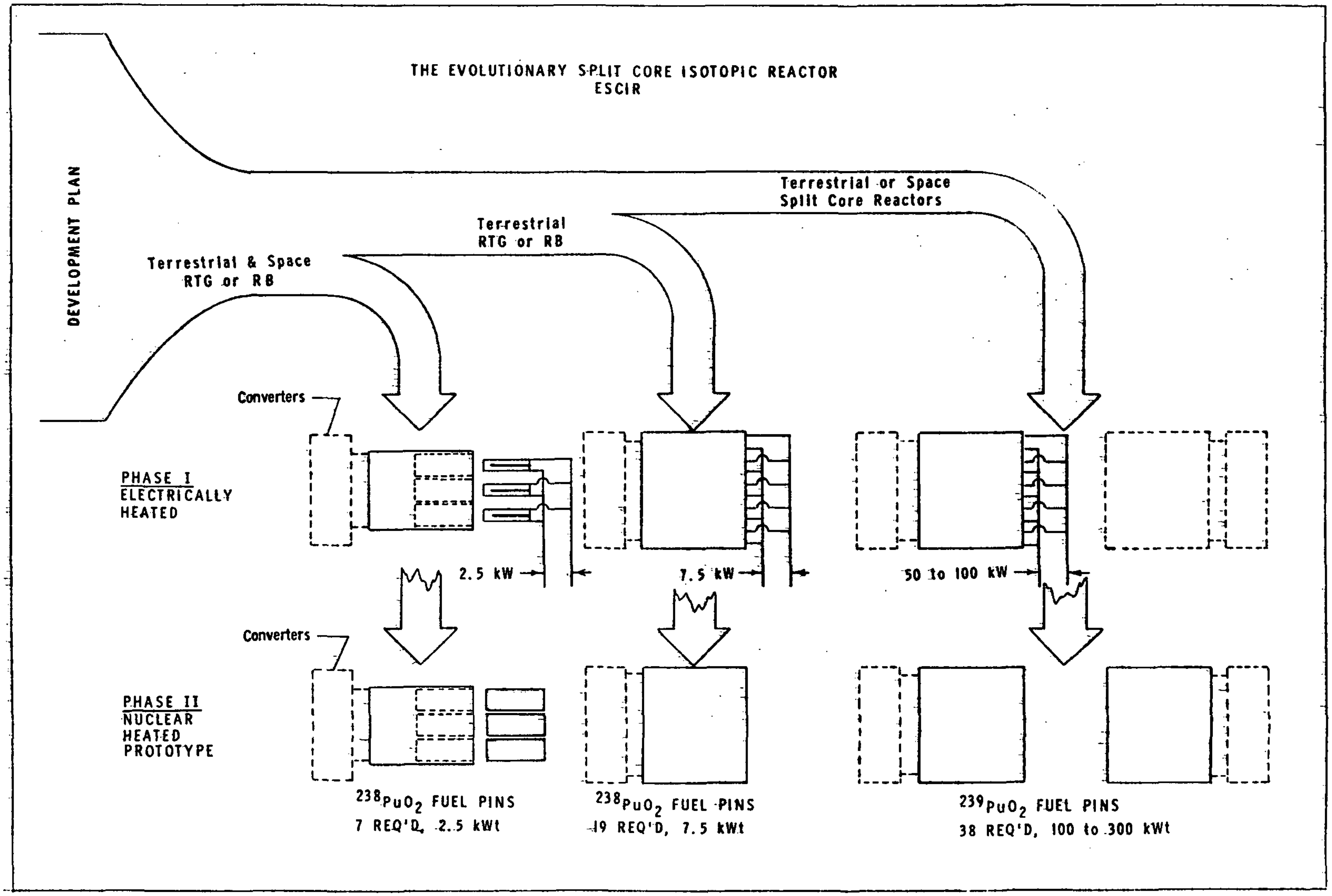

FIGURE 1. - A DEVELOPMENT PLAN FOR A SPLIT-CORE REACTOR USING TWO ISOTOPES OF PLUTONIUM.

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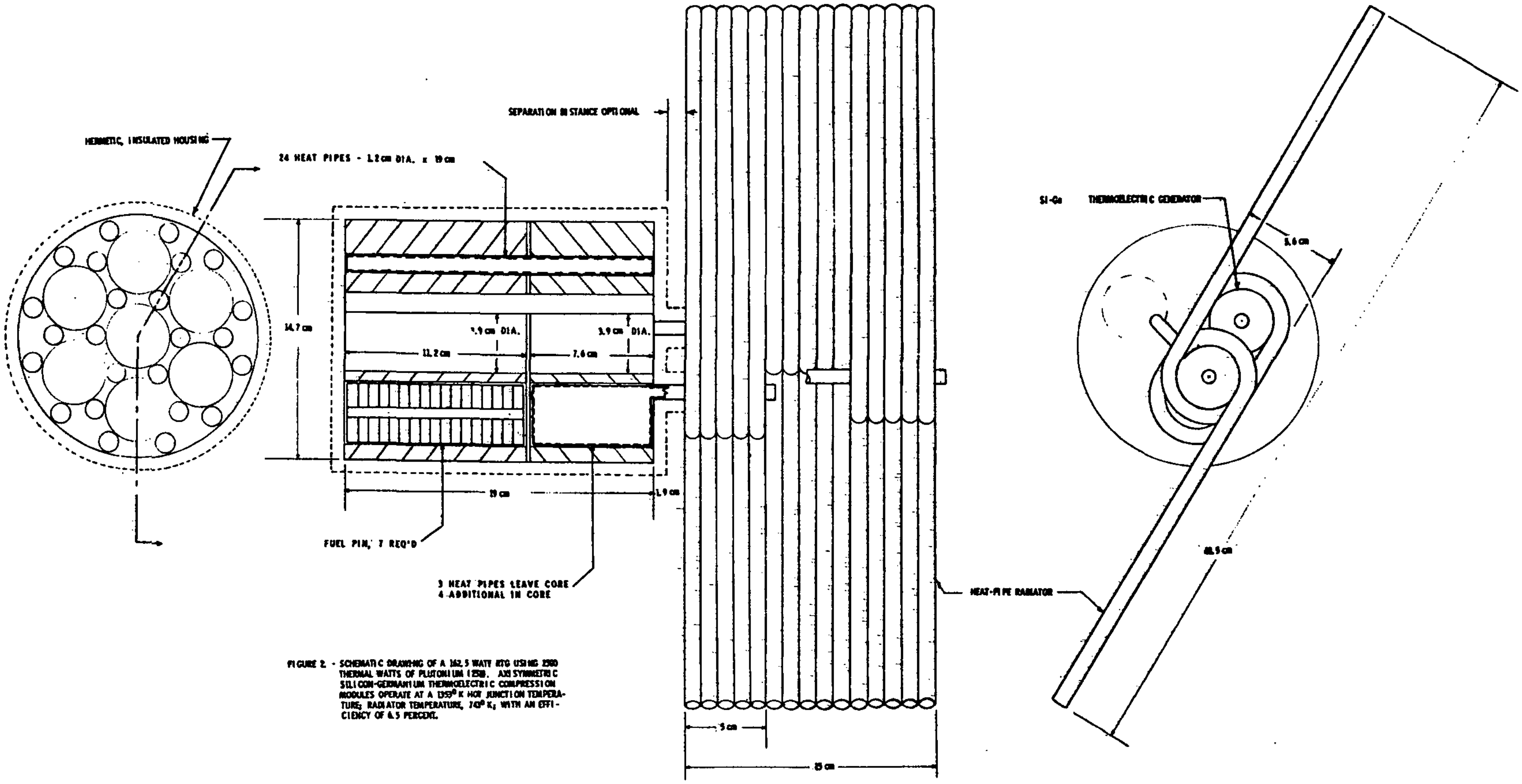

FIGURE 2. - SCHEMATIC DRAWING OF A 162.5 WATT RTG USING 2500 THERMAL WATTS OF PLUTONIUM (238). AXISYMMETRIC SILICON-GERMANIUM THERMOELECTRIC COMPRESSION MODULES OPERATE AT A 1353° K HOT JUNCTION TEMPERATURE; RADIATOR TEMPERATURE, 743° K; WITH AN EFFICIENCY OF 6.5 PERCENT.

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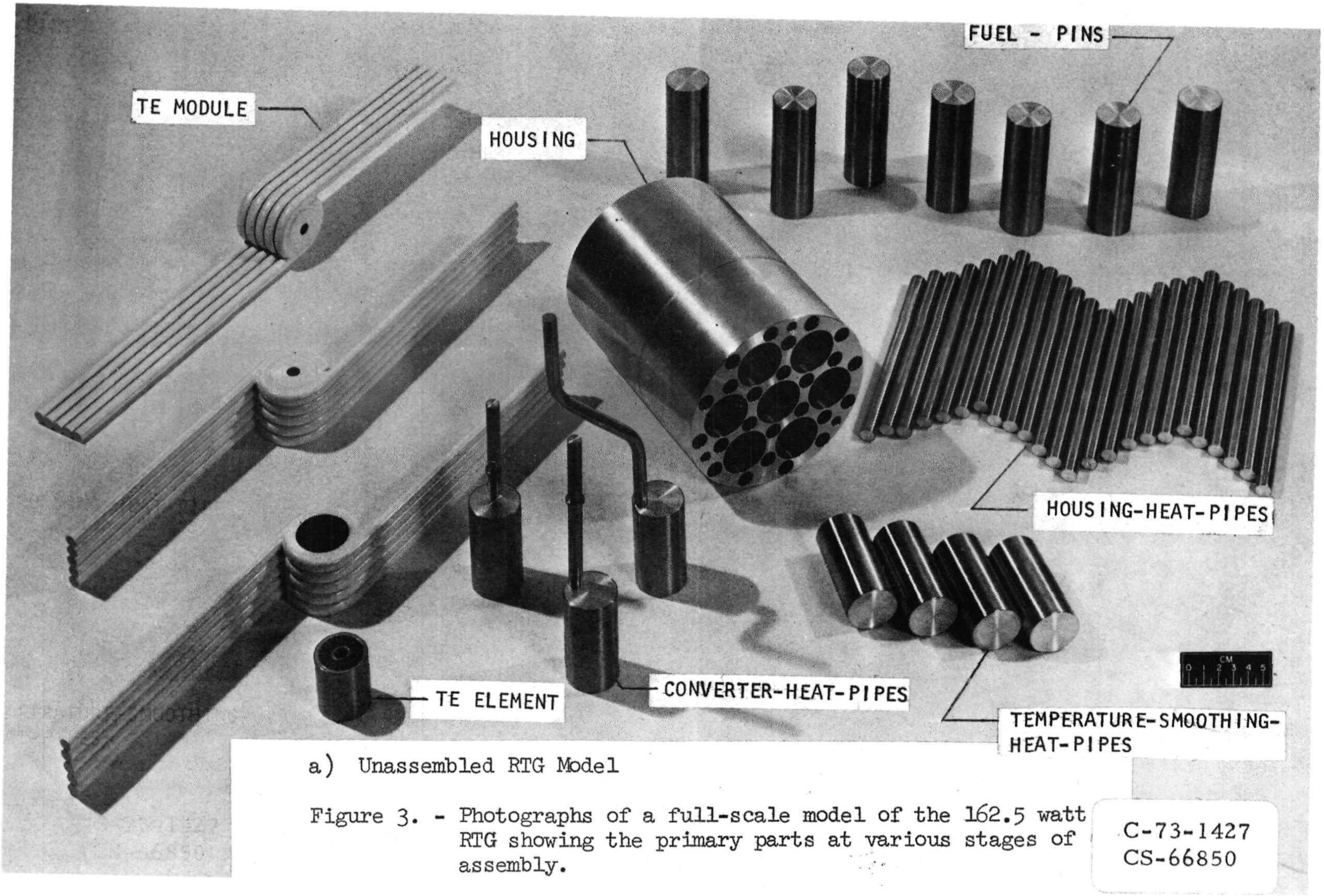

a) Unassembled RTG Model

Figure 3. - Photographs of a full-scale model of the 162.5 watt RTG showing the primary parts at various stages of assembly.

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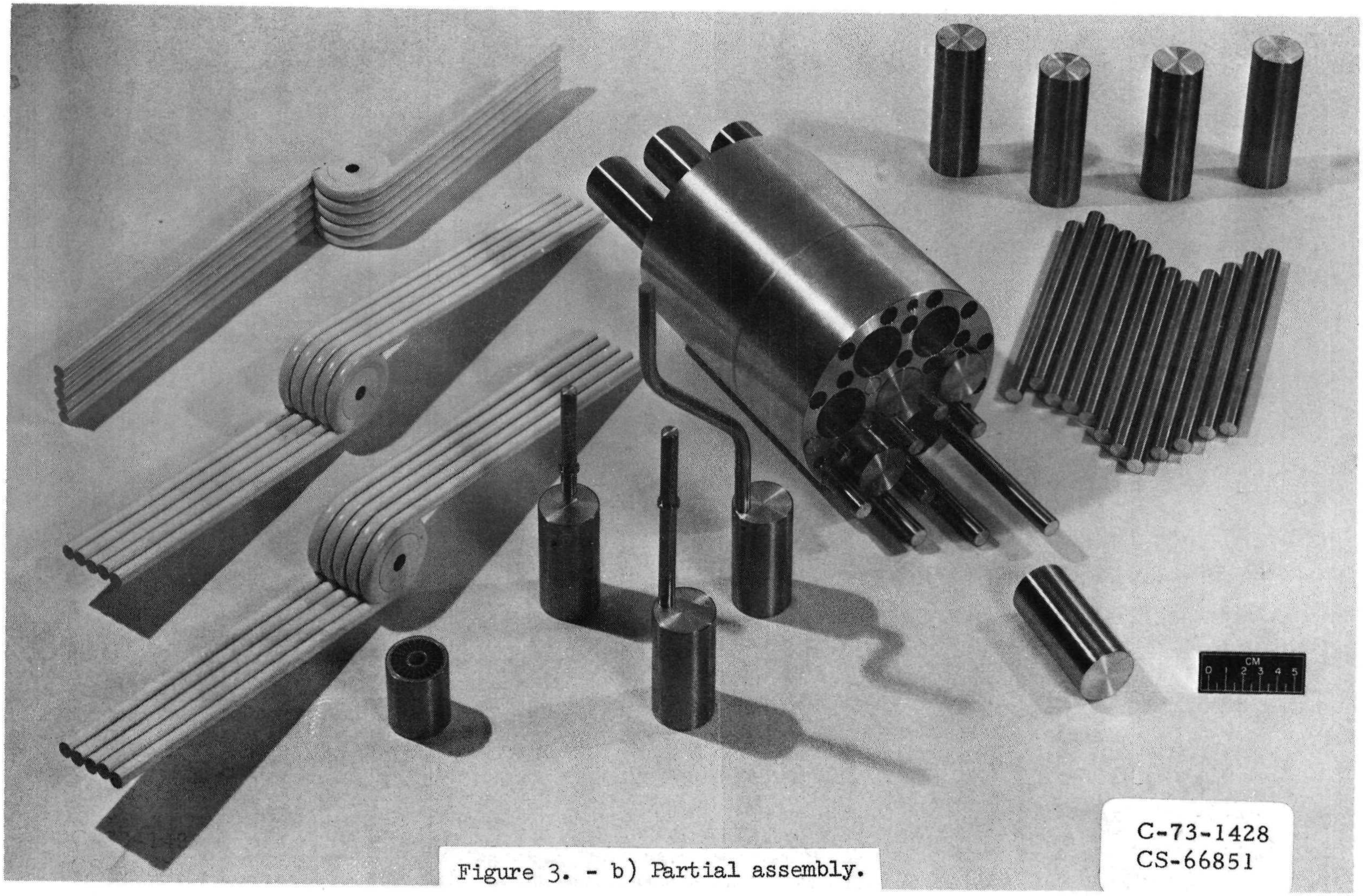

Figure 3. - b) Partial assembly.

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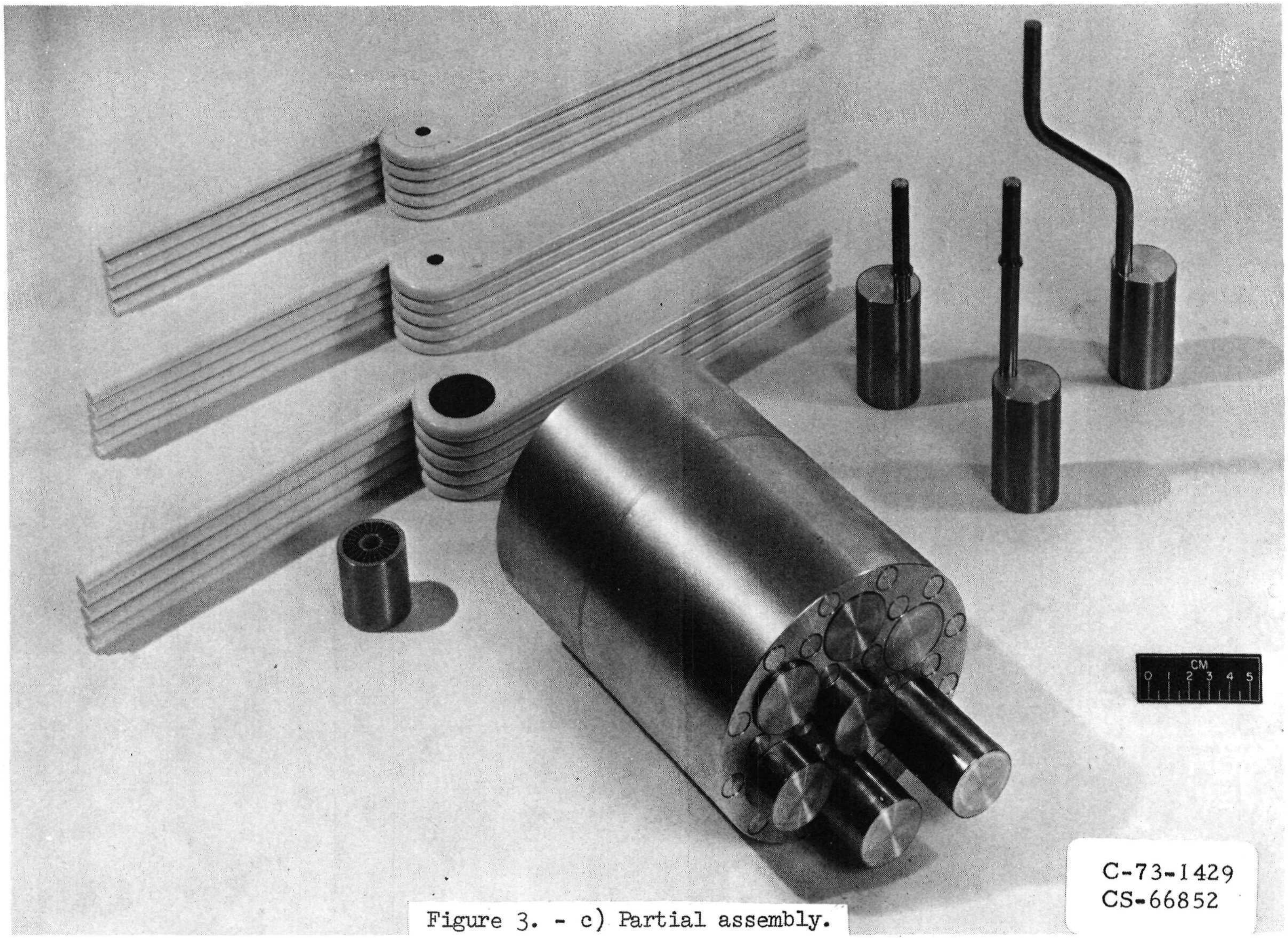

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Figure 3. - c) Partial assembly.

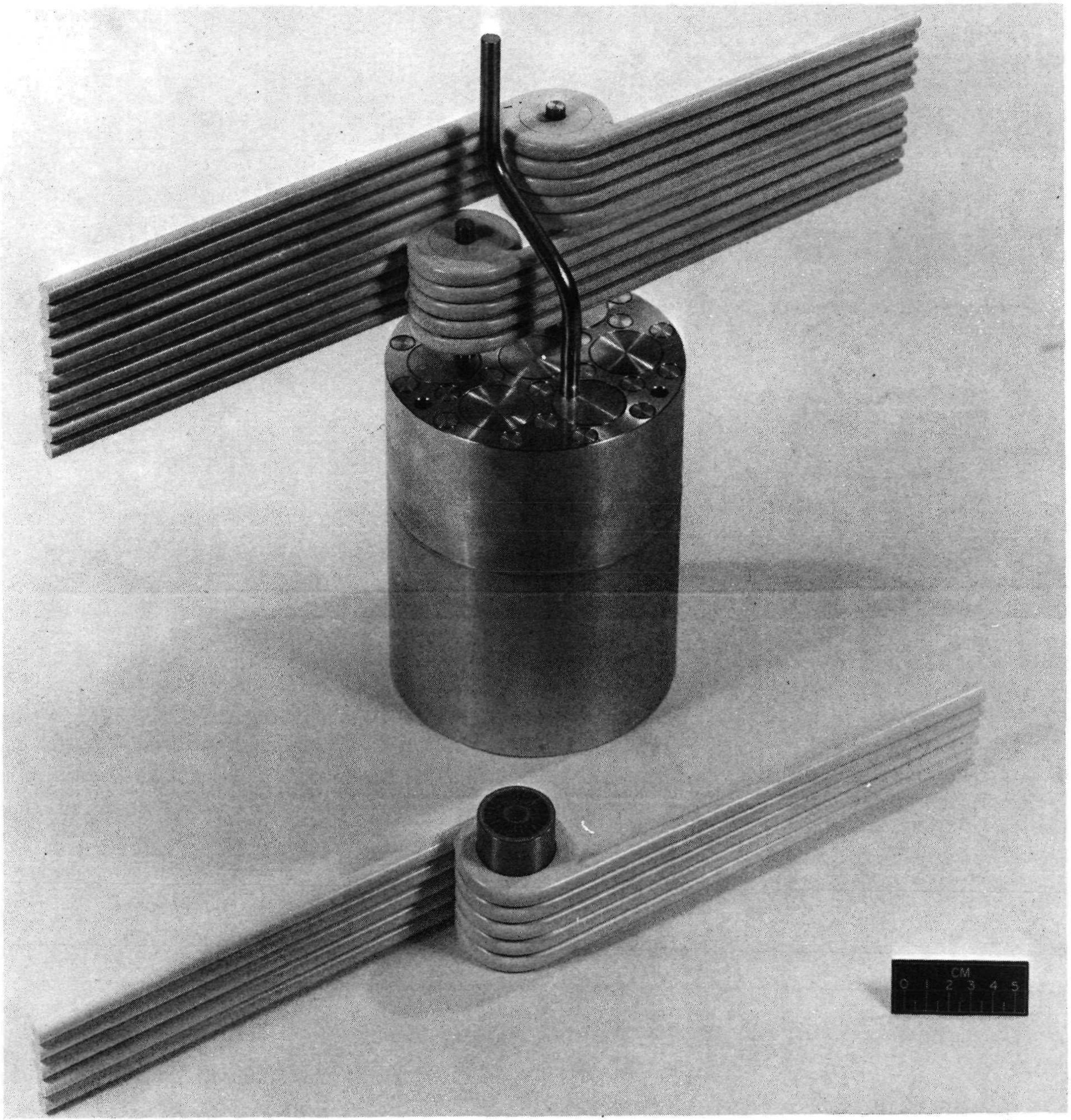

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Figure 3. - d) Partial assembly.

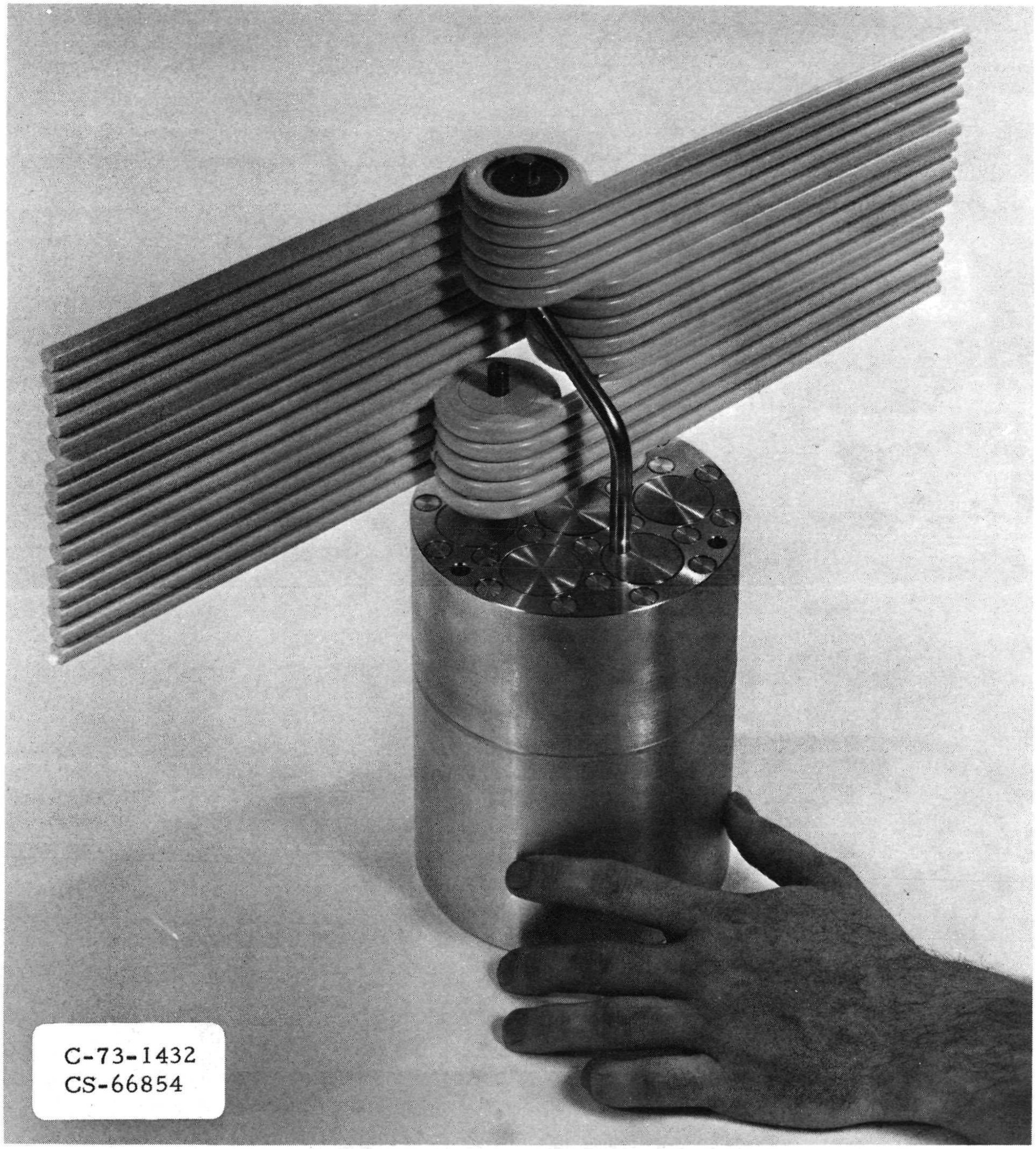

Figure 3. - e) Assembled RTG model (Hermetic insulated enclosure and electrical leads are not shown).

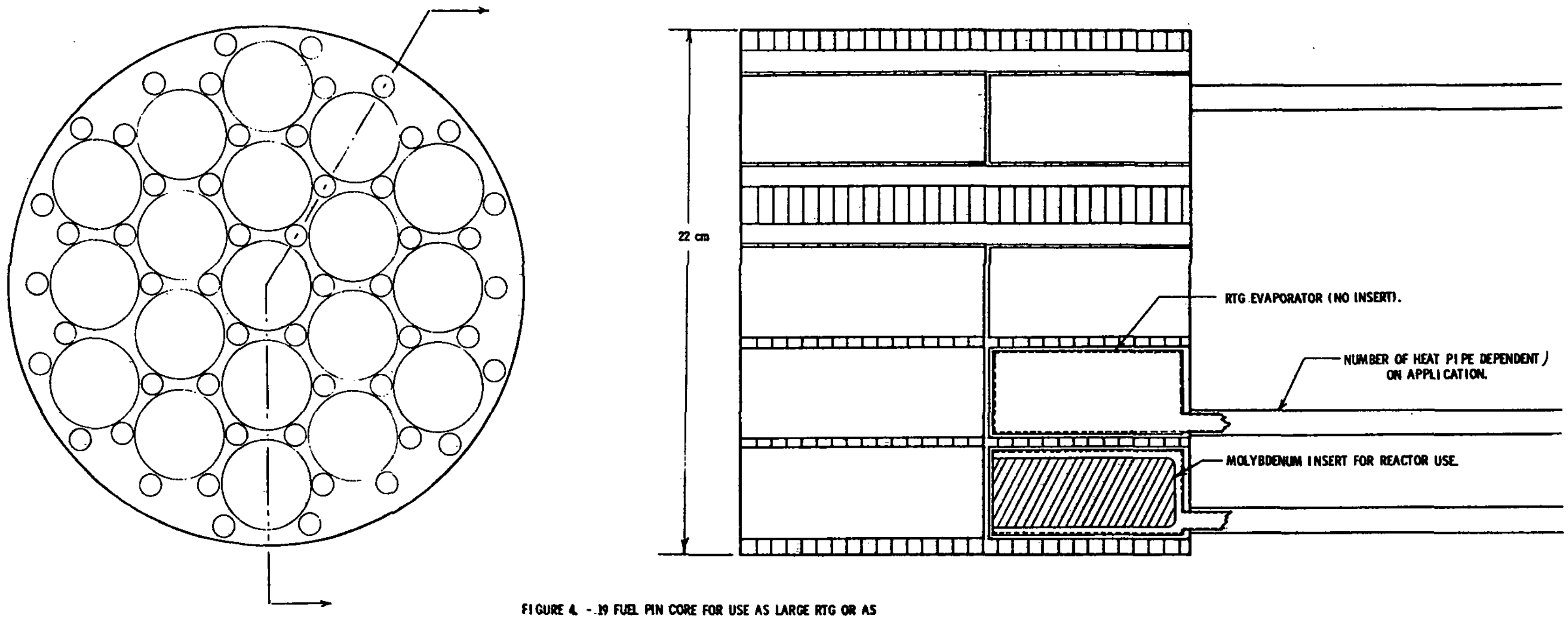

FIGURE 4. - 19 FUEL PIN CORE FOR USE AS LARGE RTG OR AS 1/2 OF A FAST REACTOR. ALL DIMENSIONS ARE THE SAME AS THOSE OF FIGURE 2 EXCEPT THE DIAMETER.

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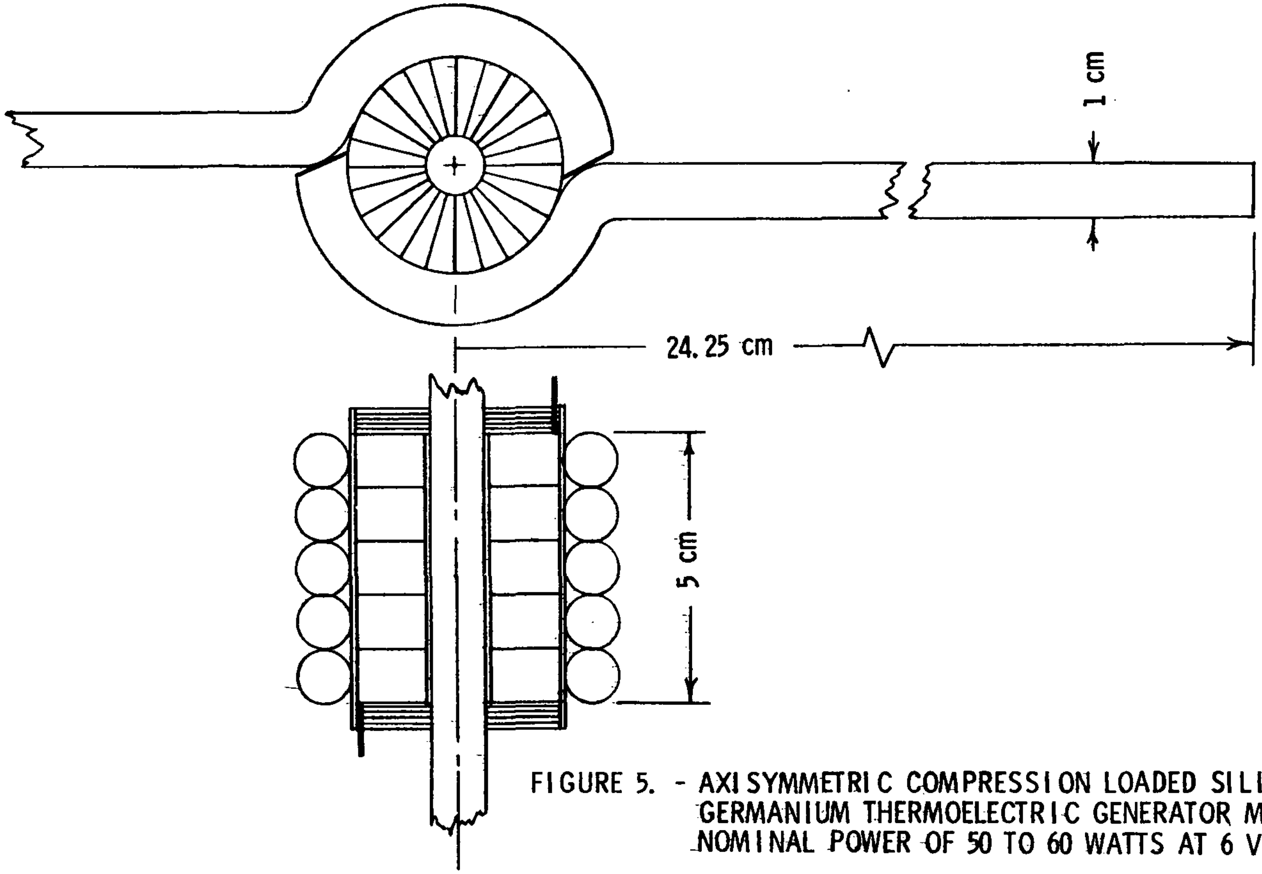

FIGURE 5. - AXISYMMETRIC COMPRESSION LOADED SILICON-GERMANIUM THERMOELECTRIC GENERATOR MODULE. NOMINAL POWER OF 50 TO 60 WATTS AT 6 VOLTS.

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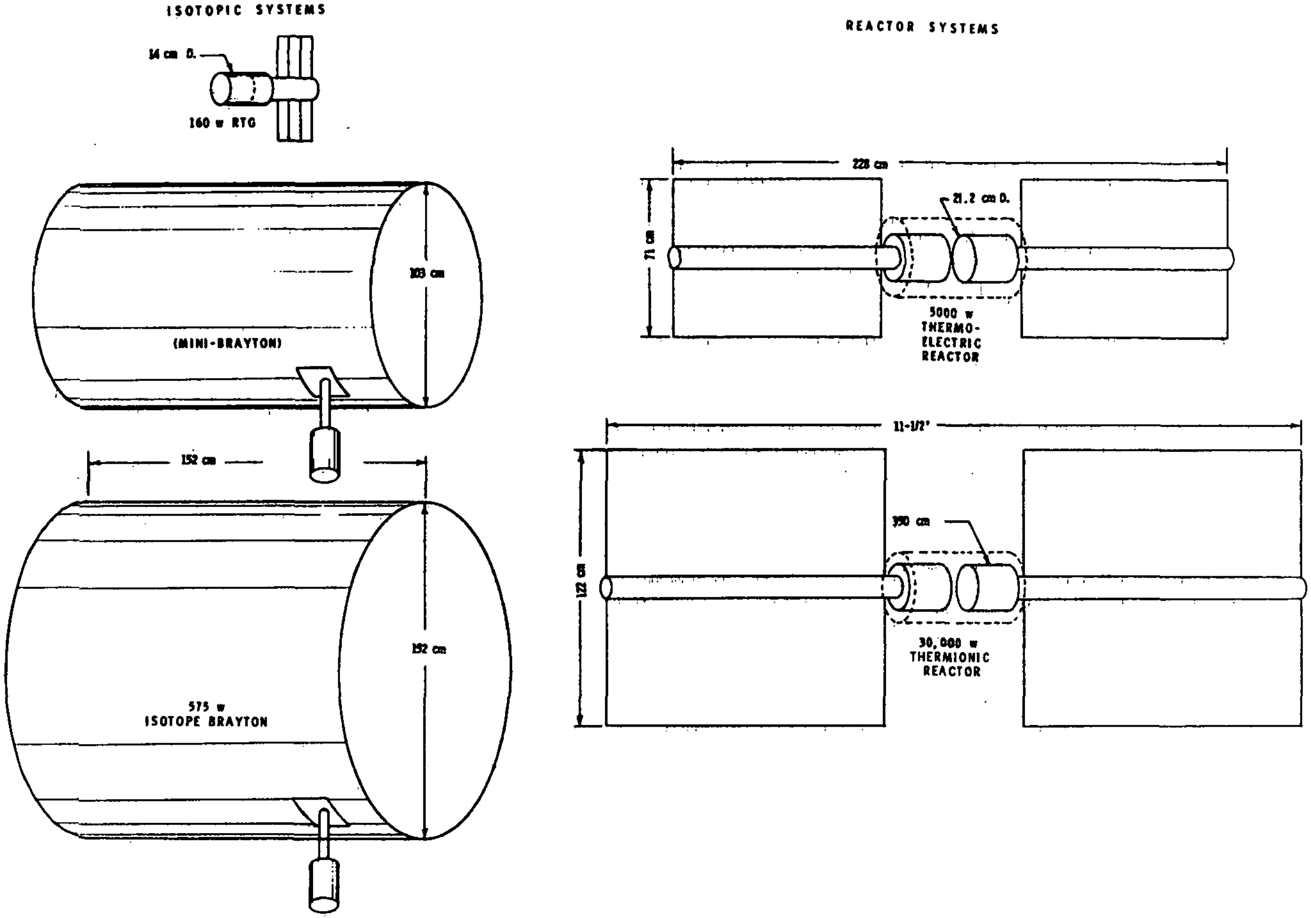
SPACE POWER APPLICATIONS



SYSTEM	SOURCE CHARACTERISTICS				η	OUTPUT POWER	RADIATOR	
	MODE	THERMAL POWER	NO. FUEL ELEMENTS	CLAD TEMP.			TEMP.	AREA
MINI-BRAYTON	^{238}Pu-ISOTOPIC	2.5 kW	7	1600° F, 1144° K	21 %	515 W	96° F, 310° K	52.5 sq. ft.
MINI-BRAYTON	^{238}Pu-ISOTOPIC	2.5 kW	7	1600° F, 1144° K	23 %	575 W	55° F, 286° K	78.5 sq. ft.
MULTI-BRAYTON	^{238}Pu-ISOTOPIC	10 kW	28	1600° F, 1144° K	28 %	2.8 kW	55° F, 286° K	314.0 sq. ft.
RTG	^{238}Pu-ISOTOPIC	2.5 kW	7	1976° F, 1353° K	6.5 %	160 W	877° F, 743° K	0.75 sq. ft.
REACTOR TE	^{239}Pu-REACTOR*	82.5 kW	38	1976° F, 1353° K	6.06%	5 kW	958° F, 788° K	27.6 sq. ft.
REACTOR TE	^{239}Pu-REACTOR*	100 kW	38	1976° F, 1353° K	6 %	6 kW	962° F, 790° K	33.2 sq. ft.
REACTOR TI	^{239}Pu-REACTOR*	150 kW	38	2600° F, 1700° K	9 %	13.5 kW	1160° F, 900° K	50.0 sq. ft.
REACTOR TI	^{239}Pu-REACTOR*	300 kW	38	2750° F, 1780° K	10 %	30 kW	1214° F, 930° K	80.0 sq. ft.

* VARIABLE 238-239 RATIOS ARE POSSIBLE

FIGURE 6. - EXAMPLES OF VARIOUS SPACE POWER APPLICATIONS THAT COULD BE PART OF A GENERALIZED DEVELOPMENT PLAN.

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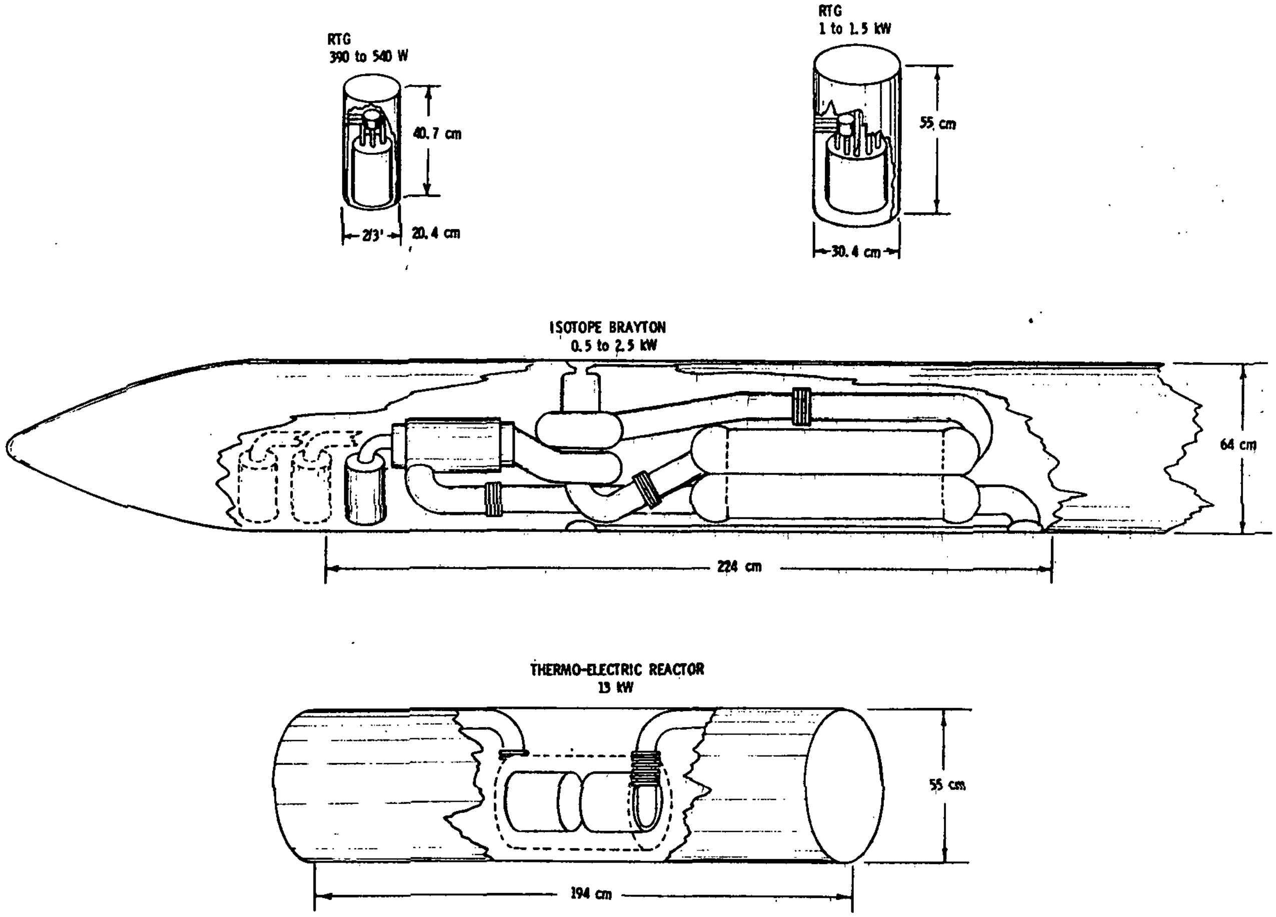

SYSTEM	SOURCE CHARACTERISTICS				OUTPUT POWER	η	REJECTION TEMP.
	MODE	THERMAL POWER	NO. FUEL ELEMENTS	CLAD TEMP.			
ISOTOPE BRAYTON	^{238}Pu-ISOTOPIC	2.5 kW	7	1600°F, 1144°K	525 W	21%	~90°F, 305°K
ISOTOPE BRAYTON	^{238}Pu-ISOTOPIC	10 kW	33	1600°F, 1144°K	2.5 kW	25%	~90°F, 306°K
RTG	^{238}Pu-ISOTOPIC	3.0 kW	7	1976°F, 1353°K	390 W	13%	~90°F, 306°K
RTG	^{238}Pu-ISOTOPIC	4.16 kW	11	1976°F, 1353°K	540 W	13%	~90°F, 306°K
RTG	^{238}Pu-ISOTOPIC	11.5 kW	37	1976°F, 1353°K	1.5 kW	13%	~90°F, 306°K
THERMOELECTRIC REACTOR	^{239}Pu-REACTOR	100 kW	38	1976°F, 1353°K	13 kW	13%	~90°F, 306°K

FIGURE 7. - EXAMPLES OF LAND AND OCEANIC APPLICATIONS USING THE RTG's AND REACTORS DEVELOPED AS A PART OF THE EVOLUTIONARY SPLIT-CORE REACTOR PROGRAM.

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