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THE PRACTICAL APPLICATION OF SPACE NUCLEAR POWER IN THE 1960'S

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by

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ABSTRACT

Three nuclear reactor space electric power units are under development by the U. S. Atomic Energy Commission office for Aircraft Reactors for the U. S. Air Force and the National Aeronautics and Space Administration. The electric power output of these three systems extends over three decades of power, from 300 watts to 60 kilowatts. The major operational, installation, and handling characteristics of these nuclear power units are described in this paper. In particular, some limitations and restrictions with regards to payload, shielding, and radiation environment are described with respect to the power plants, their mode of installation, and system weight. The ground handling and safety as well as the overall safety aspects of space reactor utilization are described in this report.

The three systems include the SNAP 10 power unit which is a demonstration system that utilizes thermoelectric power conversion. The system covers the sub-kilowatt region of power and has no moving parts. The extreme simplicity provides assurance of obtaining remote orbital startup, high reliability, and long endurance. The reactor is controlled by the strong inherent negative temperature and power coefficient of reactivity.

The next power system is SNAP 2 which utilizes a similar compact nuclear reactor, weighing about 200 pounds which is cooled with liquid sodium-potassium alloy, and coupled to a small mercury vapor turbine generator power conversion system. This system has a 3000 watt output with one turbine system; future extension would permit the use of two power conversion systems with one reactor for a total power output of up to 6000 watts. This system will be provided with a thermo-mechanical reactor control system for increased endurance and reliability. The power conversion system utilizes only one moving part, a combined rotating shaft suspended on liquid mercury bearings and rotating at 40,000 rpm. The SNAP 2 system at 3000 watts will weigh about 600 pounds; at 6000 watts output it will weigh about 900 pounds.

The third system, designated SNAP 8, is a direct outgrowth of the SNAP 2 power plant development and will deliver 30,000 watts with one mercury vapor turbine generator system. It will deliver 60,000 watts with two power conversion

systems coupled with the same SNAP 8 reactor. This system will weigh about 1400 pounds at 30,000 watts and about 2500 pounds at 60,000 watts.

Dependent upon the type of payload and the vehicle configuration the radiation shielding may weigh less than 100 pounds for some electronic payloads to over 2000 pounds for some manned payloads.

During this decade (1960 to 1970) these SNAP systems currently under development, with demonstrated feasibility, will become fully qualified and will be the predominant and most reliable source of high power that will be available for application in space satellites.

In addition to electric propulsion demonstrations and planetary probe auxiliary power, the SNAP family of nuclear power plants can, within this decade, extend our current "exploration of space" activity to one of "utilization of space."

I. INTRODUCTION

Space flight with its tremendous extension of attainable distances, observable areas and communication capabilities within compressed time periods, holds promise for important changes to our civilization. For instance, the value of worldwide, long range weather predictions made possible by weather observation satellites will be of inestimable value to world agriculture, travel, commerce and our daily living.

As indicated in Figure 1, the unmanned exploration of cis-lunar space has been initiated with the successful launching of Sputnik I and the 20 some satellites which followed during and since the International Geophysical Year. We are approaching the threshold of manned cis-lunar space exploration with the projected United States X-15 and project Mercury manned orbital flights. The Sun shots and the Venus and Mars probes which are soon to be launched, mark the initiation of trans-lunar unmanned exploration.

In the mid-1960's we will see the initiation of the utilization of space. The discussion to follow will focus primarily on this area of space activity. This aspect of space activity would include the use of earth satellites for navigational

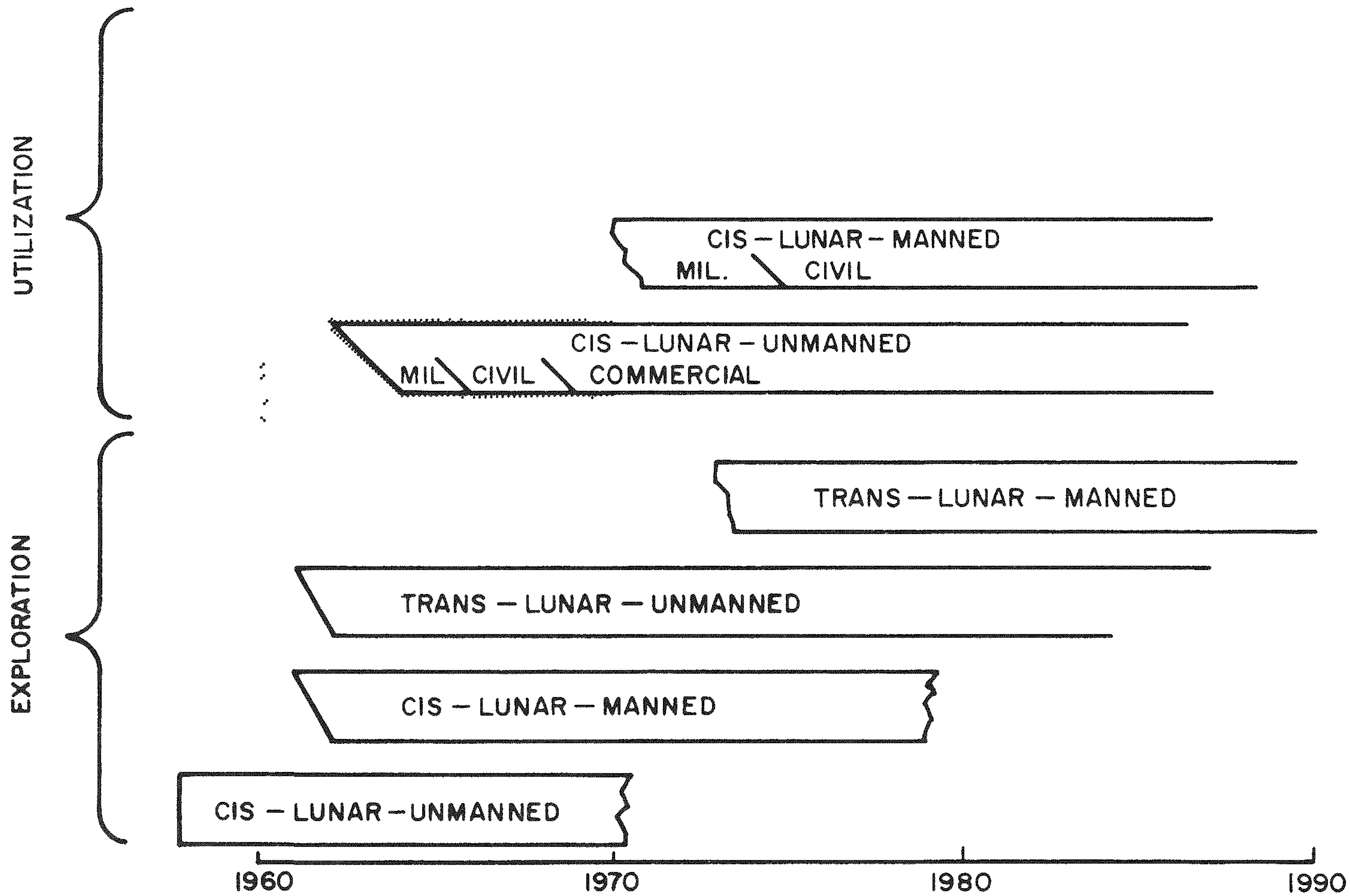

Figure 1 Estimated Space Operations

aids, mapping, weather observation, reconnaissance, early warning systems, communications, air traffic control, global all-weather radio and television broadcasting, and possibly commercial radio-telephonic communication

In order to become sufficiently practical and economic these various systems and networks must achieve a high degree of reliability, and expected life-times that measure in years. In every case, some electric power is required aboard the satellite to accomplish the intended task or combination of tasks The amount of power required by the satellite will vary from a few watts for navigational aid beacons to tens of kilowatts for civil or commercial broadcasting and combined function satellites

Current costs for raising a pound of material into a 300 mile earth orbit are estimated to be about $15,000 This cost should reduce to less than $1000 per pound with the more proven systems in the next few years. The cost of payload on orbit is greater by a factor of six for the 22,000 mile, 24 hour orbit Consequently, due to the low energy content per pound, chemical energy sources become prohibitively heavy and expensive for durations greater than a few days or weeks.

Figure 2 presents current estimates as to where various electrical energy sources are appropriate. The only practical energy sources for long lived vehicles depend upon solar radiation, nuclear fission, or radio-nuclide decay Radioisotopes and solar cells are attractive for small power requirements of a few watts to several hundred watts At higher powers these systems become excessively heavy, expensive, and difficult to handle and integrate into the space vehicle.

From a weight and cost standpoint the solar mirror collector coupled with dynamic heat engines or the nuclear fission reactor coupled with thermoelectric, turboelectric, or thermionic conversion systems are attractive as power sources The solar mirror has yet to be proven feasible and practical as a power source because of the effect of micro-meteorites on reflecting optical surfaces,* and because of the requirement for continuous accurate orientation toward the sun. For the generation of powers greater than 10 to 30 kilowatts, the solar mirror

*"Institute of Environmental Sciences 1960 Proceedings, April 6, 1960, Los Angeles, California," R. E. Henderson, Paul Stanley

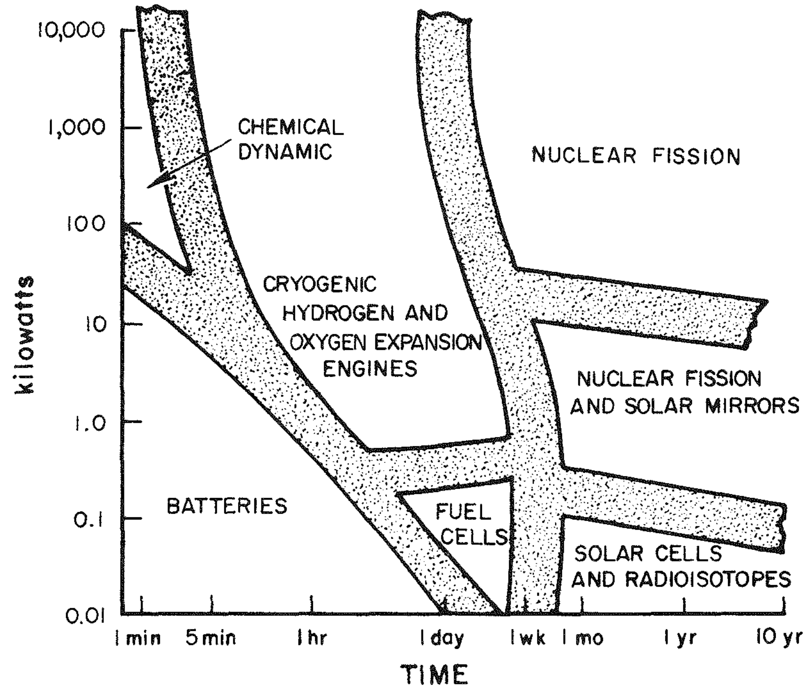

Figure 2. Applicability of Space Auxiliary Power Sources

collector becomes more impractical because of the difficulty in packaging such large collectors within the vehicles currently under development.

The high energy content of nuclear power systems (10^6 electrical watt-hours per pound) makes nuclear fission reactors the most attractive source of space vehicle power in the kilowatt, tens of kilowatts and higher ranges of electrical power output. When one considers that the nuclear power system will successfully operate regardless of sun, shade, orientation or tumbling, and the fact that its radiator area requirement is only 1 to 10 percent of the solar cell collector area requirement (Figure 3), it becomes evident that the nuclear reactor will also find application where only a few hundred watts of electric power are required.

The feasibility of constructing and operating small nuclear reactors that would be suitable as energy sources for space vehicle power systems has been demonstrated in the Systems for Nuclear Auxiliary Power (SNAP) program, by Atomics International for the U. S. Atomic Energy Commission Office for Aircraft Reactors. The SNAP Experimental Reactor (SER) completed a 1000 hour uninterrupted operational test in April of this year at 50 kilowatts thermal power and 650 centigrade degrees (1200°F). The small 100 kilogram nuclear reactor which contains 2.9 kilograms of fissionable uranium-235 produced 110,000 kilowatt hours of thermal power between the initiation of the testing program in November 1959 and April 1960.

The extremely stable, predictable, and entirely satisfactory operation of the SER lends considerable confidence to the concept of nuclear auxiliary power for space systems.

II. CONVERSION SYSTEM REQUIREMENTS

A nuclear power supply for space vehicle application is composed of three major subsystems: a nuclear reactor heat source, a power conversion system, and a heat rejection system. In selecting promising types of power conversion systems, one must consider restrictions imposed upon the power conversion by both the nuclear reactor heat source and the thermal radiation heat sink.

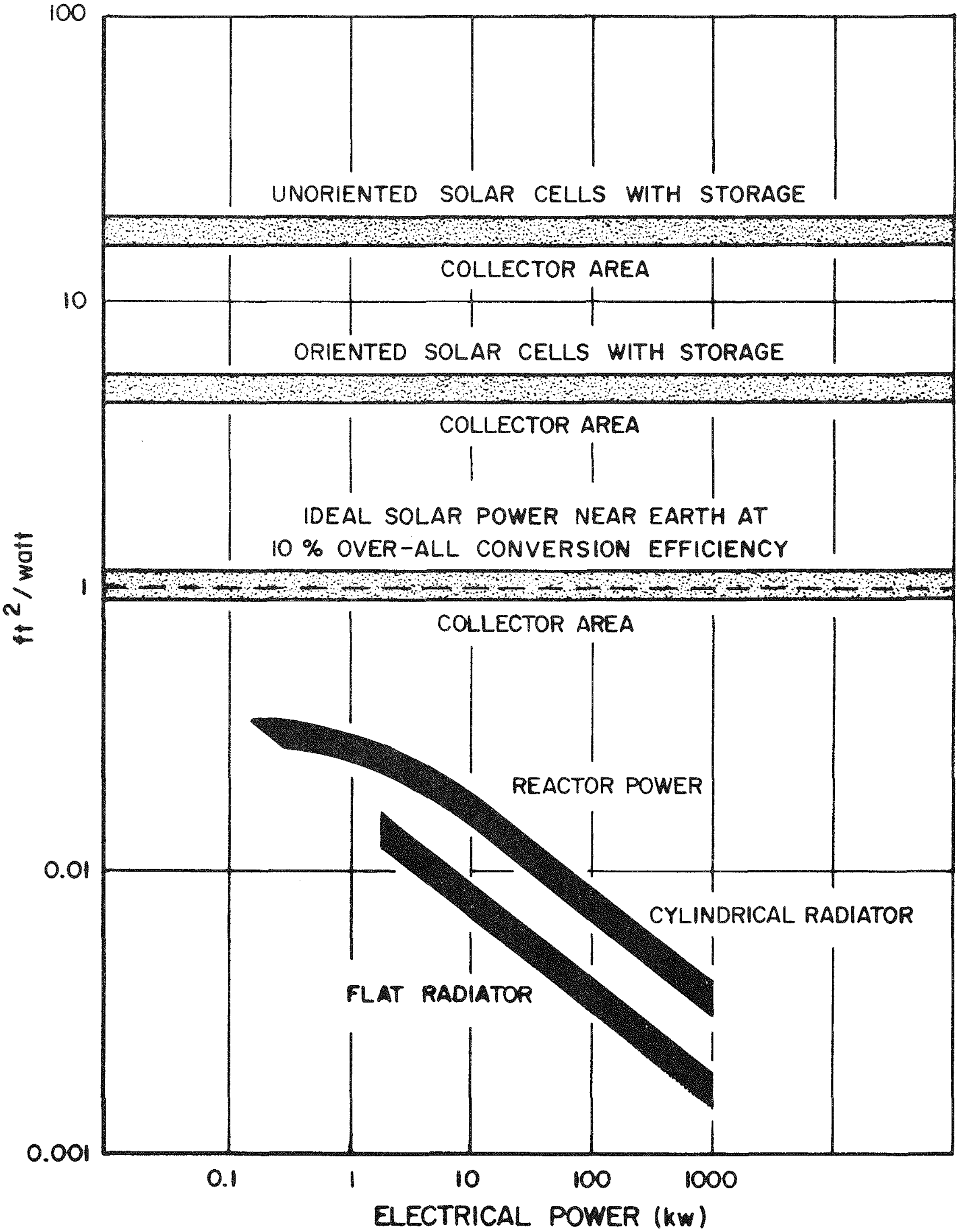

Figure 3. Earth Satellite Auxiliary Power Area Requirements

Since waste heat can be rejected from the cycle only by thermal radiation, the conversion system must operate with a high heat-rejection temperature Due to reactor heat source temperature limitations the power conversion system must recover a large fraction of the Carnot cycle efficiency at high power outputs The radiator temperature which yields the minimum radiator area is a constant fraction of the heat source temperature. For saturated Rankine cycles this optimum temperature is 75 percent of the boiling temperature, or the optimum Carnot efficiency is 25 percent. This optimum Carnot efficiency comes about because the total heat rejected is decreased linearly by lowering the radiator temperature, however, the area required to radiate the heat is increased by the fourth power of the lowering radiator temperature.

At low power levels, the reactor size is determined by criticality and is independent of the thermal power, so the conversion efficiency effects only the size of the radiator and conversion equipment. Since the reactor and shield weight are the dominant weights at low powers (about 1 kilowatt), the conversion efficiency is not as important at low power levels as at high power levels.

At high power (hundreds of kilowatts), the radiator is the dominant weight in the system and a high equipment conversion efficiency is extremely important.

High power provides another incentive for high cycle temperatures because the radiator weight not only increases from a small fraction to a large fraction of the system weight, but the larger radiator becomes more vulnerable to penetration by meteorites. Therefore, in order to maintain a given reliability for higher power systems, either higher radiator temperatures or thicker radiator tube walls would be required. Thus, as the power level is increased, the cycle temperatures must be increased to maintain a constant specific weight (pounds per kilowatt). Because of these and other design factors the minimum weight space nuclear power plants will be in the 300 to 3000 kilowatt electrical size range (Figure 4).

Currently the most attractive forms of power conversion and the expected specific weights (pounds per kilowatt electrical) for nuclear space power systems, are indicated in Figure 5. At low power outputs the thermoelectric systems are attractive because of the ease of orbital startup with static conversion systems, even though their efficiency is low (about 10 to 20 percent of Carnot or 2.5 percent overall).

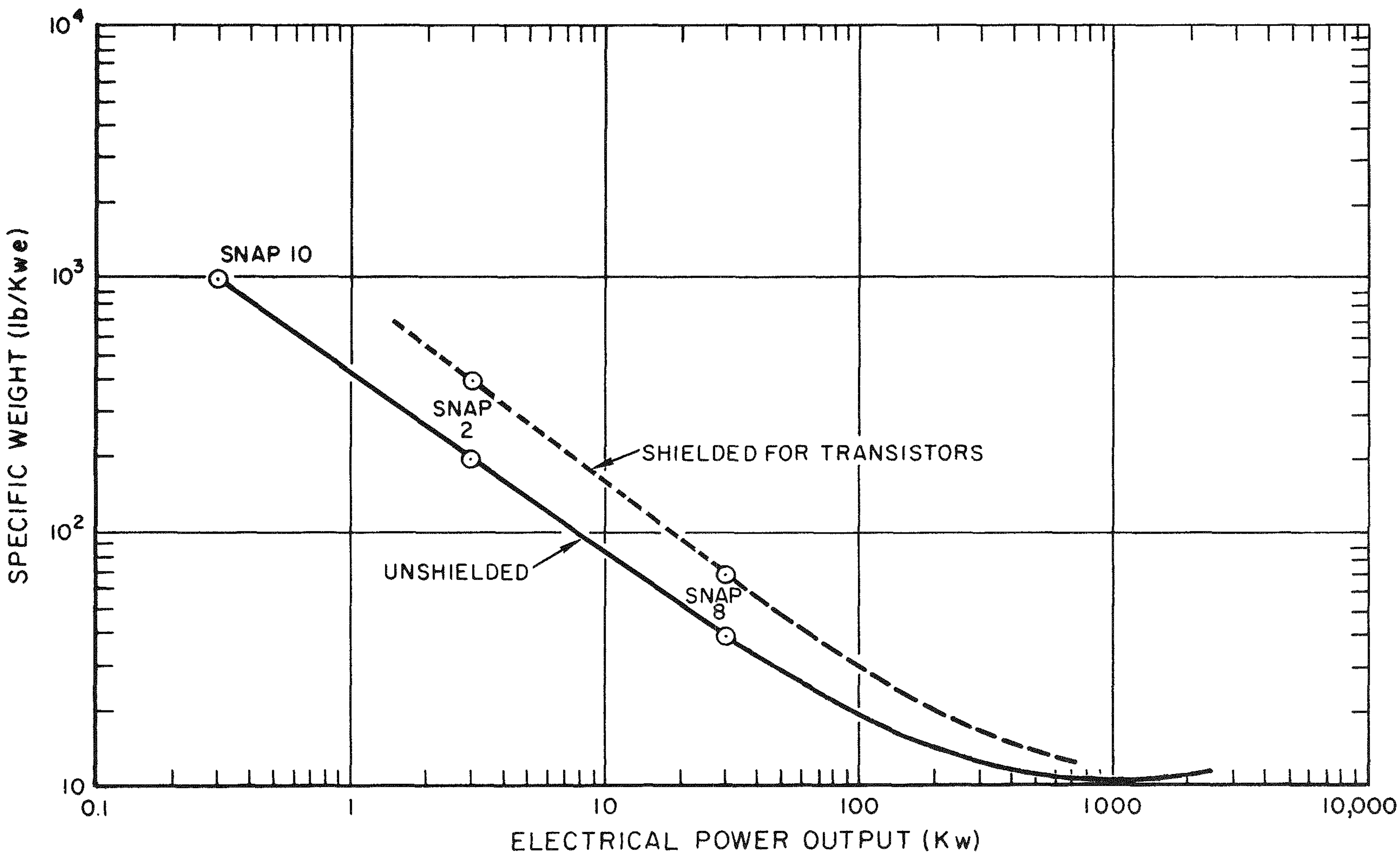

Figure 4. Specific Weight of Nuclear Power Plants

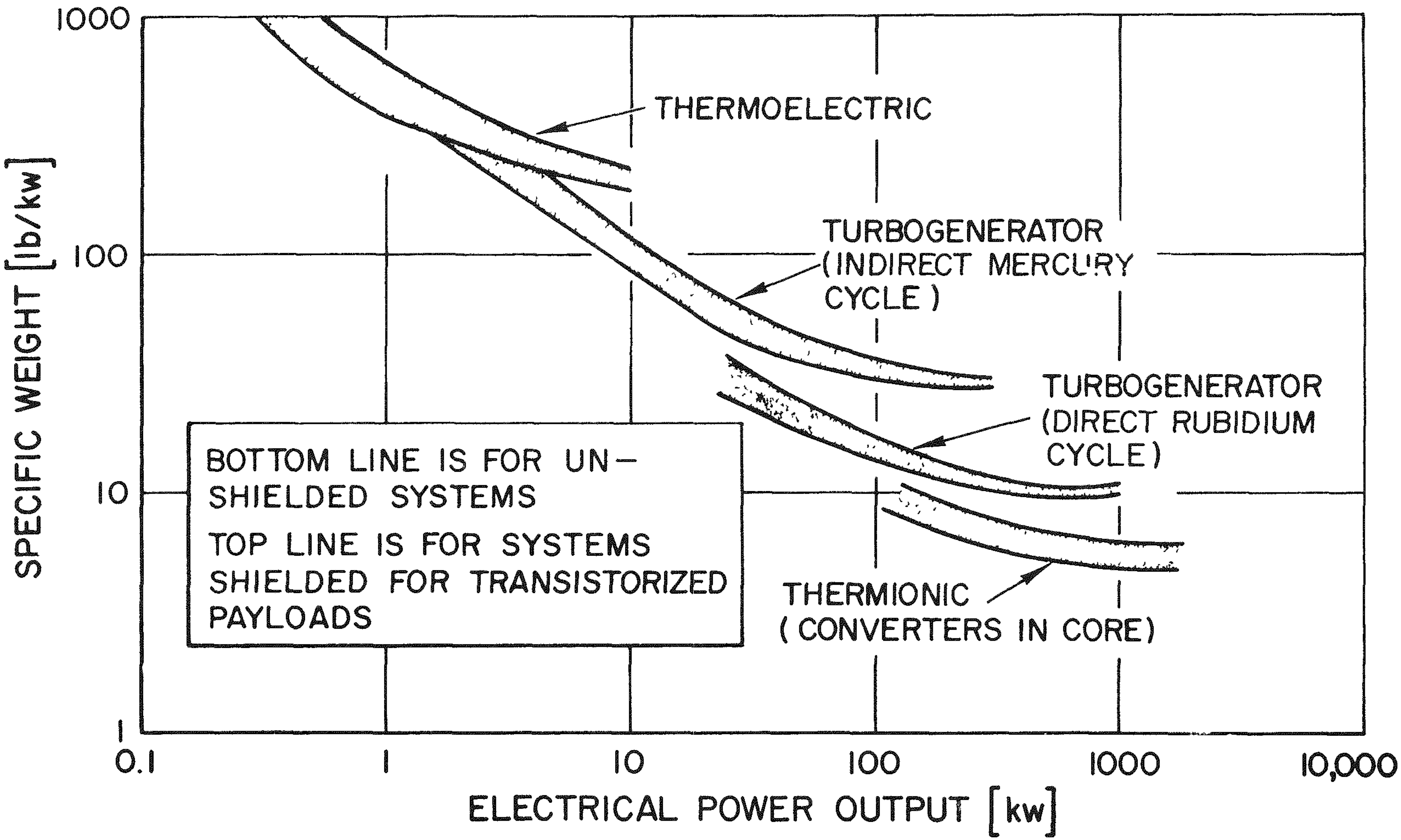

Figure 5. Specific Weight vs Power Output for Nuclear Power Systems

The higher efficiencies of the Rankine vapor cycle systems, (about 50 percent of Carnot) 12.5 percent overall, make these systems attractive for higher power outputs. Ultimately if the myriad of high temperature materials problems can be solved the thermionic nuclear power systems show promise of giving low weight and size as well as static operation.

The achievement of high temperature operation of any equipment for an extended period of time poses many materials, corrosion, diffusion, mass transfer, creep, and embrittlement problems which lead to system failures. It can be noted from Figure 6 that experience with nuclear reactors has not yet achieved the current development goals of our high temperature nuclear systems. For a space power unit the highest temperature that is compatible with materials technology must be established as the system development goal in order to minimize system weight. In order to ensure success and to minimize the development time and risk at the programs inception in 1956, the SNAP 2 system design temperature was established at 650°C or (1200°F).

As noted in Figure 7 it can be seen the heat engine cycle that would permit the highest heat rejection temperature at reasonable efficiency and at a 1000 to 1200°F boiling temperature was the mercury vapor Rankine cycle.

III. SYSTEMS FOR NUCLEAR AUXILIARY POWER PROGRAM

Let us now turn our attention to the power plants specifically under development.

A. PROGRAM OBJECTIVES

The basic objective of the SNAP program is to develop the technology and systems necessary to provide long lived nuclear power for use in scientific, military, and civilian satellites and for space exploration and utilization. The specific current hardware objectives of the SNAP 10, 2, and 8 programs are to develop, test, and qualify 0.3, 3, and 30 kilowatts electrical nuclear auxiliary power units respectively for space utilization. The overall SNAP development effort is directed toward the following general objectives and requirements.

Figure 6 was not available when this report was submitted for printing.

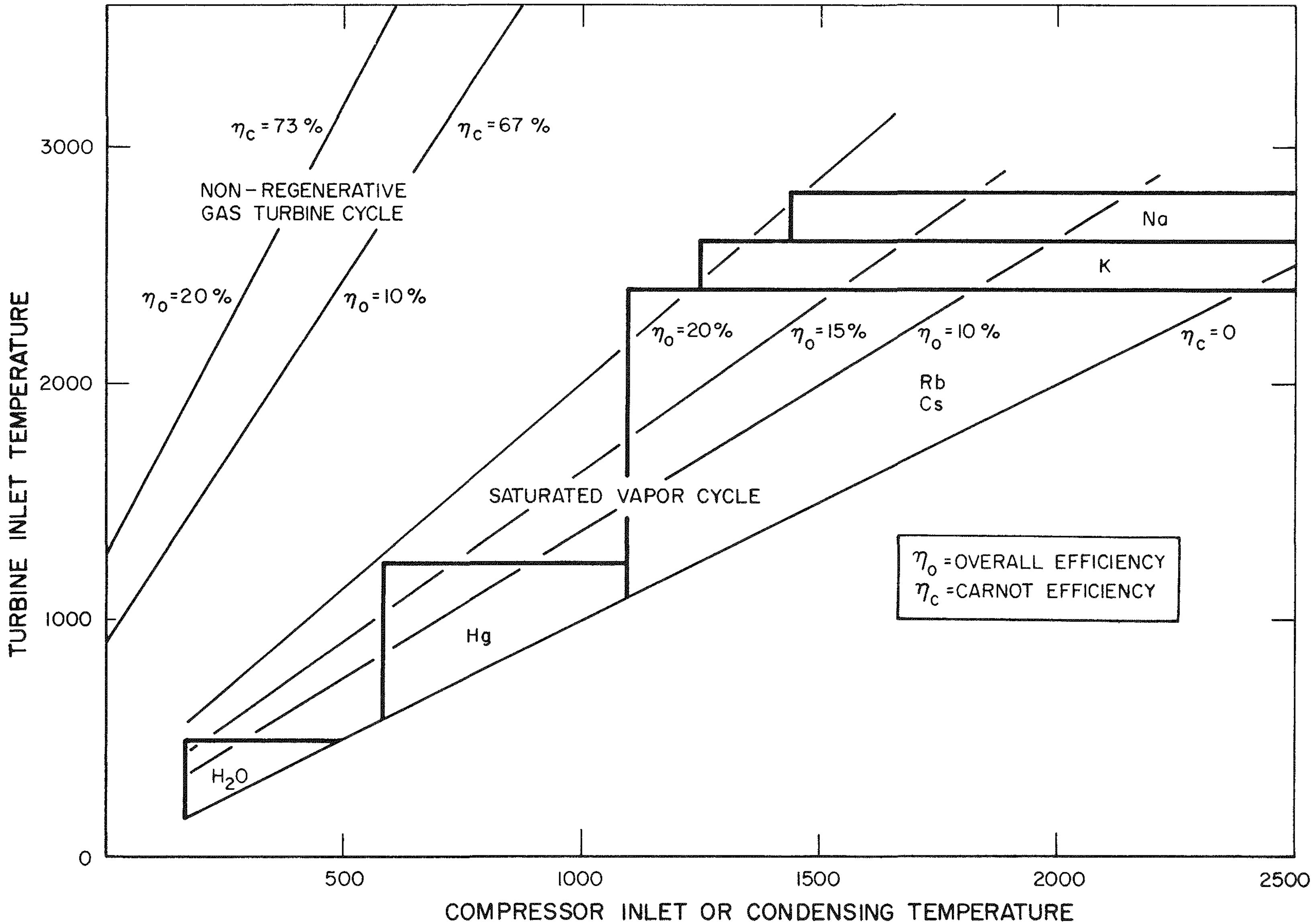

Figure 7. Temperature Requirements for Closed Cycle Heat Engines

1. Objectives

a) Unattended, automatic, maintenance free operation
b) Maximum reliability
c) Maximum ruggedness
d) Maximum lifetime
e) Minimum size and weight
f) Maximum possible safety
g) Maximum ease of production, handling, and installation
h) Maximum economy.

2. Space Power Systems Requirements

a) Operation
b) Operation at high temperature to provide for efficiency radiative heat rejection
c) Operation in 0-gravity
d) Operation in presence of space radiations and rain of micro-meteorite particles
e) Remote startup in orbit
f) Re-entry burnup of low power systems which may operate in low altitude re-entering orbits
g) Capability of withstanding the severe shocks, vibrations, gravity, pressure, and temperature transients during vehicle launch
h) Capability of operating without subjecting the vehicle to excessive disturbing torques
i) Design and installation to permit efficient low weight shadow shielding of payloads
j) Packaging and installation to permit prelaunch startup and checkout with maximum personnel safety and minimum vehicle and facility risk
k) Packaging and installation to provide for vehicle structural and flight stability
l) Development of criteria for radiation resistant payloads design.

B. DEVELOPMENT APPROACH

In the interests of safety, reliability, and economy, the U. S. Atomic Energy Commissions's Space Power Development Program consists of a well coordinated series of power systems, supported by an advanced technology research and study program. The initial power plant is as simple, safe, reliable, low power, and low cost as possible. Each successive power plant will be at a higher power, higher temperature, higher performance, and greater sophistication.

The 0.3 kilowatt electrical static thermoelectric system and the 3.0 kilowatt electrical turboelectric systems currently under development at Atomics International for the AEC Aircraft Reactors Office, will pioneer most of the complex problems involved in ground testing, launching, and in successfully operating a reactor power system in space. The low powers of these systems reduce the development and testing costs and substantially reduce initial hazards. Yet, they encounter and probe all of the perplexing technical problems of vehicle integration, remote startup, automatic control, extreme reliability, long endurance, micro-meteorite protection, re-entry burnup, 0-gravity effects, high temperature operation, ground simulation testing, ground support, launching techniques, space reactor shielding, and general space reactor safety. The development of the Atomic Energy Commission-National Aeronautics and Space Administration 30 kilowatt electrical SNAP 8 system and future higher power systems will be directly dependent upon the successful conclusion of these low power system developments.

C. SYSTEM REQUIREMENTS

In addition to meeting the objectives outlined above, the specific systems under development must meet the requirements listed in Table I.

D. SNAP 2

The SNAP 2 consists of two major subsystems, the reactor heat source and the power conversion unit. A possible vehicle installation is shown in Figure 8 and a system schematic in Figure 9. Energy is produced in the nuclear reactor by the fissioning of uranium-235. A liquid metal (NaK-78) is circulated

TABLE I

SYSTEM REQUIREMENTS

	SNAP 10	SNAP 2	SNAP 8
Net Electrical Power	300 watts	3,000 watts	30,000 watts
System Weight Unshielded	300 lbs	600 lbs	1,500 lbs
Minimum System Life	1 — 3 years	1 year	1 year
Cycle Heat Rejection Area	10 ft^2	110 ft^2	400 ft^2
Availability	1963	1964	1965
	ENVIRONMENTAL REQUIREMENTS		
Operation	Deep Space Near Earth Orbit	Deep Space Near Earth Orbit	Deep Space Near Earth Orbit
Launch			
a) Shock (all axes)	60g, 8m-sec	60g, 8m-sec	100g, 3m-sec
b) Vibration	15g sinusoidal 15g rms random Frequency 5 to 3,000 cps	15g sinusoidal 15g rms random 5g to 3,000 cps	5 to 10 cps — 0.08 inch 10 to 20 cps — 0.05 inch 20 to 200 cps — 15g White noise 0.05g^2/cps 10g (rms) random
c) Acceleration	10g longitudinal 1-1/2g radial	10g longitudinal 1-1/2g radial	10g longitudinal 1-1/2g radial
d) Temperature (prelaunch)	32° to 150°F	32° to 150°F	32° to 150°F

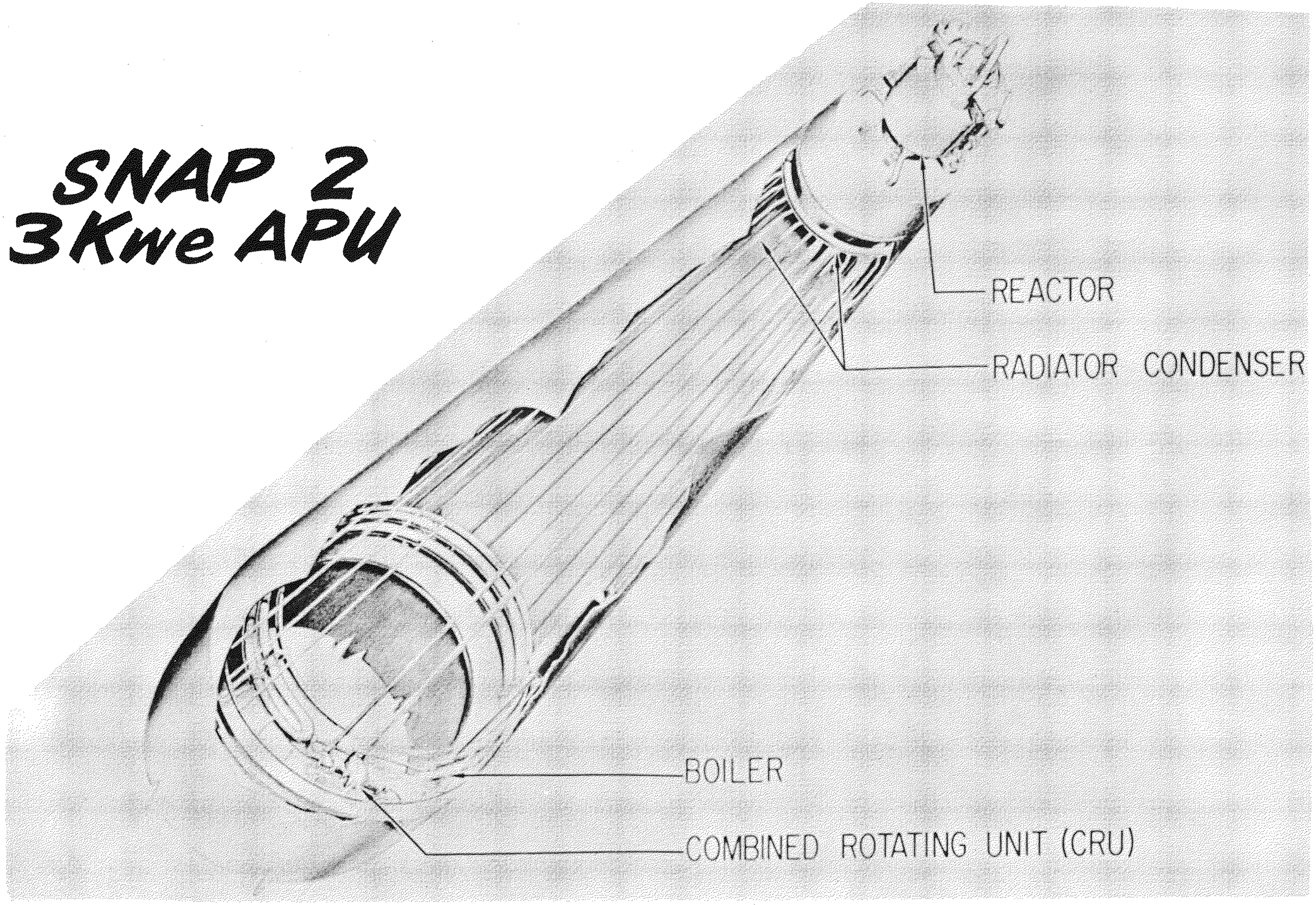

Figure 8. SNAP 2 3 Kwe APU

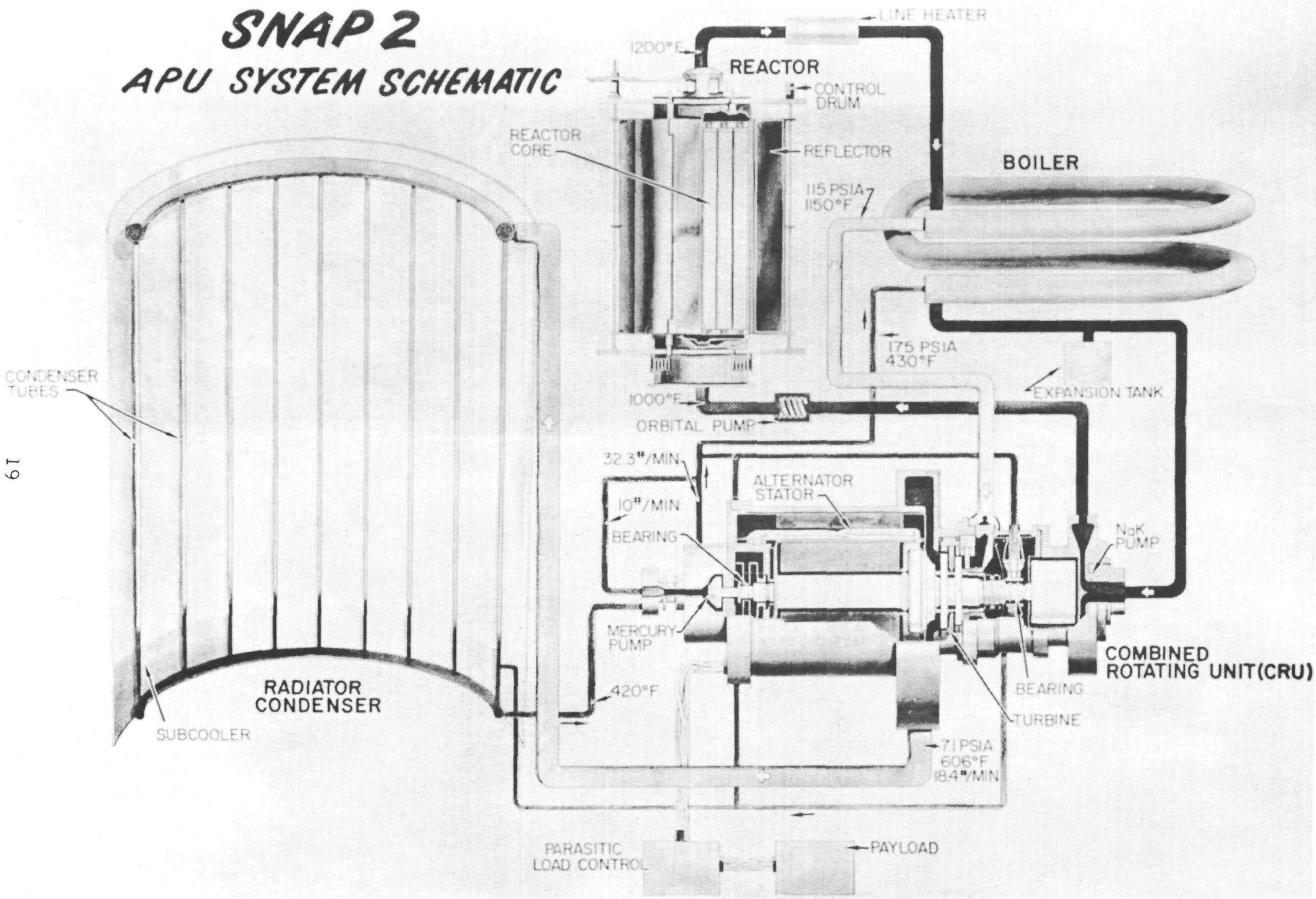

Figure 9. SNAP 2 APU System Schematic

through the reactor core and the mercury boiler superheater by a rotating permanent magnet pump. In the boiler superheater the reactor heat is transferred from the primary reactor coolant to the mercury working fluid of the Rankine power conversion cycle. The reactor heat converts liquid mercury into superheated vapor which is expanded through a turbine. The resulting mechanical power output of the turbine is converted to electrical power by the alternator. The mercury vapor exhaust from the turbine is condensed in the radiator-condenser which is part of the outer skin of the space vehicle. The mercury condensate is returned to the boiler by a boiler feed pump. The SNAP 2 incorporates the major components of a conventional nuclear electric plant with the following exceptions: 1) the cycle working fluid is mercury instead of water, and 2) the cycle heat rejection is by radiation to space instead of to a conventional heat sink such as a river or ocean.

The SNAP 2 reactor is shown schematically in Figure 10. The reactor concept employs a homogeneous fuel moderator of zirconium hydride containing uranium-235. For minimum weight, the reactor is reflected by beryllium and controlled by variation of the effective reflector thickness by means of angular rotation of two semicylindrical beryllium drums. The core is composed of a bundle of cylindrical fuel moderator elements. Beryllium slugs, located at both ends of the fuel elements form the reactor end reflectors. Each fuel element is clad in a thin wall steel tube for liquid metal exclusion. The steel cladding tubes are internally coated to prevent hydrogen loss from the fuel moderator material. The core is contained in an approximate 9 inch diameter core vessel, with the beryllium radial reflector outside the vessel. The reflector is completely separable from the core for safe reactor shutdown and handling. The 50 kilowatt thermal output is removed by the flow of NaK-78 axially through the core within the intersticial passages between the fuel elements. The coolant enters the core at 1000°F and exits at 1200°F.

All of the power conversion system rotating components are mounted on a single common shaft component which is called the combined rotating unit. Thus, the entire SNAP 2 power conversion system has only one moving part which is supported on bearing pads by liquid mercury. The combined rotating unit is shown schematically in Figure 11. The individual components of the rotating shaft include:

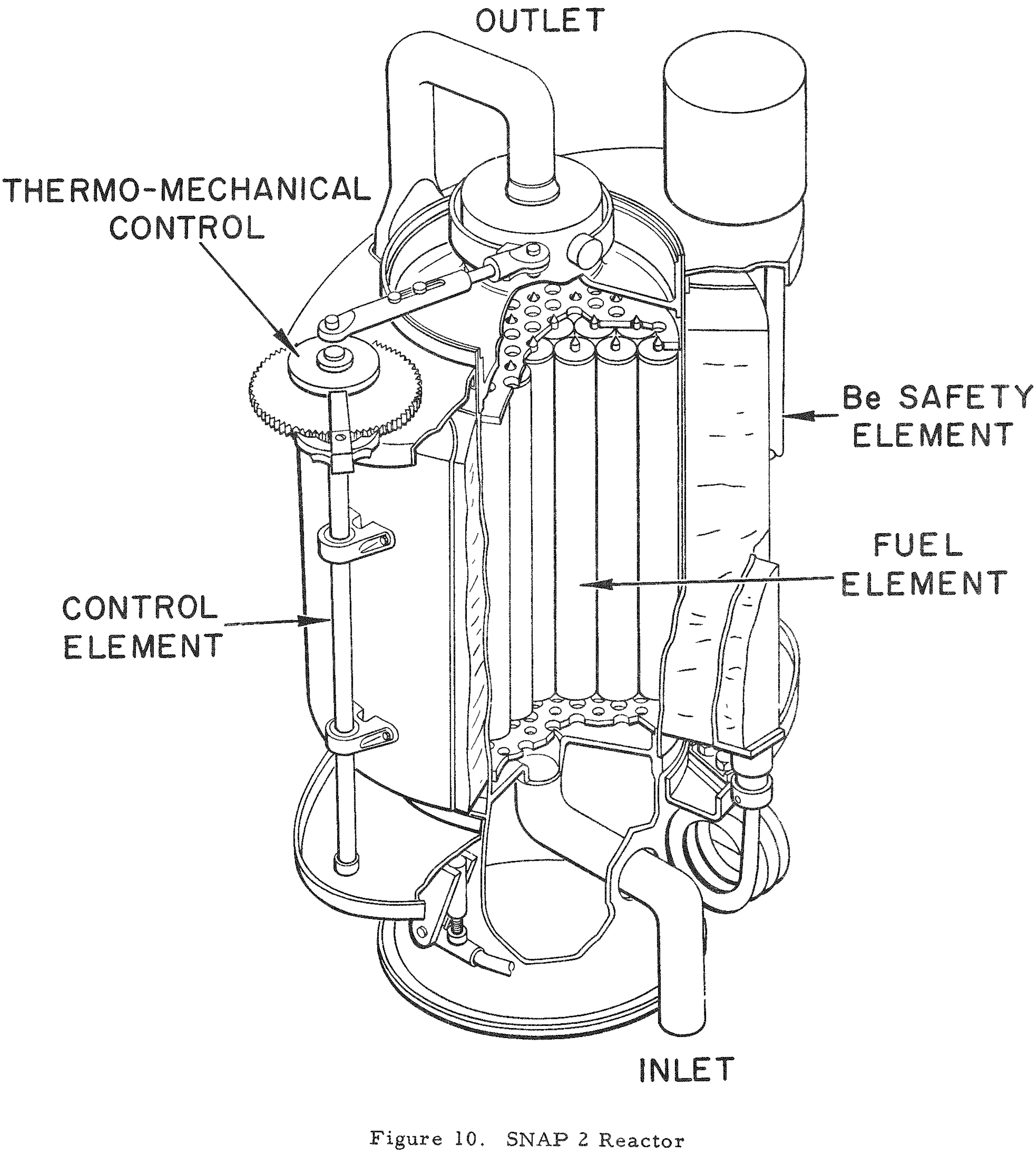

Figure 10. SNAP 2 Reactor

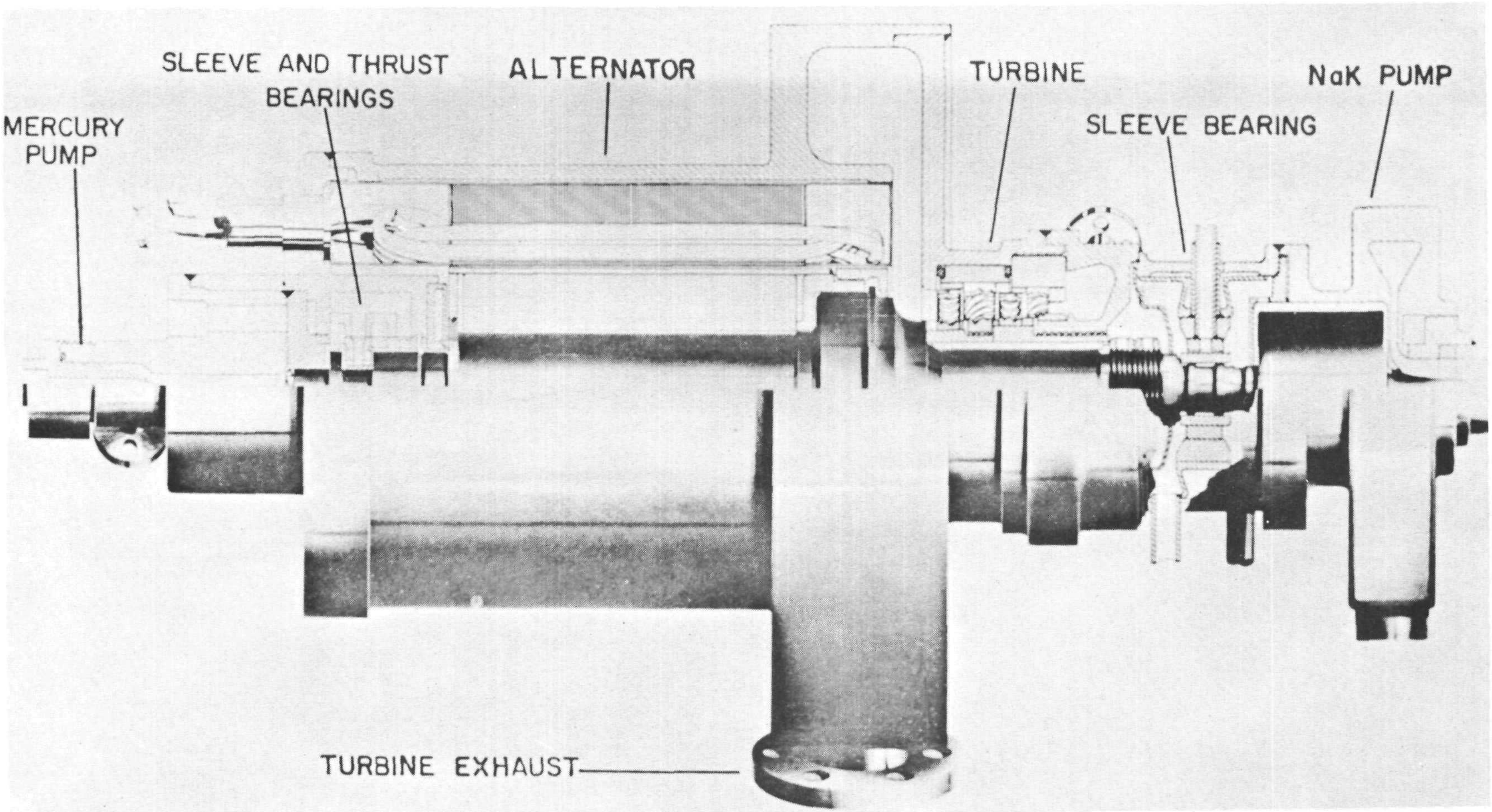

Figure 11. Combined Rotating Unit Schematic

1) The rotating permanent magnet induction NaK pump whose operation is similar to that of a conventional electro-magnetic pump with the exception that the moving magnetic field is provided by a rotating magnet.

2) The mercury turbine which is a two-stage axial flow impulse machine.

3) The alternator which is a permanent magnet machine with a sealed stator. The alternator delivers about 3.5 kilowatts at 110 volts and 2000 cps.

4) The mercury pump which is a conventional but miniature centrifugal pump supplies pressurized mercury to the boiler and to the bearings.

The shaft rotates at 40,000 rpm and is supported by liquid mercury lubricated journal and thrust bearings. The entire assembly of rotating machinery is enclosed within a hermetic housing which prevents the loss of the mercury working fluid during the system life.

The mercury boiler-superheater is a concentric tube, counterflow, once through boiler with NaK in the outer annulus and mercury in the central tube. The boiler is in a helical configuration in order to provide an artificial gravity environment by centrifugal acceleration.

The cycle rejection heat is radiated to space by a combined radiator-condenser which forms part of the outer structural skin of the space vehicle. Mercury condensation takes place at 600°F and 6 psia within a number of small diameter parallel tubes which are attached to a high thermal conductivity (aluminum) skin which in turn radiates the heat of condensation to space. The total area necessary to radiate 40 kilowatts at 600°F is about 100 square feet.

The system will have the following approximate weight breakdown:

Reactor - 200 pounds

Boiler - 100 pounds

Combined rotating unit with insulation and mounting brackets - 50 pounds

Radiator with liquid inventory - 150 pounds

Controls - 20 pounds

Structure - 50 pounds

Piping - 30 pounds

TOTAL 600 pounds

A detailed list of SNAP 2 operating characteristics and performance specifications is given in Table II.

TABLE II

SNAP 2 SYSTEM SPECIFICATION

Net electrical output power	3 kwe
Reactor thermal power	50 kwt
Electrical frequency	2000 cps
Voltage	110 volts
Radiator area	110 ft^2
Auxiliary Power Unit weight	600 lb
Lifetime objective	1 year
Cycle conditions	
Reactor outlet temperature	1200°F
Reactor inlet temperature	1000°F
Mercury superheat temperature	1150°F
Mercury boiling pressure	110 psia
Mercury boiling temperature	924°F
Mercury turbine exhaust temperature	600°F
Mercury turbine exhaust pressure	6.8 psia
Radiation temperature (fin centerline)	580°F
NaK-78 flow rate	61.3 lb/min
Mercury flow rate	17.4 lb/min
Reactor heat loss	5 kwt
Parasitic load	0.300 kwe
Control power requirements	0.100 kwe
Rankine cycle efficiency	0.22
Subcooling	200°F
Preheat power (component inefficiencies)	2.00 kwt
Boiler and pipe losses	2.00 kwt
Overall system efficiency	6%
Component performance	
NaK pump developed pressure	2 psi
NaK pump efficiency	2%

TABLE II (Continued)

NaK pump power	0.44 kw
Mercury pump developed pressure	214 psi
Mercury pump efficiency	10%
Mercury pump power	0.150 kw
Bearings power	0.600 kw
Alternator efficiency	80%
Turbine output power	5.44 kw
Turbine efficiency	55%
Turbine pressure ratio	16.1
Radiation levels	
Dose rate at 1000 ft	1 rem/hr
Dose rate at 10 ft (behind shield)	3×10^4 neutrons/cm^2-sec
	1×10^3 r/hr
Operational objectives	
Ground startup (electrical heat for checkout)	
Complete orbital startup	
Non-nuclear launch operation - nuclear orbital startup	
Angular momentum	
Combined Rotating Unit momentum	1.67 lb-ft-sec
NaK and Hg flow (balanced) (1 axis)	0.30 lb-ft-sec
(2 axis)	0.02 lb-ft-sec

E. SNAP 10

The development of thermoelectric conversion materials with increased conversion efficiency has given rise to their recent use in low power devices such as the SNAP 3, 5 watt isotope device that was announced last year. In particular the doped n and p lead tellurides are capable of 10 to 15 percent of Carnot conversion efficiencies at temperatures below 1200°F. Even though such materials lead to only 2 to 4 percent overall conversion efficiency in space systems, the attractiveness of their overall inherent static operation can offset this low efficiency at low power outputs. The attractiveness of a completely static nuclear-powered Auxiliary Power Unit lead to the establishment of the SNAP 10 program. The SNAP 10 system employs a SNAP 2 reactor with a combined thermoelectric converter-radiator coupled to the reactor by means of a pumped liquid metal (NaK-78) coolant loop.

For 300 watts electrical output the reactor power required is about 12 kilowatts at an average temperature of 950°F. The reactor inlet is 900°F and the outlet is 1000°F. At these temperatures and this power, the reactivity change due to hydrogen loss, fuel burnup, and fission product poisons during the lifetime of the system is insignificant. The result is that the reactor can maintain a nearly constant average temperature without the need for an active control system. Minor temperature changes (5 to 10°F) coupled with the negative temperature coefficient of reactivity (-0.5¢/°F) will compensate for any drifts in system reactivity throughout its life of 1 to 10 years.

The thermoelectric converter is divided into thirty 10 watt devices. The thermocouple hot junction is maintained by means of contact with the liquid metal piping of the reactor coolant loop. The thermocouple cold junction is maintained by contact with a radiator fin which at 85 percent effectiveness rejects sufficient heat to maintain the necessary temperature gradient and heat flow through the converter. The cold junction temperatures at the radiator fin are designed to operate at 710°F on the hot end and 650°F on the cold end of each coolant passage. Each 10 watt converter unit contains 20 thermocouple pairs of doped p and n lead telluride.

The liquid metal coolant is pumped at 4 gpm by means of a d-c conduction electro-magnetic pump which derives the necessary current from a thermocouple operating between the reactor inlet and outlet coolant pipes. This current coupled with the magnetic field of a permanent magnet provides a few tenths of a psi for circulating the NaK-78 coolant.

The SNAP 10 concept employing a SNAP 2 reactor and a thermoelectric converter produces 300 watts at an unshielded system weight of 325 pounds (Table III)

TABLE III

SNAP 10 WEIGHT SUMMARY AT 300 WATTS ELECTRICAL

	Pounds		Pounds
Reactor	200	Converters	30
Startup	20	Radiator	15
Reactor supports	25	Converter-radiator supports	15
Piping	10	d-c pump	10
	255 pounds		70 pounds
	TOTAL - 325 Pounds		

After startup the system operates without the aid of active control systems and has no moving parts. The coolant flow can easily be arranged to essentially eliminate any angular momentum. System startup is greatly simplified over that of a dynamic conversion system as a result of the single phase heat transfer system.

The SNAP 10 concept is such that its power output can be extended into the kilowatt range before the reactor becomes heat transfer limited. The converter arrangement is such that the output power can be increased by the simple addition of converter modules. For example, a 600 watt system will weigh about 400 pounds.

F. SNAP 8

The SNAP 8 nuclear power plant is quite similar to SNAP 2, however, it produces 30 to 60 kilowatts electrical or 10 to 20 times the power of SNAP 2. The system produces 30 kilowatts with one power conversion unit and 60 kilowatts with two power conversion units coupled to the same reactor. The reactor utilizes the same fuel material as SNAP 2 but in smaller rods (0.6 inch diameter) to provide for the higher power. The outlet NaK coolant temperature from the reactor is 1350°F. To provide for the greater control requirements four control drums are needed and BeO axial reflectors are used instead of beryllium metal because of the higher temperatures.

The power conversion system specifications are not firm at this time but the system will utilize a mercury Rankine cycle as in SNAP 2. Generally higher operating temperatures and pressures will be needed. The combined rotating unit philosophy will be maintained except that the NaK pump will be separately motor driven for higher efficiency, and to obtain the higher NaK pressures required at the tenfold increase in coolant circulation rate. The SNAP 8 reactor is shown in Figure 12; the system operational and design characteristics are given in Table IV.

TABLE IV

SNAP 8 SYSTEM OPERATIONAL AND DESIGN CHARACTERISTICS

Power	
Power electric net to payload	30 kw
Power electric gross	33 kw
Power turbine shaft	40 kw
Bearing and seals losses	3 kw
Pumping losses (Hg and NaK pumps)	2 kw
Reactor thermal power	250 kw
Radiator heat dissipation	230 kw
Heat losses	10 kw
Heat Transfer Areas	
Reactor core	25.8 ft^2
Boiler tubes	150 ft^2
Radiator surface	360 ft^2
Temperatures	
Maximum reactor fuel	1450°F (at 500 kwt)
Average reactor fuel	1280°F (at 500 kwt)
Average fuel surface	1250°F (at 500 kwt)
Coolant inlet	1150°F
Coolant outlet	1350°F
Working fluid boiler outlet	1200°F
Working fluid saturation	1100°F
Working fluid boiler inlet	700°F
Subcooler outlet	500°F

TABLE IV (Continued)

<u>Turbine-Alternator</u>	
3 stage axial impulse flow turbine	24,000
Frequency	400 cps
Voltage	208
<u>Reactor</u>	
Critical mass	5.2 kg
Core radius (with pressure vessel)	4.6 in.
Core length (active)	11.5 in.
Radial reflector thickness, Be	2.5 in.
Axial reflector thickness	1.5 in. BeO
Number of control elements	4
Number of safety elements	2
Peak flux	3×10^{12}
Temperature coefficient	-4×10^{-5}
Power coefficient	-0.2¢/kw
Reactivity per control drum	3%
Reactivity per safety element	4.2%
Number of fuel rods	163
Fuel rod diameter	0.63 in.
Fuel rod pitch	1.011
<u>Weight Summary</u>	
Reactor core and vessel	205 lb
Reflector and control elements	85
Control activation	8
Supports	20 lb
Boiler	300 lb (wet)
Combined Rotating Unit (CRU) (turbine-alternator-bearings and pumps)	100 lb plus 50 lb for separate NaK pump
Condenser tubes and bonding and manifold	
Micrometeorite protection	
Vehicle radiator skin	
Radiator-condenser - Total	400 lb

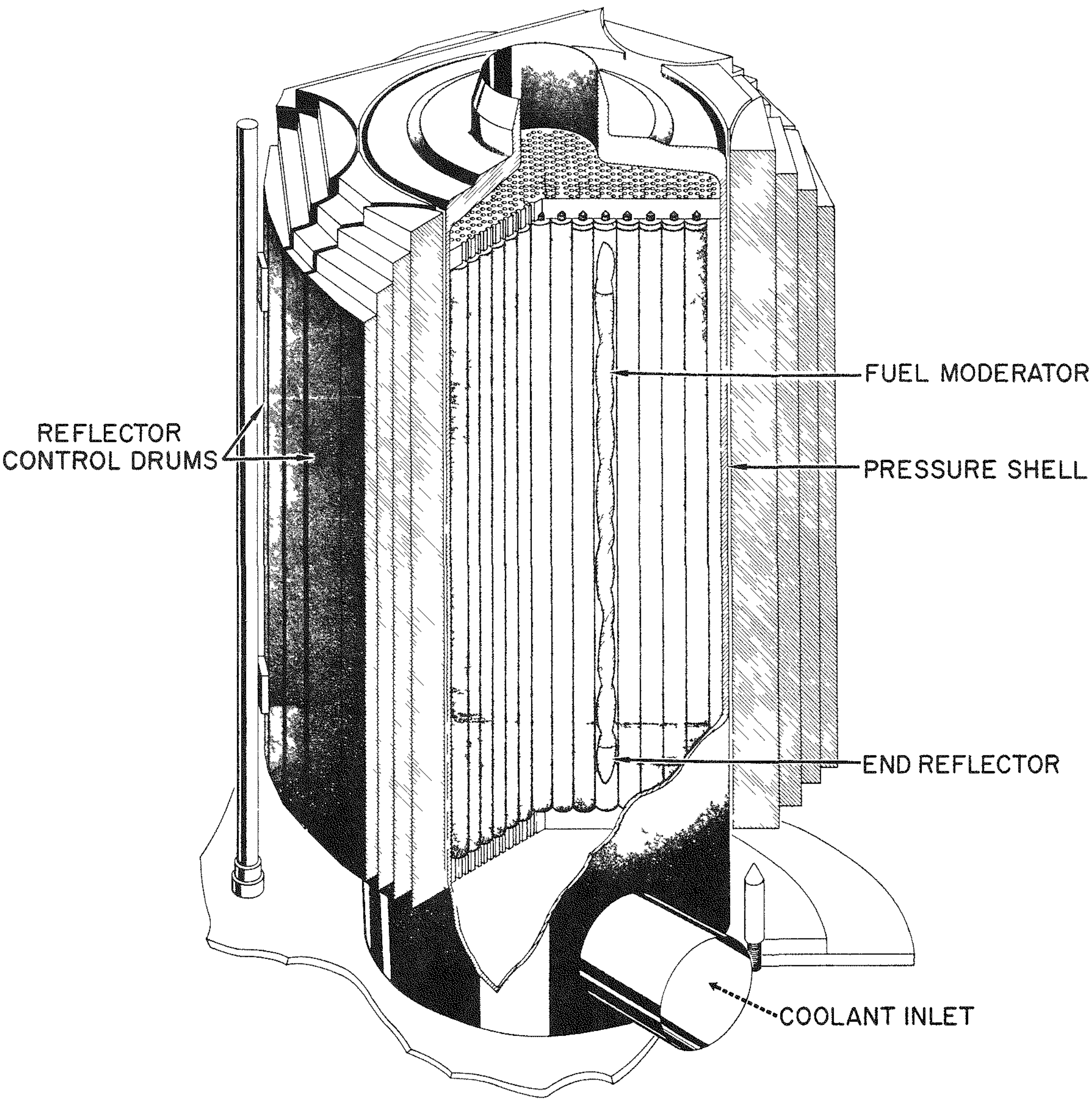

Figure 12. SNAP 8 Reactor

IV. SNAP VEHICLE INTEGRATION

Structural scatter of nuclear radiation emitting from the reactor can cause a high payload dose if shielding for the scattered radiation is not used. Thus, if the reactor is located in the vehicle nose and the nose cone skin is jettisoned as shown in Figure 8, and if the payload is extended back below the radiator, an optimum shield results. The reactor and shield are on the vehicle thrust line and no structural scatter occurs since the entire vehicle-payload complex is within the shadow of the shield. With a conventional transistorized payload of any practical volume, the shield weight will be reduced to 250 to 300 pounds.

This layout does introduce disadvantages, however. The SNAP 2 is about 13 feet long instead of 7 feet as in a modular cylindrical design. Of course the possibility of nestling the payload within the radiator cone during ascent exists in this layout whereas a modular layout precludes this. The SNAP access on the launch pad is better with the nose cone location but payload visual access in orbit can be difficult unless the propulsion system is jettisoned. Placing the reactor-shield combination at the tip of the vehicle increases gravitational restoring torques for satellite applications but can perturb the vehicle flight stability. Re-entry burnup of the reactor is more easily obtained with the exposed nose location.

In Table V it is shown that the payload tolerance affects the shield weight a great deal. It appears that a conventional payload utilizing transistors can be subjected to 10^7 r of gammas and 10^{12} nvt of fast neutrons. A payload especially designed for SNAP would utilize vacuum tubes or radiation resistant transistors in especially designed circuits which are tolerant of component drifts. Such a payload could be expected to withstand greater than 10^{14} nvt and 10^9 r.

Extremely radiation sensitive payloads, i.e., photographic film, should be equipped with individual shields so as to raise their tolerances to the payload design value.

Van Allen and cosmic radiation sources are usually no problem for unmanned systems. Exceptions occur in the case of photographic film and a few other very sensitive components. The yearly dose in the inner Van Allen belt (at about 2000 miles) taking in to account various geometric factors, fraction of time

TABLE V

MINIMUM SHIELD WEIGHTS - pounds

(Nose Cone Configuration - 1 Year Dose)

	Core to Payload Separation (feet)	Hard Electron Tubes (10^{16} nvt 10^{11} r)	Special Transistors and Diodes (10^{13} nvt 10^{8} r)	Present Germanium Transistor (10^{12} nvt 10^{7} r)	Man (7.6×10^{7} nvt 2.6 r)
SNAP 10	6	0	170	250	-
	30	0	70	100	-
SNAP 2	13	0	170	250	2140
	30	0	130	190	1640
SNAP 8	20	35	220	320	2300
	30	0	190	270	1900

spent in the maximum dose rate region, etc., is about 10^5 r. That in the outer belt (about 13,000 miles) is somewhat higher but also more easily shielded. In either case, a great deal of attenuation can be obtained by use of the vehicle skin and other structure members as shielding since the primary source of radiation consists of relatively easily attenuated electrons.

The requirements for manned applications depend heavily upon mission and upon the vehicle arrangement. If the mission is to spend most of its time in the Van Allen belts, the crew compartment will have to be well shielded and as a result the reactor shielding need not be significantly different than for electronic missions. If Van Allen radiation is to be avoided, the crew compartment shield will be quite light and other steps must be taken to reduce reactor shielding. Normally, a configuration such as Figure 13 would be used with the crew compartment extended well to the rear of the SNAP. This not only provides the geometric r^2 reduction in dose rates but, more important, reduces the cone angle that the shadow shield must cover. The design is optimized when the incremental reduction in shield weight is offset by the incremental increase in telescope extension members and power conductor weights.

The SNAP 2 radiator will operate at 600°F; therefore, it may be undesirable to have any payload components near by. In a configuration such as shown in Figure 13, a payload package may be carried to orbit nestled within the radiator and then extended to the rear prior to SNAP startup. This eliminates temperature interactions and significantly reduces shield weight.

Since a more reliable SNAP can be developed if it operates at constant electrical load and since induced torques are minimized under this condition, it is usually desirable to provide a dummy load control which insures a constant load to SNAP. It is necessary that payload transients be integrated into the design of the dummy load control although serious interactions are not likely.

In the case of an earth satellite, the axis of the combined rotating unit will normally establish the pitch axis of the vehicle. It herefore, may be necessary to have a very accurate alignment between the combined rotating unit and the vehicle. Allowable deviations in vehicle attitude will be reflected as rpm tolerances on the combined rotating unit and as allowable torques resulting from other

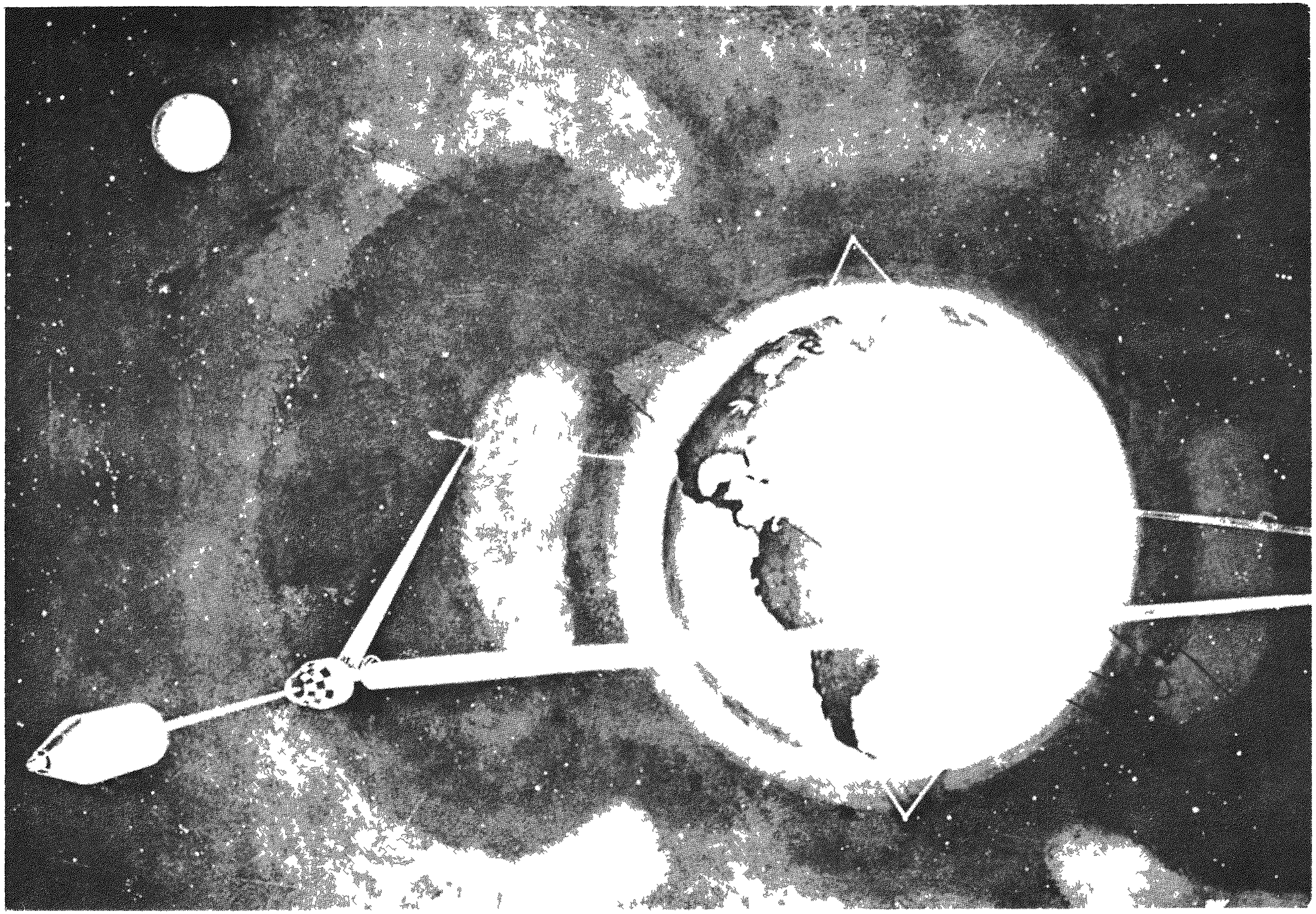

Figure 13. SNAP - Communication or Manned Satellite Configuration

angular momenta in the vehicle. At low altitudes, it may be feasible to obtain attitude control from natural restoring torques and an oscillation damper. At very high orbital altitudes, a dynamic attitude control will probably be necessary or possibly a tumbling vehicle could be used.

The SNAP 2 with the combined rotating unit aligned to the vehicle pitch axis system has the following characteristics influencing attitude stability.

Moment of inertia of combined rotating unit	0.00072 ft-lb-sec^2
Roll axis angular momentum	$<$ 0.01 ft-lb-sec
Pitch axis angular momentum	3.00 ft-lb-sec
Yaw axis angular momentum	$<$ 0.20 ft-lb-sec

A frequency drift of 1 percent per year corresponds to a torque of 9.7×10^{-10} ft-lb. A shaft acceleration of 1 radian/sec^2 corresponds to 7.2×10^{-4} ft-lb.

V. GROUND HANDLING AND SAFETY

The SNAP units are being designed for complete factory assembly, calibration, and testing. All operational acceptance testing except very short time tests will be accomplished with electrical heating in place of nuclear heat. Actual nuclear testing would be limited to 5 to 10 minutes either at the factory or after it has been installed on the launch vehicle. From Figure 14 it can be seen that such a test can be conducted in the vehicle for SNAP 2 with normal launch exclusion distances (3500 feet). Figure 15 shows the launch vehicle and the surrounding dosages after 30 minutes of test operation and one hour of decay. Figure 16 presents the dose rate from the reactor after 30 minutes of test operation. Figure 17 presents the rate of activity buildup and decay for several operating times. For SNAP 2 the worst plausible accidental excursion would be limited to about 20 megawatt-seconds of energy release due to the strong prompt negative temperature coefficient of reactivity and hydrogen loss. The worst conceivable burst would be limited to about 50 megawatt-seconds for either of the SNAP units. Figures 18 and 19 present the fission product inventories and dose rates that arise from this implausible situation. The examination of these possible dosages interms of normal industrial tolerances and rather normal launch pad and countdown procedures indicates that an inplace vehicle nuclear operational test that

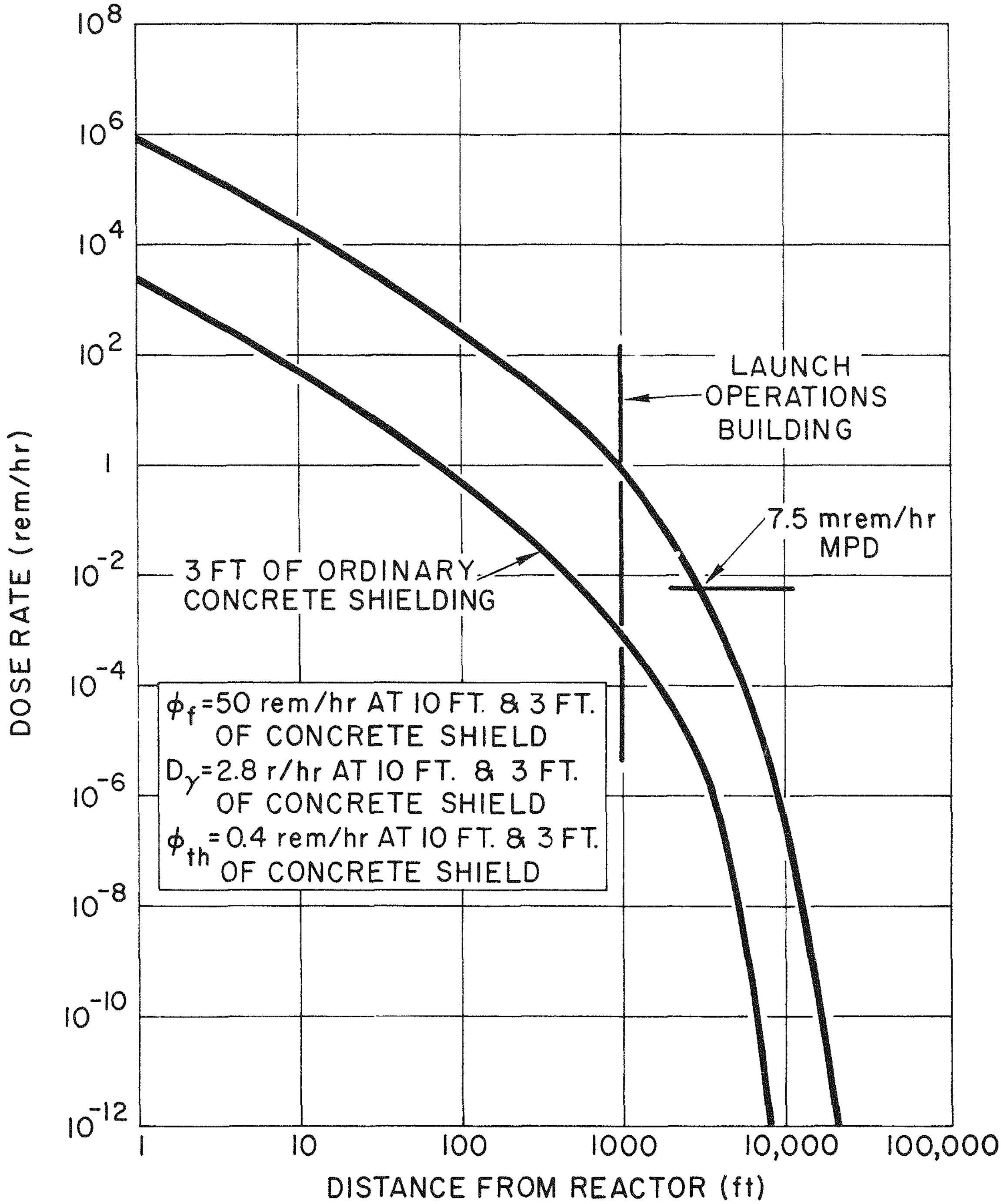

Figure 14. Total Dose Rate as a Function of Distance in Air from SNAP 2 APU During 50 kw Reactor Operation

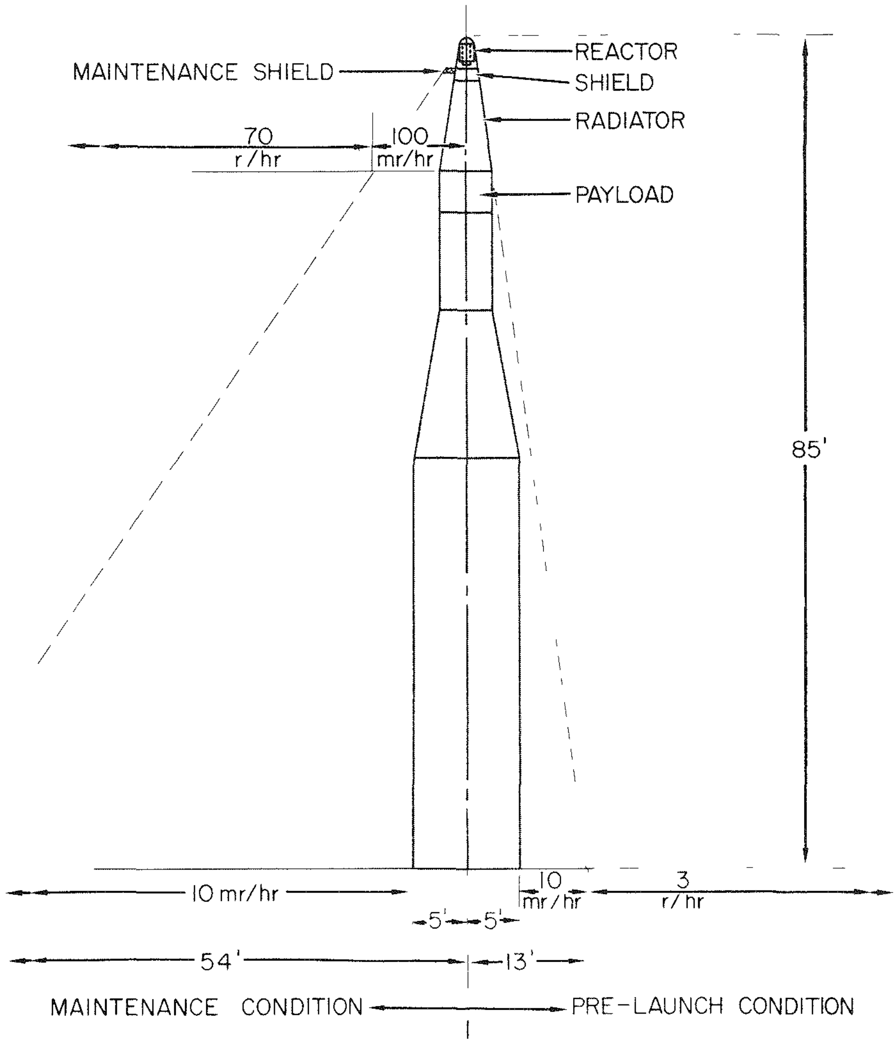

Figure 15. Tentative SNAP 2 APU Launch Configuration

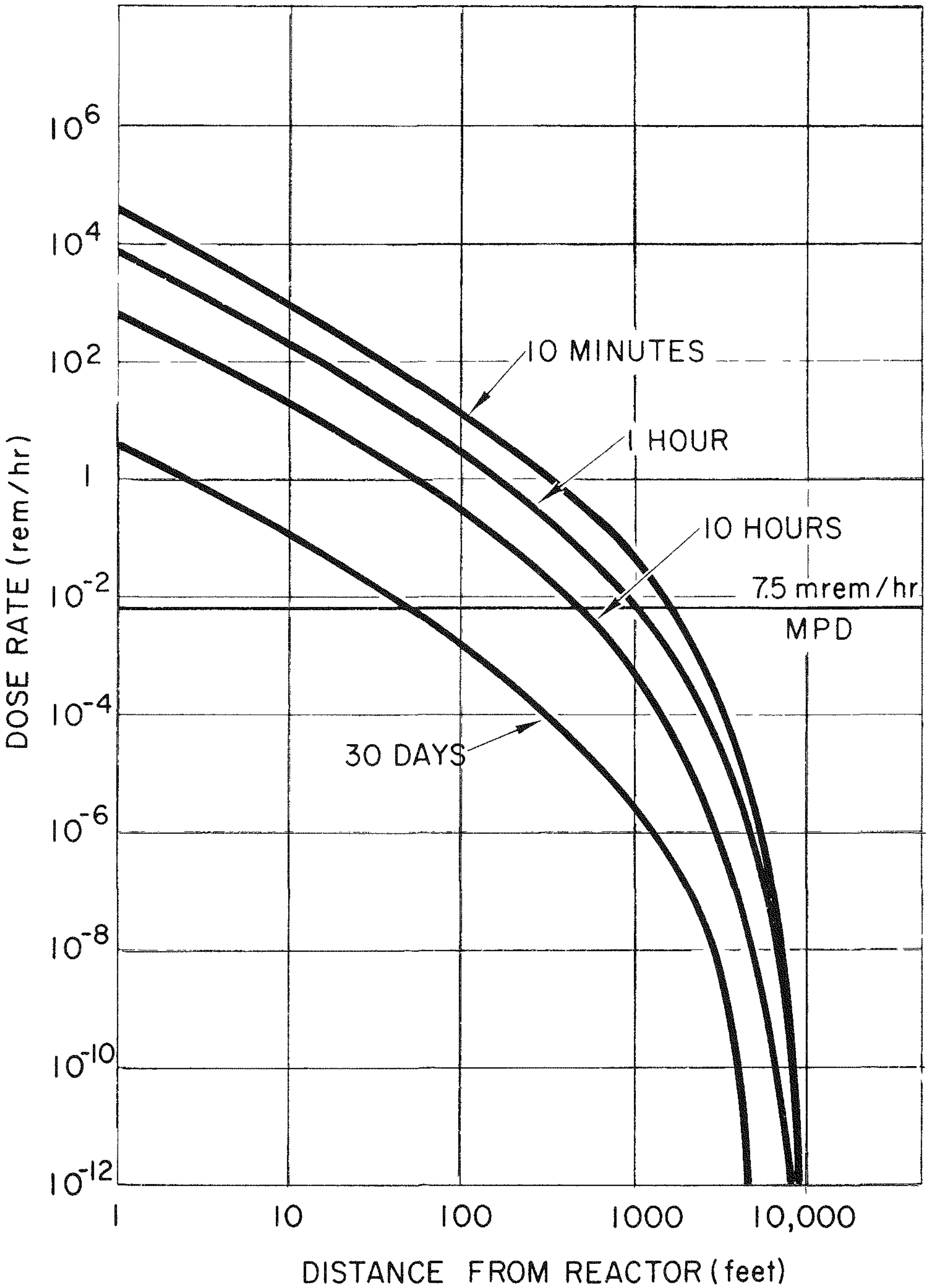

Figure 16. Gamma-Ray Dose Rate from SNAP 2 APU After 30 Minutes Operation at 50 kw

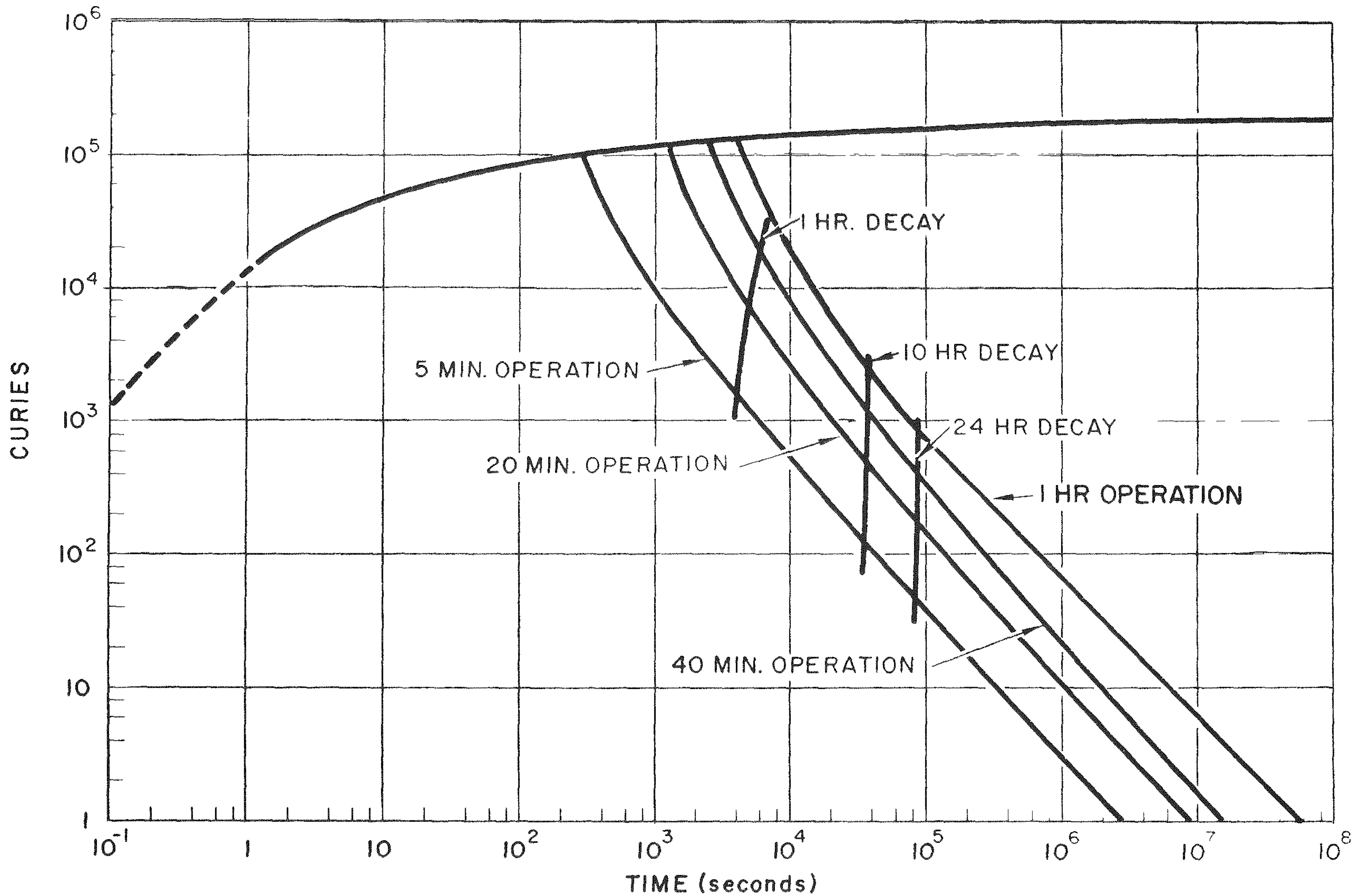

Figure 17. Fission Product Inventory for SNAP 2 vs Time of Operation at 50 kw

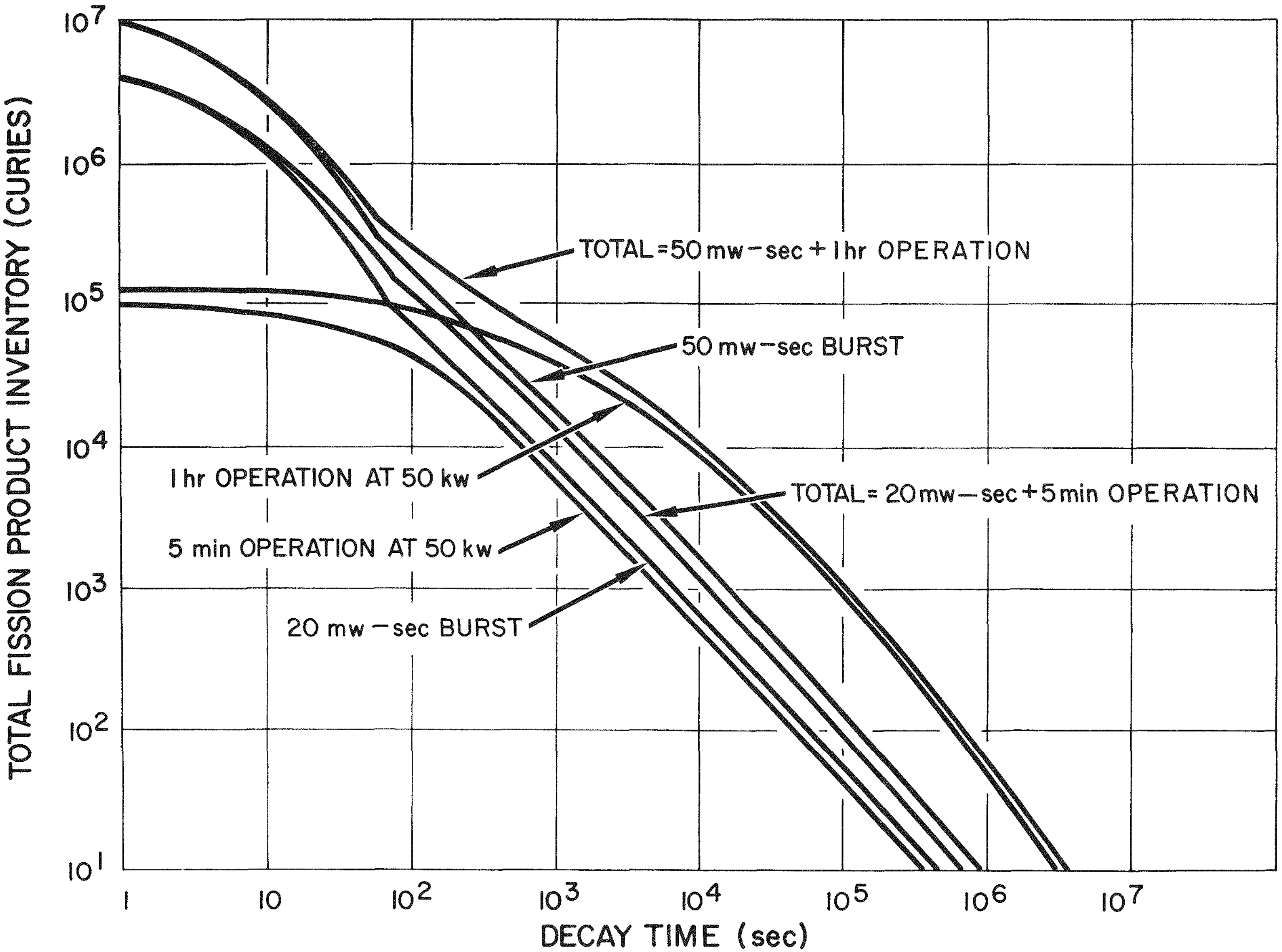

Figure 18. Fission Product Inventory for SNAP 2 vs Decay Time for Reactor Conditions Noted

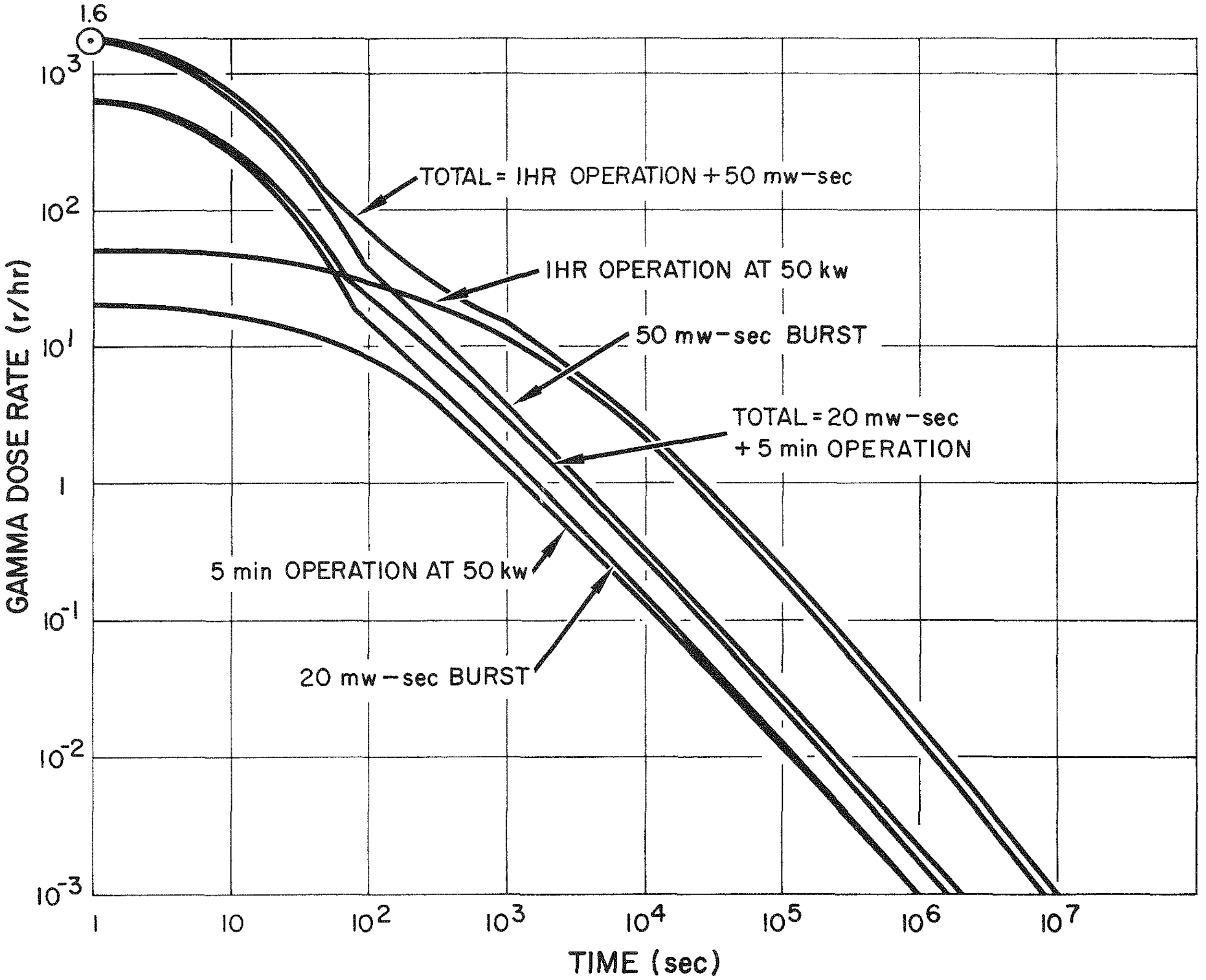

Figure 19. Dose Rate vs Decay Time at 100 Feet from SNAP 2 APU

is limited to a few minutes of reactor operation a few days before launch can be reasonable and safe.

It appears that all questions regarding public safety during the launch phase can be satisfactorily answered by not starting the nuclear reactor up until it has achieved a safe and stable orbit, and the flight path and orbital life have been established. Thus all SNAP systems are being designed for orbital startup.

VI. REENTRY SAFETY

If the SNAP units were operated in low orbits such that they would re-enter after some time, and if the reactor did not burn up and disperse on re-entry, the permissible time that may be allowed to evacuate to a safe distance is presented on Figure 20. From Figure 20 it can be seen that, if SNAP 2 were operated in a 400 mile altitude circular orbit for a year, evacuation would not be required beyond 100 meters according to U. S. Atomic Energy Commission industrial tolerances. Curiosity seekers would have several hours to linger; a week is available to evacuate a 10 meter radius area around a re-entered reactor. If the SNAP 2's were operated in orbits above 500 to 600 miles in altitude no evacuation would be required from an intact re-entering reactor.

However the SNAP units are being designed to burn up and disperse on re-entry above 100,000 feet in order not to restrict their usefulness and operating altitudes. Analysis and arc-plasma jet simulated re-entry heating indicate that burnup should occur above 200,000 feet. Future tests will include actual re-entry of non-activated specimens to confirm these studies.

From Figure 21 it can be seen that if a SNAP 2 re-entered from a very low orbit (less than 100 miles) every year it would take 60 years to build up the strontium-90 background (a particularly bothersome isotope) to a fraction of 1 percent of the background level that will exist if all bomb testing is halted. Of course due to the decay that would occur in high altitude cases the background buildup would not be measurable.

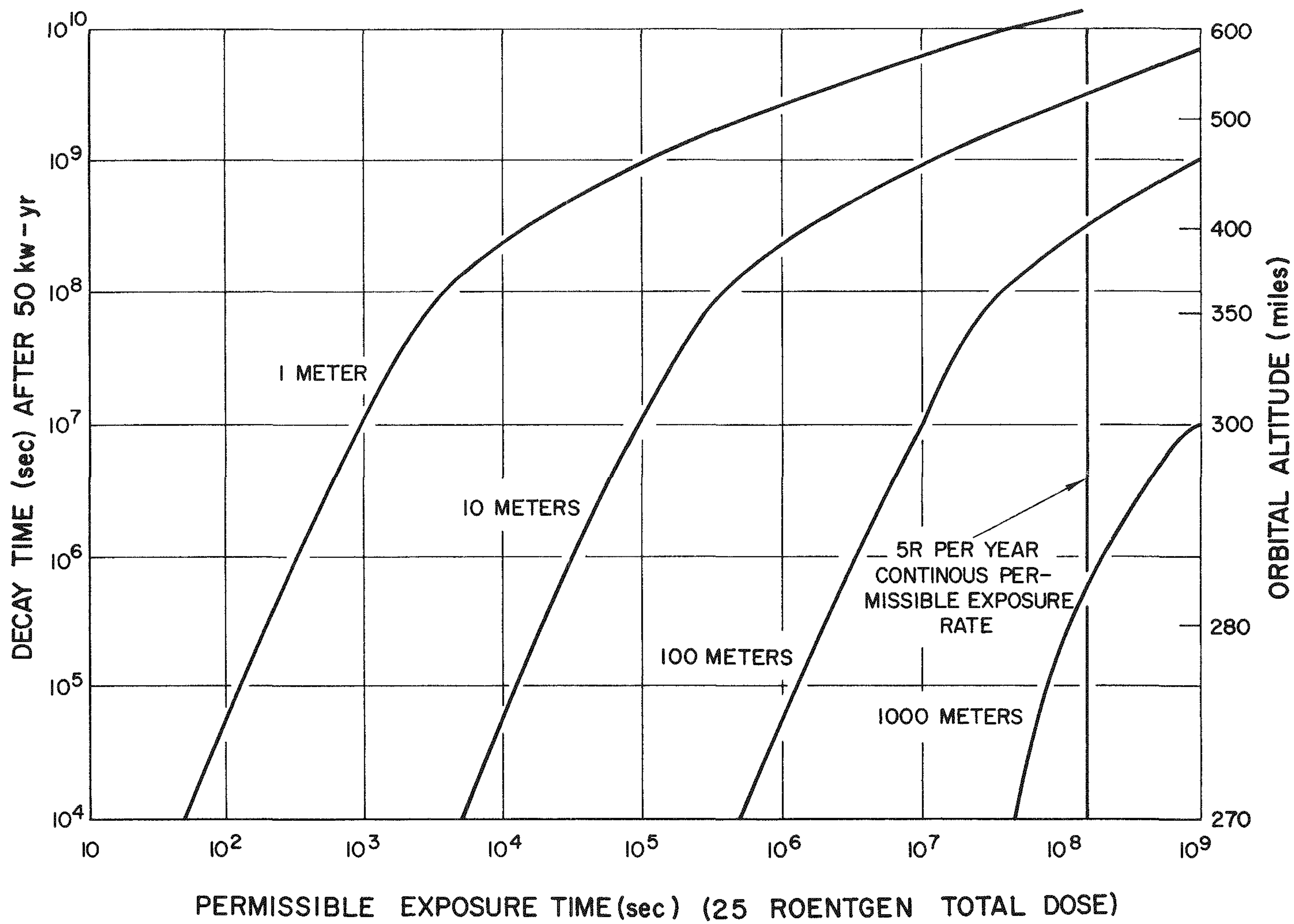

Figure 20. Permissible Exposure Time and Distance for Intact Re-entry vs Decay Time in Orbit or Orbital Altitude

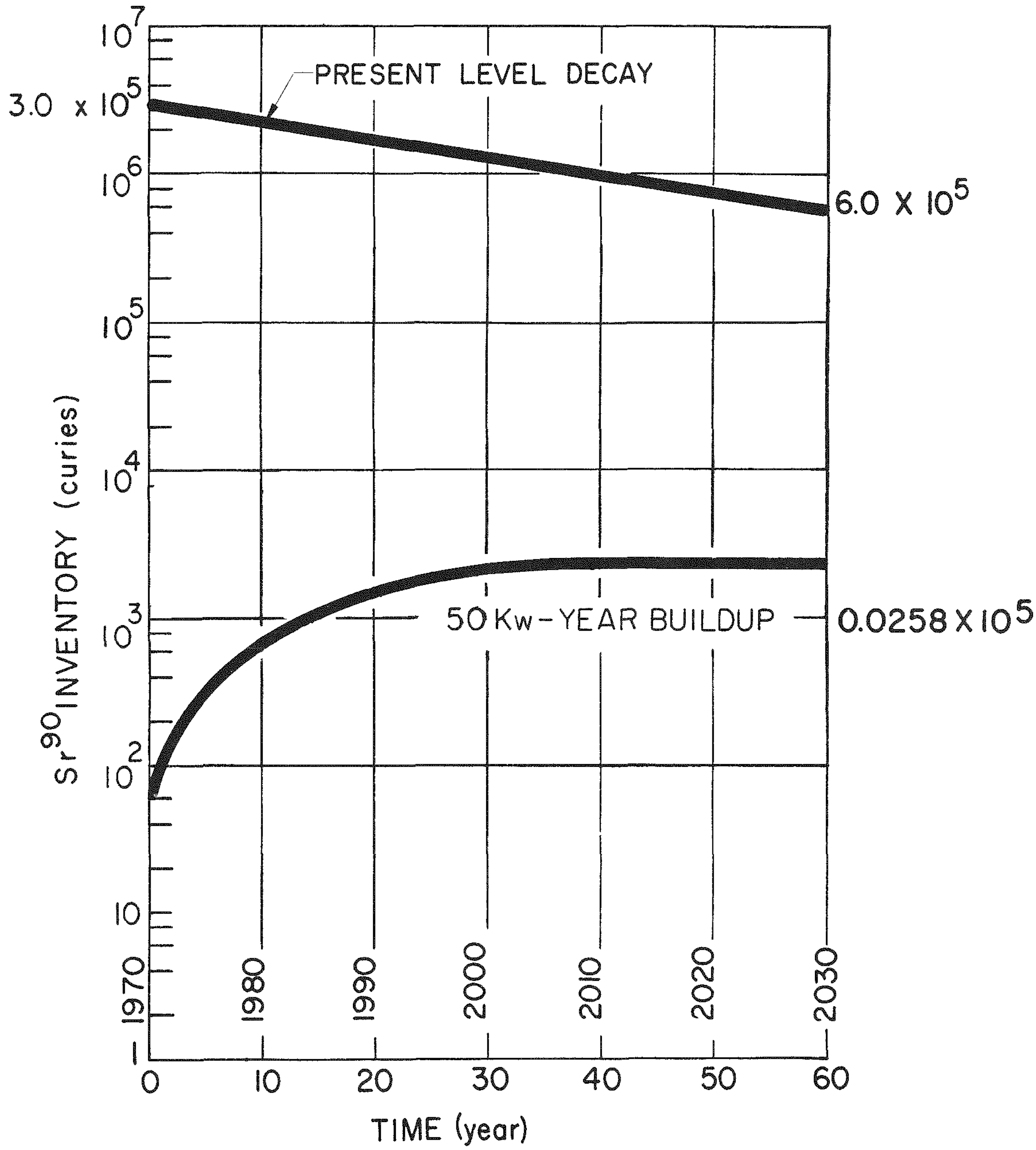

Figure 21. Comparison of Sr^{90} Inventory in Upper Atmosphere from Past Nuclear Tests and Possible Space Programs

VII. TYPICAL APPLICATIONS OF SNAP SYSTEMS

At the present time a system engineer concerned with the design of a space system is constrained to think primarily in terms of technical feasibility. Many of the key components of his system have technical limitations which tend to establish or at least severely limit the design considerations concerning other parts of the system. This situation results for the most part in the relegation of many economic considerations to a position of secondary importance in over-all system design.

As man progresses in the field of space technology as he has in other technological fields, he will undoubtedly find that the systems he designs must enter into economic competition. The economic optimization of a system at this stage is further complicated by the fact that the range of technical choice has been greatly enhanced by technical progress. That part of the technical progress that is of particular concern at this time is the advent of SNAP units for application to space systems. The particular advantage of SNAP units that is of interest to the system engineer concerned with space systems is the potential they offer for a long lived, reliable and continuous high power source. With the advent of SNAP units, space system engineers will find their horizons considerably broadened from what they are now. The technical disadvantages of present APU systems are well known and need not be particularly discussed. In many cases these disadvantages have been overcome by enhancing the capability of other system components to achieve satisfactory system performance. Sometimes at moderate cost but more often at very high costs indeed. However, the system designer did not have to be greatly concerned by this fact since in general, he had no alternative. However, designers of future systems will find themselves more constrained to optimize their system from an economic standpoint and in many cases the higher power available from SNAP units can be used to advantage in reducing system costs.

In order to illustrate this point, it is probably best to show by specific example how system design considerations from an economic standpoint can be affected by the advent of SNAP units. The example that we have chosen for this demonstration is a possible "single thread" design of a communication satellite network. This example is by no means offered as a communication satellite system design. The design of a communication satellite system will be a very complex undertaking and many factors must be taken into account which have not been taken into account in our example but we do believe that the considerations we have arrived at are valid and do serve to illustrate the economic advantages of a SNAP unit in certain space systems.

We also feel that this particular application, i.e., a communication satellite system, is one of the most important applications of satellites to human progress. A commercial communication satellite network has the potential for not only providing intercontinental wideband communication links which are now technically feasible, but a commercial communication satellite system also seems to have the potential for competing economically with present intercontinental links such as submarine cables.

In Figure 22 we have a pictorial representation of a satellite vehicle having a 24-hour orbital period stationed over the Atlantic. Five ground stations located in major population areas use the active repeater aboard the satellite vehicle to link themselves together. These stations, in turn, are associated with a conventional ground distribution system to provide customer service throughout the geographical area served.

Our first basic assumption is the use of the 24-hour orbit. Systems based on the use of lower orbit altitudes have been and must continue to be examined. However, a system based on the 24-hour orbit is generally considered to be a promising possibility.

Our second assumption concerns the selection of a frequency. It is generally agreed that near optimum frequencies for earth to space communications lay between 300 to 3000 mc. At lower frequencies, ionospheric effects are troublesome; at higher frequencies, receiver noise first becomes a problem and at still higher frequencies, atmospheric absorpiton is a limiting quantity. We have, therefore, selected 1700 mc as a probably frequency as it is currently reserved for such purposes.

Given these basic assumptions we may examine the effect of satellite transmitter power on ground station cost.

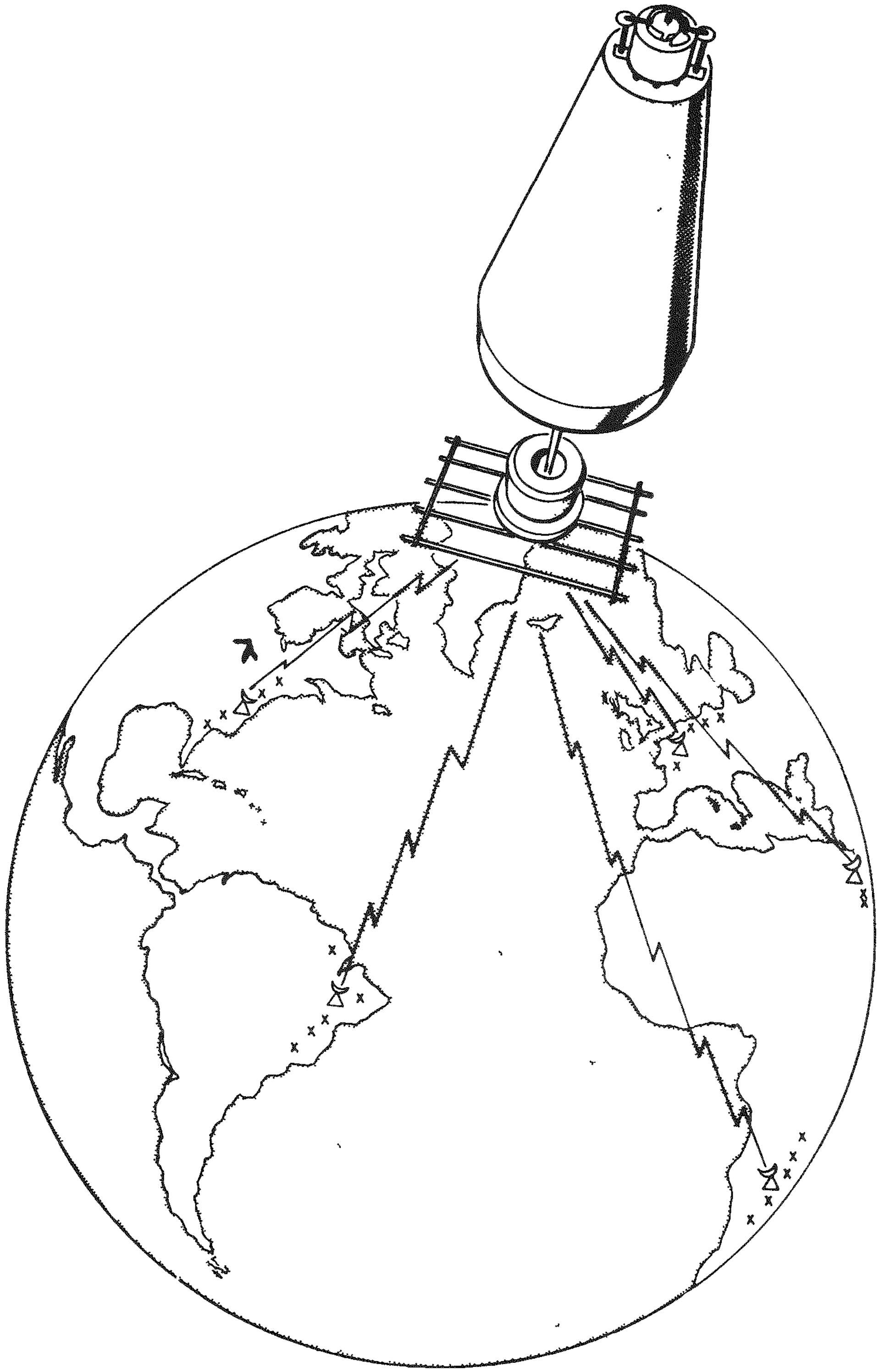

Figure 22. Visualization of a Single Thread Design of Atlantic Leg of a Commercial Communications Satellite System

Figure 23 illustrates the relation of radiated power, at 4 mc bandwidth, of the satellite transmitter to the ground station antenna cost, which in the extreme case of very large antennas is the major factor in the station cost. The three different antenna gains have been selected on the basis of the complexity of the satellite attitude stabilization requirement, in that this requirement is a major factor in determining vehicle cost, reliability and expected useful life.

At 0 db gain there is no requirement for attitude stabilization and with a SNAP unit could tumble at a reasonable rate. At 3 db gain, we illustrate the requirement for only the type of attitude stabilization to keep the vehicle pointed only generally in the direction of the earth. At 16 db gain and greater, the vehicle must be stabilized within a few degrees at all times.

From this chart we can see that the use of very low power introduces a high cost factor for ground station installations. Moderate ground station costs do appear to be achievable with the use of moderate power for a stabilized vehicle. With unstabilized vehicles the power requirements are of the order of those available with SNAP 2. The radiated power shown here must, of course, be multiplied by about a factor of 5 to arrive at an approximation of the total APU requirements. Then for ground antenna costs of $50,000 each, we have a 3000 watt APU requirement for an unstabilized vehicle, and a 50 watt plus stabilization power requirement for a stabilized vehicle.

The foregoing considerations assume a vehicle capability for 330 voice channels and 1 video channel (Bandwidth 4 mc). However, if past history is any indication, this system will open new markets for communication services with an attendant increase in bandwidth requirements which must be compensated for by either enlarging the ground station antennas, increasing vehicle stabilization and achieving greater transmitting antenna gain, or by an increase in the vehicle power. With the advent of space nuclear power the increase in vehicle power would most probably be the least costly of the alternatives.

A. ELECTRIC PROPULSION

By coupling the SNAP 8 system at 60 kilowatts electrical to an electric propulsion device the Atlas boosted Centaur vehicle (9000 pounds) could be carried

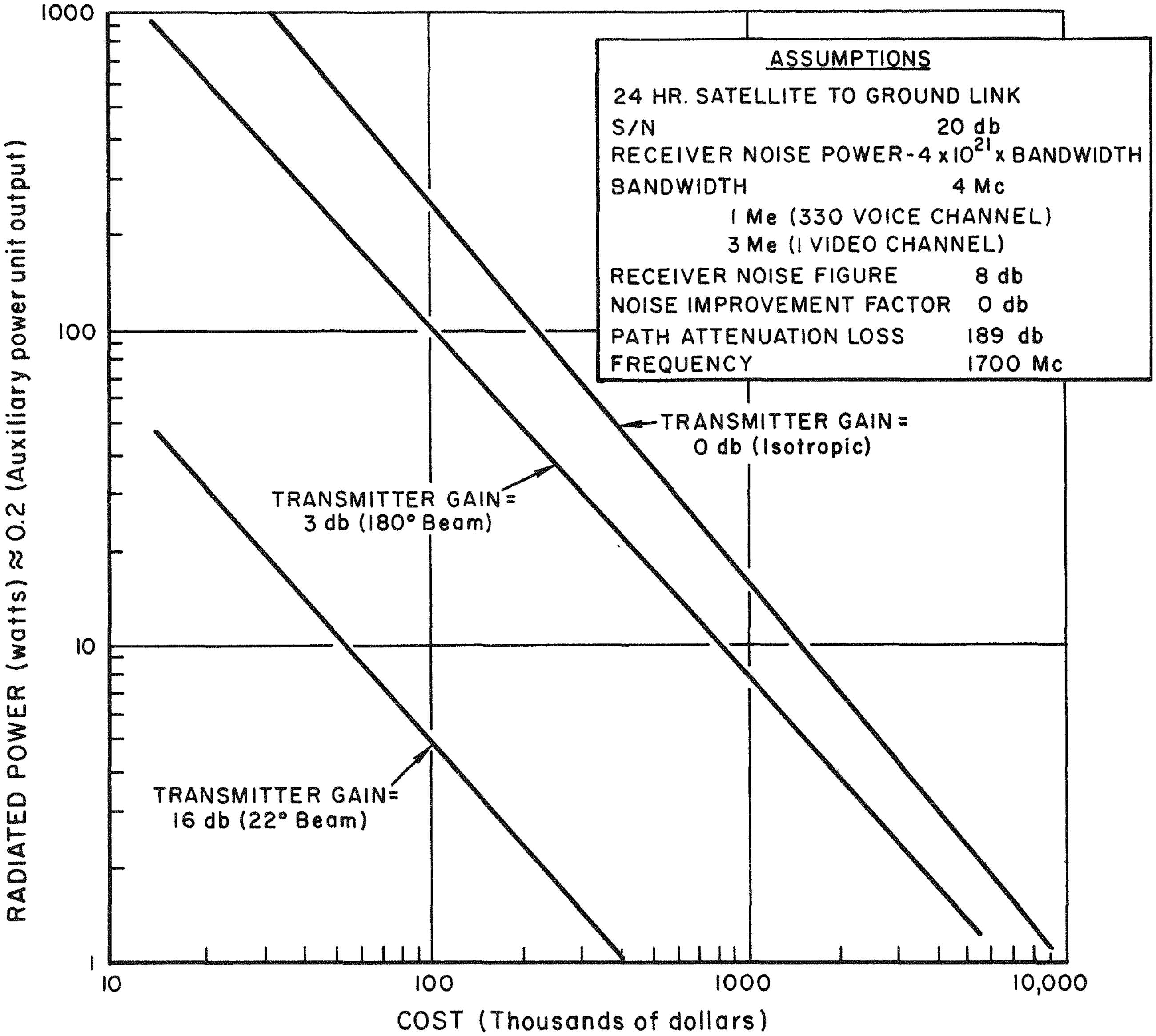

Figure 23. Trainable Antenna Cost for Ground Installation vs Radiated Power

from a 200 mile orbit to a 22,000 mile (24 hour) orbit. Due to the low thrust (4.5×10^{-5} g) that would be available the trip would require about 2 months rather than the 5.4 hours of an all chemical vehicle. However, where time is less important (unmanned flights) the same payload is placed on 24 hour orbit with the 5 million dollar Atlas-Centaur and a 1 million dollar SNAP 8 as would otherwise require a 20 million dollar all chemical Saturn vehicle.

In conclusion, the new degrees of freedom that are provided the space system designer by the advent of Systems for Nuclear Auxiliary Power can lead to many new and useful applications of space vehicles and technology.