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PROPULSION POWER SYSTEM

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ABSTRACT

The SNAP-8 Electrical Generating System is a nuclear-turbo-electric space power plant which is ideally suited for utilization with electric propulsion. In this paper, several of the more promising applications and the program objectives are reported. Further, the overall system and the design of the major components are described; the program status is delineated; and future plans leading to an early flight test and equipment endurance demonstration are defined.

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I. INTRODUCTION

SNAP-8 is a nuclear turbo-electric space power system employing a two-loop Rankine cycle. Under joint sponsorship of the National Aeronautics and Space Administration and the Atomic Energy Commission the system is being developed basically to generate 30-kw electrical output with one power conversion system, and to produce 60-kw by coupling two power conversion systems with a single reactor. The system has an operating life of 10,000 hours and a specific weight of 50 to 60 lb per electrical kilowatt. After being propelled into orbit by a suitable rocket vehicle, SNAP-8 will be started and will operate for its long life in the gravity-free environment of space. Thence it will provide power for scientific instruments, for communication and for propulsion of the space vehicle. Before discussing further the characteristics of the SNAP-8 system it would be appropriate to describe a few of its potential applications.

II. POTENTIAL APPLICATIONS

The SNAP-8 Electrical Generating System represents a new horizon in space power plants and a major advance in the U. S. Space Program. For the first time the spacecraft designer will have available more than small kilowatt power supplies in space, for the SNAP-8 system is designed to exceed the present space power capability by at least two orders of magnitude; and that of space power plants which are now in advanced stages of development by at least one order of magnitude.

In the past, the space mission planners have had to cope with very limited power availability, and were therefore motivated to demand the development of low weight,

minimum-power control and scientific instrumentation. These efforts have proved remarkably successful, resulting in the acquisition of much useful scientific data with very modest power requirements.

It might be assumed that, except for electric propulsion applications, the SNAP-8 power capability will surpass the demand of the payload designer. We are confident, however, that the power requirements of scientific payloads will greatly increase within the decade, keeping pace with the growth of rocket booster capability and the planning of ever more extensive space missions. But SNAP-8 is the first power plant which will make feasible a scientific mission employing electric propulsion techniques. It is therefore not surprising that interest in SNAP-8 has thus far centered on its use as an electric propulsion power source. Many investigators have analyzed the potentialities of SNAP-8 powered, electrically propelled vehicles and have made comparisons with other competing systems. They have found that the SNAP-8/electric engine partnership can advantageously perform many missions, including unmanned interplanetary missions. In addition, they have found certain missions which can be accomplished only by an electrically-propelled vehicle.

The results of a comprehensive study of mission performance of various sized electric propulsion systems and boosters are presented in Reference 1. The conclusion reached was that the 60-kw model of SNAP-8 boosted by an Atlas Centaur could perform satisfactory capture and orbital missions for the nearest planets and out of the ecliptic probes. Deeper planetary, or space probes, will have to await either longer life or higher powered space power plants. Figure 1 is a composite graph from Reference 1 showing several missions for which a SNAP-8 electric propulsion package can compete very favorably with other existing or planned propulsion systems. It should be noted that the deliverable payload capabilities do not include the SNAP-8 equipment even though it could obviously be used as a power source at the mission destination.

A second area where the SNAP-8/electric propulsion systems can provide a useful function is the mapping of radiation, magnetic, or micrometeorite fields in space. In this application, the SNAP-8 power could be divided between the propulsion and the instrument payload to perform both functions in a long-life exploratory space vehicle.

The SNAP-8/electric propulsion combine could also be utilized in a general space bus. The low acceleration capability of such a system makes it ideally suited for rendezvous operations. Typical of functions of this nature would be the use of a vehicle powered and propelled by a SNAP-8/electric engine package to collect and assemble the separately boosted components for an advanced orbital-launched mission. The advantage of such a system is that the equipment required for rendezvous and assembly procedures would not have to be duplicated in each of the several individually-boosted space packages, but could be concentrated in one highly reliable space vehicle in which ample electric power and specialized equipment would be available to complete the necessary assembly procedures.

The most prominent of the presently conceived, non-propulsive applications of the SNAP-8 power supply is in the field of communications. Its relatively large power availability could provide super power space transmitter and receiving stations; a multiple-channel, active repeater, television system; or possibly a high-volume, world-wide postal transmitting mechanism. Even in these applications, electric propulsion devices would be useful for positioning, stabilization, or orientation.

As space power technology is advanced, the higher power, lower specific weight systems can be expected to be used for both near and far planetary missions, thereby supplementing the SNAP-8; however, we foresee a continued utilization of the SNAP-8 system as a highly reliable and proven space workhorse.

As the U. S. Space Program progresses to manned missions, the SNAP-8 could be modified as an auxiliary power supply, fulfilling many life-supporting functions both during transit and at the mission terminal. The relatively long operating life of a SNAP-8/electric propulsion combination could provide the final backup for course control in manned planetary exploration of space.

The examples outlined above illustrate in a general way the utility of the SNAP-8 system. The system characteristics and design features will next be described.

III. SYSTEM DESCRIPTION AND PERFORMANCE OBJECTIVES

The general schematic of the binary loop system is shown in Figure 2. The primary loop, consisting of reactor, boiler, and electric motor-driven pump, uses eutectic

sodium-potassium alloy as the working fluid. It operates between the temperature range of 1100 and 1300°F. The SNAP-8 reactor, being developed for the Atomic Energy Commission by Atomics International, Division of North American Aviation, Inc., uses zirconium-hydride fuel elements and is controlled by beryllium reflectors surrounding the core. The reactor design is based on technology developed for the smaller SNAP-2 reactor. The secondary loop, consisting of boiler, turbine, radiator and pump, utilizes mercury as the working fluid. The cycle conditions are as follows: The mercury boils at 1075°F and 275 psia, and is superheated to 1200°F. The mercury vapor is then expanded through a turbine and enters the condenser-radiator at a temperature of 706°F at a pressure of 20 psia. There it is condensed and sub-cooled to 558°F at 15 psia. The liquid is then pumped back to the boiler where it enters at approximately 650°F and 330 psia. Before returning to the boiler the mercury is used to cool the alternator and electrical controls. In order for the system to generate its rated electrical power of 30 kw, the reactor must produce approximately 300 kw thermal. Of this, approximately 250 kw is rejected from the radiator. In fact, the reactor is designed for 600 kw thermal in order that it will have a capability of powering the dual 60 kw system. Figure 3 shows a typical installation of the SNAP-8 Electrical Generating System. In this configuration, the reactor is located in the nose of the spacecraft. The power conversion components, except for the radiators, are mounted as a compact assembly located aft of and in the shadow of the nuclear shield. The two panels of the radiator extend outward in a radial plane to minimize neutron scattering. The two radiator panels for a 30 kw electrical generating system are each 15 ft long by 10 ft wide. The boiler and main rotating package comprise an assembly approximately 4 ft long and 2 ft in cross section. The reactor and shield are approximately 4 ft long. The total weight of the entire 30 kw system is 1950 lbs. For a 60 kw system the total weight is estimated to be 3100 lbs.

The primary performance objectives of the SNAP-8 program are, as previously stated, to generate 30 or 60 kw electrical while operating continuously and reliably for 10,000 hours in the space environment. Secondly, the system must be of minimum weight consistent with reliability. Underlying these objectives is the philosophy that the design should make maximum use of the existing technology in order to minimize development time.

Within the framework of these broad objectives, the various system design parameters which make up the specific operating cycle were chosen after consideration of numerous alternatives. For instance, the Rankine cycle was chosen over the Brayton and Stirling cycles because of its relatively advanced technology and relatively high efficiency.

The relative merits of two or three loop systems were next considered. The two-loop system was selected on the basis of simplicity and the lower weight of the heat rejection system.

The working fluid for the primary loop was limited by the design of the nuclear system to choice of sodium or sodium-potassium (NaK) eutectic. The selection of NaK was based on its low melting point which alleviates the possibility of freezing prior to startup in orbit. This advantage outweighs the slightly better heat transfer properties and lower pumping power requirements of sodium.

The selection of the secondary loop working fluid was determined by the confines of maximum reactor temperature, structural requirements of the secondary loop, and availability of suitable containment material. The only two substances whose vapor pressures are acceptable in the temperature range of interest are mercury and sulfur. Selection of mercury was based on the pioneering work in the development of binary-cycle stationary power plants and on the earlier SNAP programs. Conversely, little is known about the properties of sulfur, except that it is highly corrosive.

A good illustration of the kind of design compromise which led to the selection of the specific operating temperature of the SNAP-8 secondary loop is shown in Figure 4. This graph shows the effect of boiling and condensing temperatures on overall efficiency and on radiator weight. Here it is seen that lowering the condensing temperature will increase efficiency, but will also increase radiator weight. On the other hand, increasing the boiling temperature will increase efficiency and decrease radiator weight. However, the controlling consideration is one of material compatibility. The higher boiling temperature involves greater risk to reliable operation. The SNAP-8 design point was selected on the basis of the best available data on mercury-corrosion. Clearly, an appreciable advance in system performance can be made if it can be shown that the system will contain mercury for 10,000 hours at higher temperatures. This might well be considered for product improvement after the present design objectives are successfully met.

IV. COMPONENT DESIGN CONCEPTS

In the discussion which follows the design features of the major system components will be described with the intent of showing how the environmental conditions of zero-gravity, nuclear radiation and high temperature combine to influence their design.

The reactor coolant pump is an electric motor-centrifugal pump assembly operating on the 1000 cps electrical power produced by the turbo-generator. The unit is completely sealed and utilizes liquid NaK lubricated bearings. Because of the high temperature and the radiation environment, only ceramics, metals and other inorganic materials of construction are being used. The pump assembly has been separated from the turbo-generator shaft to provide greater flexibility for startup and permit independent component development. This type of pump was chosen over an electromagnetic pump because of its higher efficiency and lower weight.

The boiler and condenser for the system, operating at zero-gravity probably involve the most critical physical phenomena in the development program. The design concept must assure satisfactory heat transfer to the mercury in the boiler and reliable separation of the liquid and vapor phases in the condenser. In the boiler artificial gravity forces are produced by using a vortex-generating ribbon inside the boiler tube. Preheat, boiling, and superheat are achieved in a single pass through multiple parallel tubes. In the radiator, similar kinetic principles are employed to allow the liquid droplets to agglomerate and establish a stable vapor-to-liquid interface. The cylindrical surface of the Atlas-Centaur spacecraft could accommodate the heat rejection area required for a 30 kw SNAP-8 system with some weight penalty. However, to provide greater flexibility and minimize redesign for the 60 kw system, an extendable radiator with flexible joints has been selected.

The turbine, generator and mercury pump are mounted on a common shaft to utilize the minimum number of bearings and eliminate external seals. To satisfy the long-life requirements at high temperature, mercury-lubricated journal and thrust bearings are used to support the rotating assembly. Each bearing is provided with dynamic seals which separate the liquid from the vapor regions of the machine. Although maximum turbine performance is desired, serious consideration must also be given to erosion problems, thermal stress problems, clearances and critical speed during the selection of a suitable design. A two-stage, full-admission axial flow

impulse machine appears to satisfy the overall requirement most completely.

The electrical generator for this application must operate at high temperatures (950°F estimated hot-spot temperature) and the windings must be hermetically sealed from the mercury vapor in the rotor cavity. Since the generator must operate at turbine shaft speed, the temperature in the rotor cavity must be high enough to prevent condensation of mercury, thereby minimizing windage and friction losses. An axial air-gap, electromagnetically excited, induction type generator has been selected because it affords the simplest configuration of stator seal and because the structural aspects of the rotor are favorable.

To provide satisfactory startup capability, the condensate pump must operate free of cavitation at very low net positive suction head. A jet-boosted centrifugal pump design has been selected to satisfy this requirement.

The electrical control components, such as voltage regulator and frequency regulator, are designed to use subcomponents which are insensitive to the high temperature and nuclear radiation environment which is characteristic of their application in SNAP-8. Magnetic amplifiers, saturable reactors, and high-temperature ceramic diodes permit the design of circuits which will not require auxiliary cooling or radiation shielding. While these subcomponents are heavy when compared to transistors, their ability to operate without "crutches" results in a net weight saving.

A summary of component design data is presented in Table I.

V. DEVELOPMENT STATUS

The initial phase of the SNAP-8 program has been devoted primarily to the development of the components and to preparation and activation of test facilities. The following discussion is a brief status report of the accomplishments to date.

A materials evaluation program is being conducted to determine the suitability of candidate materials for mercury containment. Long-term capsule tests are in operation and forced convection flow loops are being set up to investigate such phenomenon as mass transfer, intergranular penetration and structural changes as a function of temperature and time. Type 405 stainless steel and Haynes 25 alloy are the two primary materials being examined in the capsule test program.

Initial results after 2000 hours at 1100°F are encouraging, but they are not conclusive. Continued testing to the full 10,000-hour duration is planned.

In the development of heat transfer components, single-tube boiling-and-condensing mercury heat transfer and fluid flow tests have been conducted to establish heat transfer coefficients and pressure drop relationships. Test results have yielded sufficient information to construct a rated-power experimental boiler of Haynes 25 alloy which is currently being installed for tests with a non-nuclear heat source. A full-scale experimental tube and fin radiator is currently in fabrication.

Performance testing of turbo-machinery components has been completed on several experimental designs. Turbine tests conducted with both gaseous nitrogen and saturated nitrogen vapor under conditions which simulate design-point operation indicate mercury vapor efficiency of 61%. Mercury pump tests, on a jet-centrifugal pump operating at 20,000 rpm, have demonstrated 30% efficiency at design head, capacity, and NPSH. Tests of the NaK centrifugal pump at 6300 rpm have indicated an efficiency of 65%, at design operating conditions. In mercury bearing development, the first of several configurations of journal and thrust bearings, utilizing mercury lubrication, has been operated for several hours at 20,000 rpm, in both horizontal and vertical positions. Continued testing will emphasize vertical operation of the bearing test assembly to investigate the potential stability problems associated with lubricant film whirl at light loads.

Laboratory tests of the first experimental generator are currently being conducted. In general, the tests to date have indicated a satisfactory performance. The design of a second generation laboratory model is being developed which will incorporate design modifications to improve the basic performance of the machine and which will place emphasis on the inclusion of those features required to provide mercury environment capability. Meanwhile, laboratory evaluation of ceramic potting compounds, glass ceramic insulation, ceramic-to-metal stator seals and structural magnetic materials is being performed. A number of low-alloy and cobalt steels have been subjected to several thousand hours of high-temperature tests at 1000°F without degradation of magnetic properties. Laboratory tests of control components have also been conducted; magnetic amplifiers and saturable reactors have been successfully operated at 1000 cps at high temperatures.

Figure 5 is a composite photograph showing some of the major components being tested at the present time. While component testing will continue, sufficient test data has now been obtained to warrant the initiation of subsystem tests in order to examine component interactions. At the present time a full-scale NaK and mercury flow loop for testing the boiler and the combined turbine, alternator and mercury pump is being set up. Future testing plans include the testing of many full power conversion systems with and without the nuclear heat sources. The first of four non-nuclear systems is being assembled, and testing of the breadboard loop is scheduled to commence operation late this year. The next three non-nuclear test loops are scheduled to commence operations at intervals in 1962. The objective of the non-nuclear test program is to demonstrate system stability and endurance prior to starting the full nuclear system tests, and to continue endurance testing, if possible, until all units have operated approximately 10,000 hours. Each successive test loop will approach closer to flight configuration and flight component design.

The extensive ground testing program culminates in the operation of complete SNAP-8 systems, including the nuclear reactor and control systems. In order to provide early data on the performance of the overall system, the nuclear system test program will be performed in two phases on separate systems in separate facilities.

In the first facility, the tests will be conducted with essentially flight design equipment, but the test cell has been designed to permit isolation of the nuclear system to facilitate access to the power conversion equipment. The objectives of the first nuclear test loop are to provide early compatibility data for the nuclear and power conversion equipment, to demonstrate the startup methods, and to confirm 90-day endurance capability prior to the first feasibility flight in 1965. After meeting these objectives, the operation of this test loop will be continued to obtain long-term reliability information. The test facility for the first complete SNAP-8 ground test is presently under construction.

The second nuclear test phase will be carried out with final flight equipment in flight configuration. The objectives of these tests are to insure satisfactory performance in the flight configuration, to demonstrate 10,000-hour endurance capability, and to provide complete backup to the first nuclear test phase. The test facility is presently being designed and

and will consist of a large underground test vault capable of accepting a full 60-kw SNAP-8 system with radiators extended.

VI. CONCLUSIONS

In the paper, we have described the objectives, accomplishments and plans for the development of a high performance space power plant.

The current development of the SNAP-8 system has been under contract for approximately a year and a half. During this period, the basic concept has been reviewed, the determination and acquisition of basic design information has been initiated, and the first component designs have been fabricated and tested. The results obtained thus far substantiate our early confidence in meeting all of the major program objectives; namely, an engineering feasibility flight test in 1965 and 10,000-hr endurance capability.

While existing knowledge indicates a high probability of success, it must be pointed out that the attainment of the major program objectives requires conducting long-term tests with and without the nuclear subsystem. The most difficult part of the program, that of achieving and demonstrating long life and reliable operation of the system, is just commencing, and it is too early to foretell whether the system can be successfully developed without violating our self-imposed weight restrictions.

Looking ahead to the attainment of the program objectives, it is appropriate to conclude that SNAP-8 will find wide application in the space power field. It can be confidently predicted that SNAP-8 will be used in early electrically-propelled spacecraft in missions to the nearest planets, and in various types of high-powered space communication packages.

The ultimate conquest of the far reaches of our planetary system will require the larger power availability of the more advanced power supplies; however SNAP-8 represents a useful technology stepping stone for the higher powered space systems and a vital tool required to test the various electrical propulsion devices. In addition, SNAP-8 will find extensive application in near earth missions where it is desirable to use the smaller but more available boost vehicles.

REFERENCE

1. "Applications for Electric Propulsion Systems," J. W. STEARNS, American Rocket Society Paper 1751-61, presented at ARS Space Nuclear Conference, Gatlinburg, Tennessee, May 3-5, 1961.

TABLE I

SUMMARY OF COMPONENT DESIGN DATA

TURBINE

Speed, rpm	20,000
Power, hp	61
Efficiency, %	65
Pressure Ratio	14/1

ALTERNATOR

Speed, rpm	20,000
Frequency, cps	1,000
Voltage (rms), a-c	43.6/75.6, 3-phase, 4 wire
Power Factor	0.9 - 1.0
Efficiency, %	90

MERCURY PUMP

Speed, rpm	20,000
Head Rise, ft	57
Capacity, gpm	1.1
Efficiency, %	25

ELECTRICAL CONTROLS

Voltage Regulation	+ 5%
Frequency Regulation	+ 1%

NaK PUMP AND MOTOR

Speed, rpm	6,330
Head Rise, ft	31.6
Capacity, gpm	67
Efficiency	25%

SNAP-8 ELECTRIC PROPULSION CAPABILITIES

TYPICAL 60 KW MISSIONS WITH ATLAS CENTAUR BOOSTERS *

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SNAP-8 POWER CONVERSION SYSTEM

147 015

Figure 2

SNAP-8 ELECTRICAL GENERATING SYSTEM

EFFECT OF BOILING AND CONDENSING TEMPERATURE ON OVERALL EFFICIENCY AND RADIATOR WEIGHT

Figure 4

SNAP-8 DETAILED COMPONENTS

**EXPERIMENTAL Na&K
PUMP COMPONENTS
FOR TEST RIG**

**RATED-POWER LOOP
BOILER ASSEMBLY**

PDA BEARINGS

**PDA TURBINE-ROTATING
ASSEMBLY WITH 2ND-STAGE
NOZZLE**