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Summary of Snap Nuclear Space Power Systems

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The ever-increasing payload capabilities of space-vehicle booster sys-
tems require lightweight, long-lived, high-power, reliable electrical
power-generating systems. The space power requirements vary from
several hundred watts of auxiliary power into the megawatt range for
large electrical propulsion applications. The nuclear space power plants,
because of their low specific weight, become extremely attractive in the
range of several hundred watts and appear to be the only feasible sys-
tem for power levels over about 30 kw. The paper reviews developments
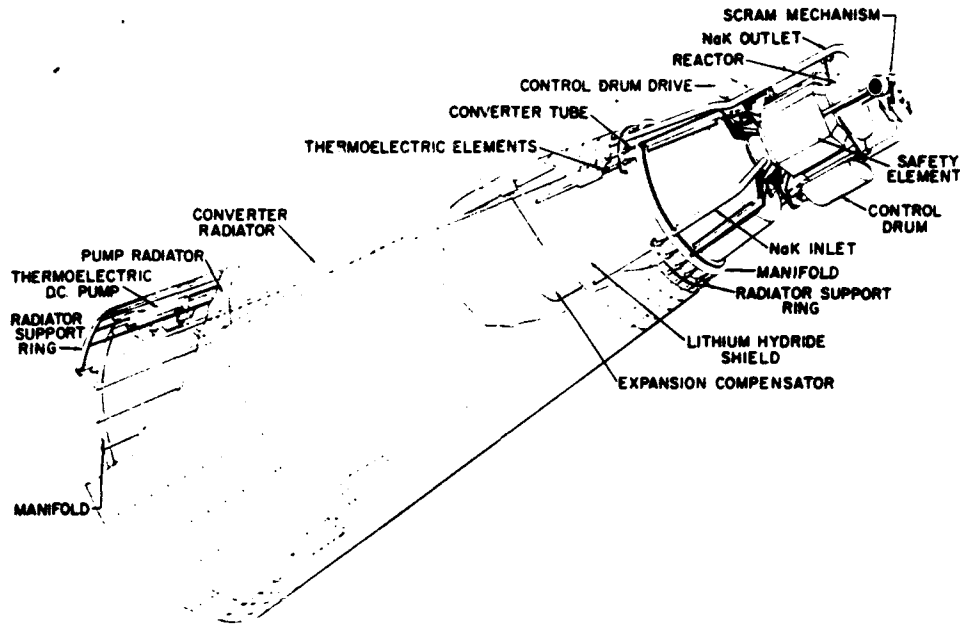in this area.

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Fig. 1 SNAP 10A auxiliary power unit

Summary of Snap Nuclear Space Power Systems

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To meet the need for space power, the Atomic Energy Commission currently has under development three space reactor power systems as part of the SNAP (Systems for Nuclear Auxiliary Power) program. These are the SNAP 10A, a 500-w thermoelectric system; SNAP 2, a 3-kwe turboelectric system; and the SNAP 8, a 30 to 60-kwe scale-up of the SNAP 2 system. The systems will meet the requirements of rugged compact design, light weight, high reliability, and long life. In addition, the systems will be capable of remote startup in orbit, and will present no biological hazard throughout the sequence of shipment, launch, orbit and re-entry. Table 1 lists the more specific objectives of the three systems.

CONFIGURATION

The SNAP 10A configuration is shown in Fig.1. The NaK reactor coolant transports the heat to the thermoelectric converter. The heat is transferred through the converter elements producing electrical power with the waste heat rejected to space by radiation. Coolant flow is provided by a thermoelectric pump, thus producing a system void of
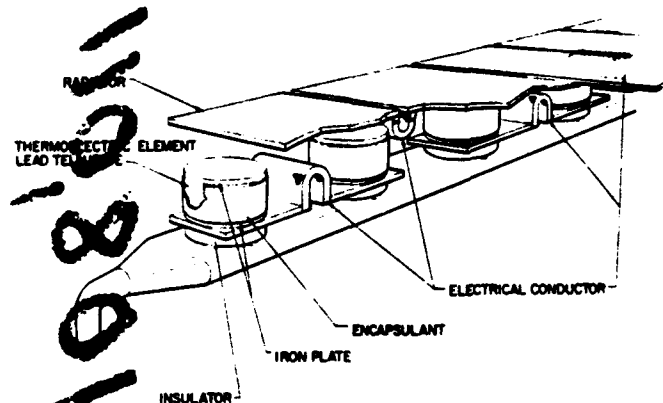
Fig.2 Thermoelectric converter module for SNAP 10A power conversion

moving mechanical parts. Reactor control is employed during system startup; however, since the long-term reactivity loss is negligible, no active control system is required after the initial startup phase. Fig.2 shows a cutaway view of the thermoelectric converter. The lead-telluride thermocouples are mounted in series between the NaK coolant tubes and the radiator, forming the hot and cold junctions. Electrical insulation isolates the thermocouples from the NaK tube and radiator. Fig.3 shows the thermoelectric pump design. Operation of this pump is similar to that

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Fig. 3 Integral thermoelectric source pump for SNAP 10A coolant pump

Fig. 4 SNAP 2 auxiliary power unit
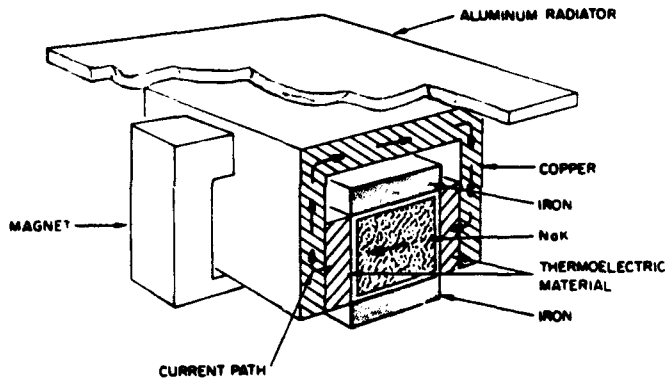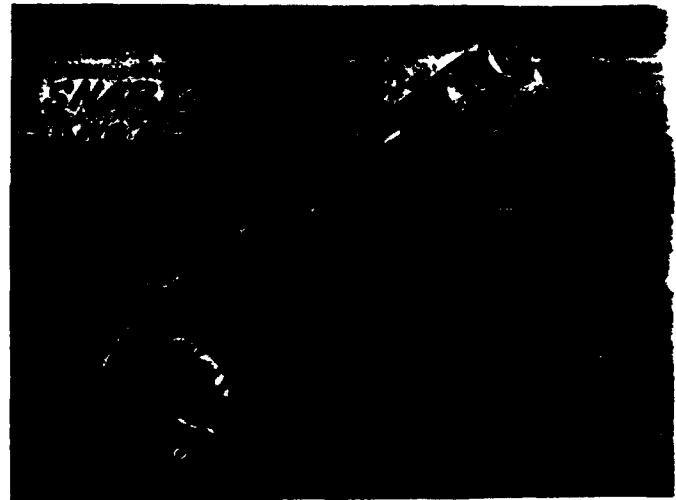
of a conventional EM pump with the current being supplied by its own integral power supply.

The SNAP 2 configuration is shown in Fig.4. The APU is located above the payload in the vehicle nose cone. In this system the reactor heat is transferred to the mercury secondary fluid in a once-through counterflow boiler. Superheated mercury from the boiler passes through a two-stage turbine and is condensed in the radiator condenser, rejecting the cycle heat to space by radiation. All of the rotating components of the power-conversion system are located on the same common shaft. The CRU (combined rotating unit) is shown in Fig.5. This contains a rotating magnet NaK pump, the turbine, the alternator, and a centrifical mercury pump. The shaft is supported by mercury-lubricated journal and thrust bearings. The mercury flow is preheated by cooling the alternator stator prior to entering the boiler. A parasitic load control maintains the CRU speed to within 1 per cent under load disturbances.

The SNAP 8 system being developed for electrical propulsion in conjunction with NASA will have a similar configuration to SNAP 2. An artist's conception of the over-all configuration is shown in Fig.6.

REACTOR SYSTEM

Fig.7 shows the reactor design for the SNAP 2 and 10A systems. The fuel elements are positioned in a hexagonal array by means of grid plates, inside a cylindrical core vessel. A beryllium radial reflector surrounds the vessel and is composed of two safety elements and two control drums. Control of the reactor is accomplished by the change in neutron leakage associated with the movement of these control drums.

The fuel material is fully enriched uranium, alloyed to 10 per cent by weight with zirconium.

TABLE 1   SNAP OBJECTIVES

	SNAP-10A	SNAP-2	SNAP-8
Electrical payload, watts...	500	3,000	30,000
Orbital lifetime............	1 yr	1 yr	1 yr
System weight, unshielded, lb......................	525	750	1500
Cycle heat rejection area, sq ft..................	62	110	400
Availability................	1963	1964	1965

TABLE 2   SNAP REACTOR REQUIREMENTS

	SNAP 10A	SNAP 2	SNAP 8
Thermal power, kwt.................	30	57.9	300
NaK flow, lb/min..................	76	76	400
Inlet temperature, deg F..........	850	1000	1100
Outlet temperature, deg F.........	950	1200	1300
Number of elements................	37	37	211
Hydrogen content, atoms/ccx10^{-22}..	6.5	6.5	6.0
Total reactivity control requirements, pct $\Delta k/k$.......	2	4	8
Startup control required..........	Yes	Yes	Yes
Long-term control required........	No	Yes	Yes
Weight, lb........................	250	250	300

This material was selected because of the ability of zirconium to absorb large quantities of hydrogen. The SNAP 2 fuel has a hydrogen density of 6.5×10^{22} atoms per cc, approximately the hydrogen density of cold water. This allows a very
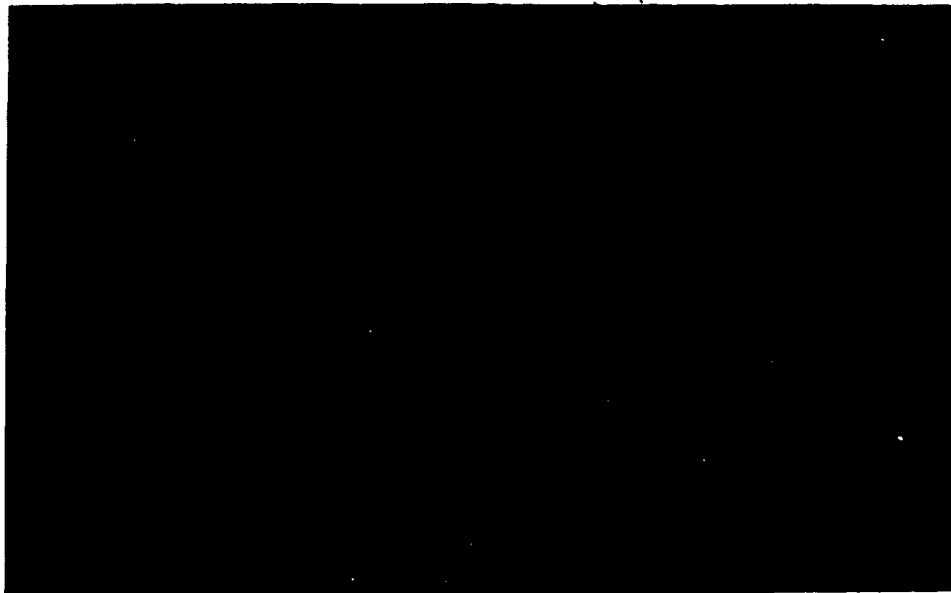
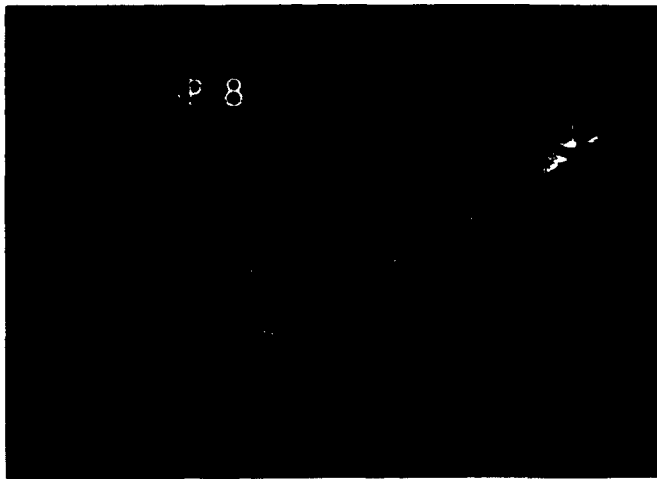Fig. 5 Combined rotating unit for SNAP-2 power conversion

Fig. 6 SNAP-9 auxiliary power unit

TABLE 3 SNAP 10A POWER-CONVERSION PERFORMANCE

Electrical payload, watts e......................500
Auxiliary telemetry power, watts e...............10
Converter degradation, watts e...................59
Long-term temperature drift, watts e.............25
Initial electrical output, watts e..............593
Reactor thermal power, kwt.......................30
Maximum hot-junction temp, deg F.......900 to 1000
Average heat-rejection temp, deg F..............600
Carnot efficiency, per cent.....................20
Converter device efficiency, per cent...........10
Over-all power-conversion efficiency, per cent...2

compact core with the elements serving as both the fuel and the moderator.

Hastalloy-N is employed as the fuel cladding because of its similar expansion coefficient to ZrH and high strength properties. The fuel exhibits a significant hydrogen dissociation pressure at high temperatures. However, by the use of a thin ceramic permeation barrier on the inside of the cladding, the loss of hydrogen through the cladding is decreased to design allowance.

Beryllium oxide end reflectors are used inside the elements to minimize reactor weight.

The SNAP 8 reactor shown in Fig. 8 is similar in size to the SNAP 2 and 10A systems. However, because of the higher power level it requires a much larger number of elements and greater control capability.

Table 2 lists the operating requirements for the three reactor systems. The initial cold excess reactivity requirement for SNAP reactors varies from about 2 per cent for the SNAP 10A system to about 8 per cent for the SNAP 8 system. For SNAP 10A this includes only the temperature defect and equilibrium xenon. SNAP 2 and 8 because of the higher temperature and power levels must also supply excess reactivity for hydrogen leakage, burnup, and fission-product poisons. Equilibrium samarium is prepoisoned into the cores.

The long-term reactivity control for the SNAP 2 and 8 reactors maintains the reactor-coolant outlet temperature within a relatively narrow deadband. This is accomplished by an
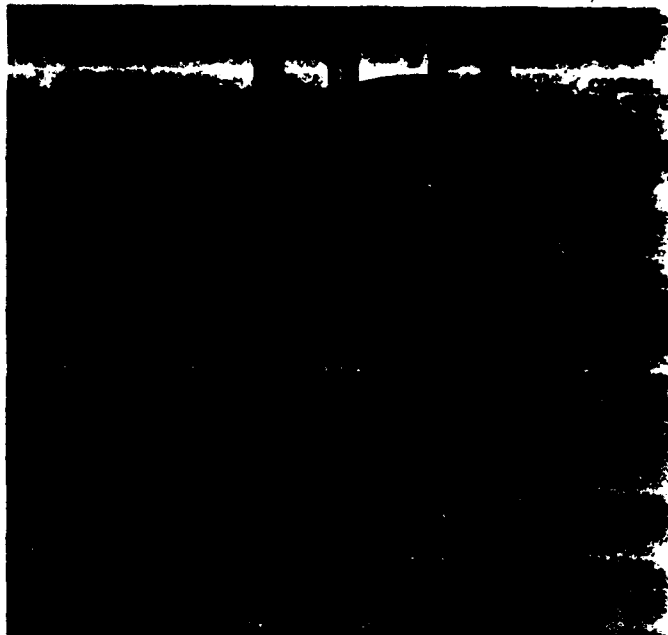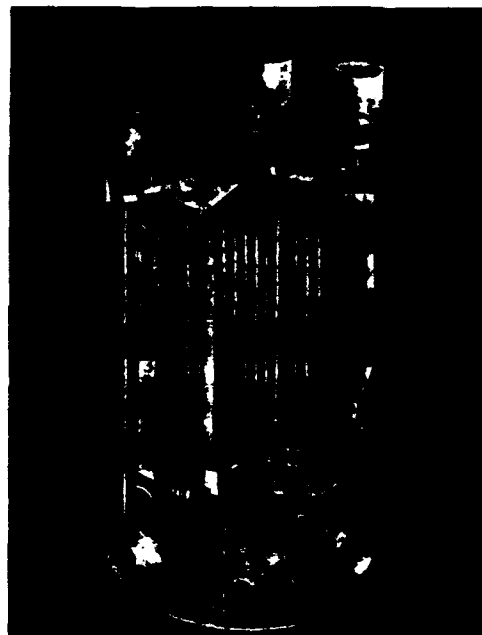
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Fig. 7 SNAP-2 reactor

Fig. 8 SNAP 8 reactor

TABLE 4 SNAP-2 POWER-CONVERSION PERFORMANCE

Electrical payload, kwe.........................3.0
Parasitic load control power, kwe..............0.1
Reactivity control and auxiliary
    telemetry power, kwe......................0.1
System degradation, kwe........................0.3
Initial electrical output, kwe.................3.5
Reactor thermal power, kwt...................57.9

System Cycle Efficiency

Heat-source efficiency.......................0.92
Power-conversion efficiency..................0.065
    Ideal Rankine-cycle efficiency....0.21
    Turbine mechanical efficiency.....0.53
    CRU component efficiency..........0.70
    Alternator efficiency.............0.84
System degradation efficiency................0.91
Auxiliary power efficiency...................0.95
Over-all system efficiency...................0.052

electromechanical control-drum drive which inserts small steps of reactivity at a fixed rate each time the temperature falls below the lower limit of the deadband.

POWER CONVERSION

Table 3 summarizes the SNAP 10A power-conversion performance characteristics. The present-day temperature limitation of the thermoelectric mate-

rials is in the range of 900 to 1000 F for long-term operation. At these temperatures the over-all device efficiencies attainable is about 10 per cent of Carnot. This includes degradation, shunt heat losses, strap losses, and so on. The SNAP 10A system operates at a Carnot efficiency of 20 per cent which allows an over-all power-conversion efficiency of about 2 per cent. As converter technology improves, higher temperatures and increased device efficiencies will allow a significant increase in the over-all cycle efficiency.

Table 4 lists the SNAP 2 power-conversion performance characteristics. The power-conversion-system components are presently under development by Thompson-Ramo-Wooldridge. The actual initial electrical output of the system is 3.5 kwe. This allows 300 w for system degradation and 200 w for telemetry and the active reactor and load controls. The superheated mercury vapor enters the turbine at 115 psia and 1150 F, and exists at 7.5 psia with 97 per cent quality. This relatively high exhaust pressure is required to avoid mercury-pump cavitation problems. The actual condensing temperature is 600 F, however, the liquid mercury must be subcooled to 375 F to avoid flashing of the mercury in the CRU bearings during sun-shade transients. Approximately 30 per cent of the turbine power output is used to drive the mercury and NaK pumps, and to overcome bearing and seal friction, with the remainder driving the alternator. The over-all cycle efficiency including heat losses is seen to be 5.2 per cent.

The SNAP 8 system will operate with an over-

all cycle efficiency of 10 per cent. The major factors allowing this increased efficiency are greater turbine efficiency because of the larger size, and parasitic losses becoming a smaller fraction of the total power. Heat rejection for the SNAP 8 system is at 700 F to allow a radiator area requirement compatible with vehicle height limitations.

ORBITAL STARTUP

All of the SNAP systems will be started remotely in orbit. This will be initiated by a telemetry signal from the ground once the orbit has been verified. In each case some auxiliary battery power will be required to supply the programmer, reactor startup control system, and about 10 per cent primary coolant flow. A signal from the startup programmer will initiate insertion of one or more reactor control drums. A slow insertion rate will be employed to reach criticality and to bring the reactor power up to the point of sensible heat generation. This will be accomplished over a sufficiently long period to avoid temperature and power overshoot limitations. After this point is reached, the negative temperature coefficient feedback will allow a faster insertion rate.

In the case of SNAP 10A, because of the thermoelectric pump, the reactor coolant flow will increase as the coolant temperature rises. Insertion of the control drum will be stopped when the reactor outlet temperature reaches 950 F. A negligible overshoot occurs and at this point the system is operating at full power. The startup control system will continue to operate for about 24 hr, maintaining reactor power and temperature while equilibrium xenon is attained. The reactivity loss after this point is negligible and the active control system is deactivated. The time from initiation of startup to full power operation is less than 3 hr.

The SNAP 2 system startup is accomplished by bringing the primary system to rated temperature at 10 per cent flow. This requires a somewhat longer time due to the transient temperature limitations of the NaK pump diaphragm.

Two startup methods appear to be feasible at the present time, both employing mercury injection into the boiler. Liquid mercury is injected into the preheated boiler by inert-gas pressure on a bellows. The static friction in the CRU is overcome by the time the boiler pressure reaches 30 psia and the turbine reaches full speed 30 sec after it begins to rotate. As the turbine speeds up, the rotating NaK pump causes the primary flow to increase, thus simultaneously increasing re-

actor power to maintain reactor temperature. The CRU speed is limited by the parasitic load control.

The mercury inventory is small in comparison to the secondary system-loop volume and therefore care must be taken to avoid condensation of the entire inventory in the radiator condenser during startup. In one method the radiator is insulated and brought up to rated temperature prior to mercury injection. The insulation is ejected as the mercury enters the boiler. In the second method an added mercury inventory allows preheating of the radiator by condensation of the mercury, thus avoiding the use of insulation. Present studies indicate the latter method to be both lighter and more reliable.

The SNAP 8 system startup will be similar to the SNAP 2 startup; however, the primary flow must be programmed up since it is not slaved to the turbine speed.

SAFETY

The basic principle to which the SNAP safety program is directed is that SNAP system flights shall not present any greater hazards than flights of missile systems which do not contain reactors.

Qualification and acceptance tests on SNAP units will be performed with an electrical heater simulating the reactor. Only zero power reactor operation will be performed during core loading and control-element calibration. The minute amount of fission products generated by these tests does not present a radiological hazard during handling procedures. Shipping and vehicle integration procedures will require precautions against accidental criticality. The reactor is launched in a shutdown condition and prevention of reactor criticality in case of launch aborts will be provided by safety features incorporated in the design. Reactor startup is not initiated until a satisfactory orbit has been verified. The initial SNAP test flights are planned for long-lived orbits such that essentially complete decay of fission products will occur prior to satellite re-entry.

A vigorous experimental program is currently under way which includes numerous tests simulating the effects of various shipping, handling, and launch abort environments on the nuclear characteristics of the reactors.

Experimental studies directed at verification of re-entry burnup have been in progress for some time. Sufficient information is not yet available to insure re-entry burnup of the SNAP systems. However, present indications are that by proper design, burnup and dispersal of the fuel elements

will occur during re-entry, thus allowing the use of SNAP units for low-altitude missions without the need for fission-product decay.

Program Status

The SNAP 2 Experimental Reactor was shut down on November 18, 1960, after more than a full year of successful operation. The objectives of this first prototype reactor were to establish the performance characteristics required for flight-system design, demonstrate long-term endurance capability, and to verify reactor stability and control characteristics. The reactor was operated for more than 5000 hr at full power, including a continuous 1000-hr endurance run at 50 kwt and 1200 F outlet temperature. Both the performance and dynamic characteristics of the reactor were established through numerous system tests.

A second and more advanced prototype system, the SNAP 2 development system is presently being tested. This system includes the first prototype power-conversion system. The objectives of this test are to establish the entire system performance, endurance, and control requirements for the flight package.

The SNAP 10A system utilizes the SNAP 2 reactor with a thermoelectric power-conversion system.

SNAP 10A nuclear auxiliary power units will become available for general purpose satellites within about 2 years. The SNAP 2 system will become operational in 1964, and by 1965 to 1967, 30 to 60 kw of electrical power should be available for electrical propulsion applications.