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by George M. Thur
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Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
Intersociety Energy Conversion Engineering Conference
Boulder, Colorado August 13-16, 1968

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ABSTRACT

SNAP-8 is a nuclear-electric power conversion system designed to explore the principles and technologies required for electric power production in space using liquid metals as working fluids. The system is designed to produce a net electrical output of 35 kWe for a minimum of 10,000 hours of continuous operation. Tests have demonstrated the capability of the present power conversion system to meet the SNAP-8 design requirements.

This paper describes the SNAP-8 system, the original design philosophy, and the present status of SNAP-8. The major part of this paper deals with an assessment of major components comprising the power conversion system. In addition, an estimate of the growth potential of the power conversion system is made using present hardware and what might be expected if major hardware changes were made.

I. INTRODUCTION

The SNAP-8 is a turboelectric nuclear space power system using a mercury Rankine cycle. It is designed to produce a minimum electrical power of 35 kilowatts, to have high reliability, and to be capable of unattended full-power operation for a minimum of 10,000 hours. Since SNAP-8 is not being designed for a specific space mission at this time, the development of the flight radiator assembly and the flight shielding is not a part of the current SNAP-8 program. The prime objective of the SNAP-8 development effort is to develop SNAP-8 components and subsystems and system technology to the point at which the major system performance and development uncertainties are understood and resolved.

The initial SNAP-8 design, based on the technology from SNAP-2 and Sunflower, included two loops and a direct-condensing radiator. In minimizing the number of loops, these systems undertook two major development areas, viz., high-speed turbomachinery using mercury-lubricated bearings and large direct-condensing radiators that necessitated minimum pressure drop, inventory control, and two-phase flow stability in an environment of 1 to 0 g. After a thorough technical evaluation by NASA, the AEC, and their respective contractors in late 1962, the SNAP-8 redesign was started in January 1963 in order to separate and to simplify the development problems experienced above. This resulted in a design that contained four operating loops, and substituted oil-lubricated bearings for the mercury-lubricated bearings previously used. In addition, more emphasis was placed on reliability than on performance and weight. As a result turbomachinery speeds were reduced by one-half at the expense of reduced system efficiency.

This paper discusses the current (May 1968) status of the technical development of the major components that comprise the SNAP-8 power conversion system, describes the major problems that were encountered during development, and makes an assessment of the major components and the power conversion system. Finally, an estimate of the growth potential of the power conversion system is presented.

II. DESCRIPTION OF THE SNAP-8 SYSTEM

1. Nuclear System

The SNAP-8 reactor, shown in Fig. 1, is designed to produce 600 kilowatts of thermal power at a coolant outlet temperature of 1300° F for a minimum of 10,000 hours. This compactly designed reactor utilizes uranium-zirconium hydrided fuel-moderator elements clad with Hastelloy N. There are 211 fuel elements in the reactor core vessel. The reactor is controlled by beryllium movable-reflector control drums, which, by their position, control the amount of neutron leakage. There is a total of six beryllium control drums, three of which are used during startup and three of which are used for long-term control. Each control drum has its own drive mechanism.

The dimensional envelope of the reactor is 27.6 inches outside diameter and 29 inches from the bottom of the inlet plenum to the top of the outlet plenum. The 27.6 inch outside diameter includes the drum in the extreme-out position. The reactor weight without the shield is approximately 795 pounds.

2. Power Conversion System

The power conversion system (PCS) for SNAP-8 consists of four loops. Thermal power from the reactor is transferred to the boiler via the reactor coolant, a eutectic mixture of sodium and potassium (NaK-78) that is driven by a NaK pump in the primary loop. The mercury loop consists of the boiler, turbine-alternator assembly, condenser, and the boiler-feed pump. Waste heat is removed in a second pump-driven NaK loop in the heat-rejection loop. The fourth loop contains an organic fluid which lubricates the bearings of the mercury-loop rotating components and provides coolant for the alternator, motors, and electrical controls. There is also an auxiliary loop which couples the two NaK loops during startup in order to provide a thermal load for the nuclear reactor prior to startup of the mercury loop. The steady-state operating condition for a SNAP-8 flight system in the present state of development is shown in Fig. 2. A detailed description of the power conversion system components is reported in Ref. 1.

III. DESIGN CRITERIA

1. Design Point

The SNAP-8 system is designed to provide a minimum of 35 kilowatts of electrical power at the vehicle-load breaker, exclusive of system control requirements or any other internal power requirements of the system, for a minimum of 10,000 hours of continuous unattended operation at the following output conditions.

Table 1

Frequency	400±2% Hz
Voltage (measured at output terminals)	120/208 VAC
Voltage regulation (from 3.5 to 35 kilowatts)	±3% measured at the point of regulation
Load power factor	0.85 lagging
Phase	3 phase, 4 wire
Harmonic content	8% rms line-to-line with balanced linear 100% load at 1.0 P.F.

2. Design Requirements

The early development of the SNAP-8 system was based on the characteristics of instrument-rated applications or missions. These mission characteristics resulted in the following design requirements on the nuclear electric power system.

(1) Relatively high radiation levels in the volume occupied by the PCS mechanical and electrical components. This permitted small nonmanrated shielding.
(2) A highly reliable initial startup requirement, but no requirement for any restart following shutdown. Thus no PCS redundancy was involved.
(3) No requirement that the reactor be encapsulated in a 4π shield. Shadow shielding would suffice.

In 1966 NASA introduced the requirement for man-rating the ultimate SNAP-8 system. Mission application studies performed for NASA Langley(2) and Marshall Centers(3), and inhouse work at the Lewis Research Center resulted in the following new design criteria for the SNAP-8 system:

(1) Both 4π and shadow man-rated shielding.
(2) A need for a number of possible shutdown and restart operations, both in orbital space and planetary surface (e.g., the Moon) environments.
(3) The desire for increased life and reliability, which resulted in the incorporation of additional primary-loop integrity and provision for redundancy in components and fluid loops.
(4) The incorporation of access capability for at least minor maintenance to the nonnuclear or nonradioactive portions of the engine.

Other design criteria which remained unchanged are:

(1) A minimum of 10,000 hours unattended automatic operation.
(2) Operation in the space environment of vacuum and micrometeoroids.
(3) Capability of withstanding the severe shocks, vibrations, gravity, pressure, and temperature transients during vehicle launch.
(4) Design and installation to permit efficient low-weight shadow shielding of payloads.
(5) Packaging and installation to permit prelaunch checkout with maximum personnel safety and minimum vehicle and facility risk.
(6) Packaging and installation to provide for vehicle structural and flight stability.
(7) Minimum interference and interaction with basic booster and payload subsystems.
(8) Order of precedence for the three major design factors are reliability, performance, and weight.
(9) Must still be suitable for the unmanned mission.

Evaluation of the SNAP-8 components as to their capabilities for adequately meeting the new mission-oriented requirements indicated that for most of the individual components, the new requirements had little effect, i.e., the components as developed were satisfactory. In three areas, however, design modifications or new subsystems were required. These are:

(1) The requirement for increased primary-loop integrity to take full advantage of redundancy and restart provisions indicated a need for double-containment boilers.
(2) The requirement for mercury recovery on shutdown and subsequent restart indicated a need for a new mercury-injection system and start-shutdown operational capability.

(3) The need to remove shutdown decay heat from the reactor core in order that the reactor would be capable of restart indicated a modification to system plumbing might be required. The full effect of this requirement has not been completely assessed as yet.

3. Life Goals

A minimum life goal of 10,000 hours was established for the SNAP-8 system early in the development as a result of known mission requirements at that time. A criterion used in the design of the system components was to use existing state-of-the-art where applicable and where such utilization would yield component life potentials well beyond the 10,000-hour point. A number of the SNAP-8 components appear capable of as much as 50,000 hours as a result of development effort in the program to date.

IV. DEVELOPMENT STATUS OF MAJOR COMPONENTS

The current status of the SNAP-8 power conversion system technology is characterized by the significant progress that has been made toward solving life-limiting problems. The component test hours accumulated during the first eleven (11) months of fiscal year 1968 are substantially greater than the total test hours accumulated over all previous years of development effort.

The maximum operating test hours achieved on single units of the major components have been very encouraging. A summary of the operating hours obtained for the major components is presented below.

TABLE 2. - MAJOR COMPONENT TEST HISTORY (MAY 24, 1968)

Component	Units tested	Cumulative hours	Maximum hours on a single component
Turbine alternator assembly	6	6,292	3,233
Boiler	7	10,827	3,597
Condenser	3	8,742	5,631
NaK pump	10	25,262	9,423
Hg pump	10	15,673	8,390
L/C pump	10	33,319	15,268
Totals		100,115	45,542

The results obtained from this testing and the inspections that were performed after 2000 or more hours of operation have been encouraging in that no fundamental problems have been encountered which would preclude achievement of the performance and long life required of the SNAP-8 power conversion system. In particular, it appears that the boiler and turbine problems have been resolved. More testing in the current phase of the program is planned to verify this tentative conclusion.

V. MAJOR DEVELOPMENT PROBLEMS

1. Boiler

The development of a successful boiler for the SNAP-8 mercury Rankine space power system was delayed because of fundamental problems associated with the Hg containment material. The most significant of these are the solubility of the containment material in mercury, and the variations in heat transfer and fluid dynamics as a result of contamination of the surface of the mercury-containment material. This solubility is accentuated at elevated temperatures and high liquid velocities. In addition, the wetting of the boiler tubes by liquid mercury is highly sensitive to contaminants.

The search for mercury-containment materials that embody both high-temperature strength and corrosion resistance has covered a wide range of potential candidates which includes austenitic stainless steels, martensitic chromium steels, cobalt-base alloys, and several of the refractory metals and alloys. The original SNAP-8 boiler material was a cobalt-base alloy. This alloy was selected because of its apparent successful utilization on the SNAP-2 program. Subsequent operation of this material at the SNAP-8 boiler temperature, however, revealed an unacceptable rate of corrosion and an embrittlement which limited the life of this component.

To overcome these deficiencies, 9-chromium - 1-molybdenum steel was chosen as an interim containment material. This selection was based on the results of a reflux-capsule screening program for SNAP-8 mercury containment materials(4) which was conducted at Lewis Research Center.

Typical results from these tests are illustrated in Fig. 3. The indicated low corrosion rate of 9Cr-1Mo was interpreted as providing reasonable assurance of corrosion resistance capability, and therefore of achieving the long-life system objective.

Subsequent operational experience on single-tube and full-scale boilers dramatically exposed the deceptiveness of utilizing reflux capsule results in predicting corrosion rates under realistic two-phase forced-convection boiling conditions. Severe corrosion occurred in the low-quality plug region of the boiler tubes. The obvious life-limiting consequences of the high corrosion rates required a reevaluation of the use of 9Cr-1Mo as a high-temperature mercury-containment material for the boiler. Consequently, in the fall of 1966 the SNAP-8 program selected tantalum as the new boiler mercury-containment material. Tantalum was the most corrosion resistance of all candidate materials. The use of tantalum as the mercury containment material imposed an operational problem to protect the tantalum from oxidation and from possible primary loop contaminations. The tantalum tubes were therefore isolated from these environments by enclosing each tube within a stainless steel tube(4) and by making a transition to stainless steel tubing on the mercury inlet and outlet lines. This permitted the use of a stainless steel shell which is compatible with both the primary loop fluid and the loop environment. The annulus that is formed between the tantalum and stainless steel tubes is filled with static NaK which is utilized as a thermal bonding fluid. Thus, a double tube wall failure is necessary before an intermixing of the working fluids can occur.

The second fundamental problem associated with the operation of a once-through mercury boiler has been the unpredictable thermal and hydraulic performance. Past boiler design correlations have been based on a nonwetting-droplet model. The validity of this model apparently depended on a minimum degree of wetting to attain initial boiling. Observed boiler performance varied over a wide range which encompassed the design performance and appeared to be related to the degree of wetting. This was especially evident during the startup phase when the design performance was not immediately achieved. Normally, an operational period which varied from a few hours to hundreds of hours was required before the boiler design performance was attained (boiler conditioning).

It has been verified by tests conducted by the Lewis Research Center that extremely small amounts of hydrocarbon contamination (such as normal aerosols contained in an urban environment) could prevent the mercury-droplet wetting of the heat-transfer surfaces(5). The results were later confirmed by oil-contamination tests which were conducted on a single-tube forced-convection mercury boiler at the Aerojet-General Corporation(6). It was also observed that once a boiler had attained rated performance (referred to as "conditioned") it would not degrade when exposed to reasonable amounts of injected oil, as long as the boiler operation was continuous. A performance degradation could occur, however, if the system was shut down, cooled, and restarted. This anomaly was clarified by subsequent investigation of the loop fluids and by capsule tests of oil-contaminated mercury. Samples of the mercury inventory from the liquid portions of the loop indicated that a significant percentage of the oil which was introduced into the boiler during operation would pass through the boiler without decomposing completely. The bulk of the oil that did not decompose in the boiler was entrapped at the liquid-vapor interface of the condenser. Because of required loop-shutdown procedures, high-temperature primary NaK is circulated and cooled after mercury circulation has stopped. This sequence of shutdown operations permitted the evaporation of the liquid film on the boiler-tube walls and thus exposed the clean heat-transfer surfaces to contamination by the back diffusion of oil vapors from the condenser.

This surface-conditioning problem is not unique to any one containment material. The cobalt-base alloys and martensitic chromium steels exhibited a sensitivity to oil contamination which resulted in poor boiler performance. By contrast, only minor boiler performance variations were attributable to oxide contamination.

For tantalum as the containment material, both oxygen and hydrocarbons have an effect on boiler performance and integrity. Tests have been conducted utilizing chemically cleaned tantalum tubes in an all-welded loop. Stable and repeatable wetted-boiler perfromance has been attained. Hydrocarbon and air-contamination tests of these clean surfaces are being conducted to determine the degree of "deconditioning" associated with the level and type of contamination. This information will be utilized to determine the effect on both the mechanical properties of tantalum and on the thermal and hydraulic performance.

It must be remembered that although air can be completely removed by proper disciplines in loop operation, the hydrocarbon problem is a potential power-conversion-system problem. The source of the hydrocarbon is leakage through the space seals of the turbine-alternator and mercury motor-driven pump during either steady-state operation or during transients. Considerable effort is being exerted in these areas to minimize this problem.

2. Turbine

The major developmental problem of the SNAP-8 turbine has been that of the structural integrity of the turbine nozzles and rotor. The original material for these components was Stellite 6B, selected on the basis of its superior resistance to erosion in a mercury environment plus adequacy of the other parameters at the design conditions. During the initial turbine tests, both rotors and nozzle diaphragm assemblies had cracked and caused a catastrophic failure. An investigation of these failures revealed that a transformation of the metallurgical structure of the Stellite 6B had taken place; that is, the material had changed from a face-centered-cubic to a hexagonal-close-packed structure and in so doing had become very brittle (elongation less than 2 percent). It was found that this transformation takes place at elevated temperatures (800° to 1300° F) over a period of 24 to 200 hours that depends on the temperature. Subsequent testing of turbines that used modified 6B hot parts revealed additional cracking.

The turbine rotors and nozzle-diaphragm assemblies were redesigned to improve turbine performance and the material changed to S-816. This material is not quite as erosion resistant as Stellite 6B, but is much more ductile. SNAP-2 mercury turbine experience of over 7000 hours on individual nozzles and rotors of similar erosion resistance (NIVCO) indicates that mercury-turbine erosion is not as severe as originally thought.

Since the material change, over 3000 hours of mercury-vapor turbine testing without failure or performance decay indicates that the structural problem has apparently been solved.

3. NaK Pumps

(a) Motor problems. - The NaK motor-driven pumps have suffered two bearing malfunctions which were caused by abrasive NaK oxides and are considered to be a loop problem rather than a pump-bearing problem. The major problem with the NaK-pump motor has been the electrical insulation of the motor windings. The high-temperature environment requires an inorganic insulation which includes a ceramic encapsulent. A complex process introduces the encapsulent into the stator windings where it is allowed to harden prior to machining for installation of the Inconel-X sealing can. During testing of some 10 pumps, a number of failures occurred due to electrical short circuits to the can which resulted in ruptures of the can. This allowed NaK to enter the stator windings and to cause additional damage to the insulation. It was also found that some failures were caused by differential thermal motion between windings and encapsulent. Thermal cycling of the pump motor during start/stop operations caused abrasive rubbing of the windings by the large "stones" in the encapsulent. The solution was to reduce the aggregate size. A reduction in the wire size also provided better flexibility and so eased the stator-winding assembly problems which were evident on some occasions.

These modifications habe been introduced into a new motor design that is presently under test. It must be noted that one of the original motors has accumulated over 10,000 hours and 700 starts.

(b) Other deficiencies. - Difficulty experienced in starting the NaK pump during the early phase of testing required bearing-design changes. It was found that the extremely flat and smooth surfaces of the thrust-bearing pads and runner were "wringing" together. The solution to this was to cut a very shallow taper or conical surface on the shaft runner, thus preventing intimate contact of the entire bearing surfaces. An additional starting problem occurs when the bearings become contaminated with oxides. If the required starting torque exceeds the capability of the motor, the motor will not start until the oxides are removed. The main solution to this problem is to maintain low oxide levels in the NaK loops. New motor assemblies will use also laminations of Hyperco 27 material, thus permitting larger magnetic flux densities and higher starting torques.

VI. ASSESSMENT OF MAJOR COMPONENTS

The assessment of the major components of the power conversion system that follows is based on over 100,000 hours of component operation and the results of component inspection after approximately 2500 hours of operation. Another major inspection is planned when each component accumulates 10,000 hours of operation. For many of the major components, this will occur during the next six months.

1. Boiler

To date, a full-scale single-tube test section employing the bare refractory double containment (BRDC) concept has completed 2859 hours of operation. During this period the boiler was subjected to various levels of oxide contamination and to a chemical cleaning process. Post-test metallurgical examination of the test section is currently in progress; however, visual examination reveals no corrosion nor erosion nor, indeed, any other life-limiting problems.

Three full-scale BRDC boilers have been fabricated. The Serial No. 1 boiler was operated for 1444 hours in the W-1 facility at Lewis Research Center after which it was removed and sent to General Electric-Evendale. This unit was installed in the GE Boiler Test Facility and has accumulated 2000 additional test hours as of May 19, 1968, for a total of 3444 hours of operation. Consideration is currently being given to continued operation to 10,000 hours before destructive examination of this assembly. Thermal and hydraulic operational checks have revealed no significant changes in performance during sustained operation.

Serial No. 2 boiler has been installed in the PCS-1 facility at Aerojet and has accumulated approximately 900 hours of operation at the design conditions. A slight change in boiler performance has been related to the accidental introduction of air into the loop. The boiler has since essentially recovered its initial thermal and hydraulic performance. The PCS-1 facility is currently being prepared for a 2500-hour endurance run.

Serial No. 3 boiler has been installed in the W-1 facility at Lewis Research Center. This loop will be utilized for dynamics testing (startup and shutdown) and steady-state performance mapping. In this service, many thermal transients will be imposed on this unit.

As of this date, there is no normal operational mode which would prevent the boiler from attaining its 10,000-hour design life. There are, however, two significant areas associated with the function of the boiler that need further clarification: (1) the measurement and minimization of liquid carry-over from the boiler, and (2) the reduction of the boiler pressure drop.

Various methods of accurately determining the boiler discharge quality are being investigated.

Current BRDC boiler operation has indicated a much higher overall boiler pressure drop than has been experienced in the past. This is the result of better heat transfer to the mercury at the boiler entrance, or plug section. Previous design correlations which were based on nonwetting predicted a minimum plug discharge vapor quality of 10 to 15 percent. The current boiler performance indicates a discharge vapor quality of about 30 percent and reflects the superior wetting of the tantalum by the mercury. With the maintenance of the present loop cleanliness levels, the wetting and the resultant good heat transfer will probably continue.

The BRDC boiler is currently being redesigned to lessen the inlet plug pressure drop.

Additional studies are being performed to investigate the advantages of modifying the turbulator geometry. This effort is being directed mainly to the elimination of the liquid carryover from the boiler although an overall increase in boiler performance is also anticipated. The particular geometry being considered is a single helix on a center body (as with a single-lead screw).

2. Turbine

Since the material change from Stellite 6B to S-816 on the turbine hot parts, a turbine has operated for over 3,000 hours. An inspection at the end of 2122 hours of testing revealed no major problems. A minor amount of blade erosion was found; however, the turbine was subjected to a substantial amount of liquid carryover from the boiler for 20 to 30 percent of its test time because the boiler used during this test was constructed from 9Cr-1Mo. The new tantalum boilers deliver superheated vapor on start-up have demonstrated reduced amounts of liquid-mercury carryover, and have eliminated the corrosion problem that was prevalent with the 9Cr-1Mo boilers. All of these characteristics are favorable for the turbine. A proper assessment of the turbine therefore must be made after the turbine has run for a substantial number of hours in combination with a tantalum boiler.

The seal-to-space visco, Stellite 6B, pump ring was found to be in good condition with only a small amount of cavitation damage located at the vapor to liquid interface. It must be noted that some damage is expected since the visco pump operates at a zero net-positive-suction pressure at this location. The structural integrity of the piece was satisfactory and comparison with a previously tested turbine, that showed more severe wear with a different material, indicated that pumping or sealing performance will not be affected for 10,000 hours of operation.

The bearings were in good condition but did have some minor scratches and pits. From a history of the testing of this unit, it appears likely these were caused by debris introduced early in the test. The ball banding probably occurred during startup when there was inadequate lubrication for a short period of time. However, this slight damage appeared to have no effect on bearing performance since no further damage was apparent. In previous units, no bearing failures have occurred, and damage has occurred only as a result of a nozzle or rotor failure.

The 2122-hour inspection of this unit, which now has in excess of 3000 hours operating time, revealed no failures modes which would preclude design-point operation for the 10,000-hour endurance goal.

3. Alternator

The alternator design in June 1963 was predicated on the use of existing, state-of-the-art alternator technology, wherever possible. Design goals included the requirement for a minimum of 10,000 hours continuous and unattended operation.

The development problems were those related to the requirements for long life and high reliability and are reflected in the following alternator design criteria: solid rotor, no brushes or rotating windings, maximum hot-spot winding temperatures permitted by existing insulation, triple-vacuum-melted M-50 steel for bearings, and noncontacting shaft seal.

The "state-of-the-art" approach required production of the final configuration as early as possible with minimum component development testing. The overall development resulted in an alternator with a hermetically sealed frame, welded electrical connections, and a polyimide-epoxy-glass insulation system.

The maximum hot-spot winding temperature exceeded the design goal by 27° F. This is not expected to limit alternator life since the hot spot occurs in a location of low voltage stress. Predictions of insulation life are also inexact and very conservative.

In order to improve the performance rating and to increase the life of the alternator a power factor correction assembly will be added to the vehicle load side. This assembly will reduce the maximum hot spot winding temperature and allow the alternator to operate at a higher efficiency.

A total of 10,000 hours of alternator operation has been accumulated on several machines under a variety of conditions. Maximum single-alternator endurance time exceeds 5000 hours with the machine still in test. There have been no failures arising from operation within the required alternator performance envelope. However, no vibration or shock tests have been performed and only limited static nuclear-radiation tests have been completed.

4. NaK Pump

The NaK pump runs at an inlet pressure well above cavitation, uses pure-fluid-dynamic bearings, and an inorganic electrical insulation system and, as such, should have no life limitations up to the original life goal of 10,000 hours.

For the most part, the failures experienced thus far have been due to faulty fabrication workmanship, improper operating procedure, or poor loop cleanliness (high oxide levels). Steps have been taken to improve all these areas. At present a pump is running with over 12,000 hours on the stator and over 9000 hours on the moving parts with no sign of performance decay.

The NaK pump can be considered as a component with a life expectancy in excess of 10,000 hours.

5. Mercury Pump

The mercury motor-driven pump has had a leakage problem with the lift-off seal bellows. The present solution is to change the multibellows assembly to a one-piece toroidal bellows. This, as yet, has not been tested but is of a much lower stress level than previously.

The subelements of the mercury pump that could be life limiting are the visco pump shaft and housing surfaces, the main impeller, and the bearings.

The visco pump surfaces have shown light pitting after 2100 hours' running time. It was judged that an extrapolation of this amount of material removal would probably not impair the pump's operation in 10,000 hours, but for conservatism, the material in the area is being changed from 9M to Stellite 6B. With this change there should be no difficulty with this component for 10,000 hours' life.

The bearing system used in the mercury pump is similar to that in the turbine-alternator, which has a predicted 10,000-hour reliability of 0.995. The mercury pump has lower speed and bearing loading and should therefore be even more conservative. No bearing failures have been experienced in this unit and the maximum single-unit time is in excess of 8,000 hours and still in operation with no indications of bearing trouble.

Moreover, all performance parameters such as space-seal leakage, bearing temperatures, and power consumption have remained steady throughout the run. It appears that the mercury pump is fully capable of the 10,000 hours' design life.

6. Lube/Coolant Pump

Seven L/C pumps have been built and, except for two that ingested a foreign particle, no failures have occurred. One pump has 15,000 hours' operating time on it, and another over 9000 hours with no indication of performance decay.

The L/C pump has exceeded its performance endurance goal of 10,000 hours.

7. Condenser

The operational history of the SNAP-8 condenser has proven the capability of this unit meeting all of its requirements. Since the condenser is neither a highly stressed component nor is it exposed to particularly rigorous operating conditions, it is considered to have a life potential exceeding the 10,000-hour goal. The introduction of tantalum as the boiler's mercury-containment material has altered somewhat the loop-corrosion patterns. This change is recognized, and additional attention will be directed to monitoring of any change of corrosive attack in the condenser.

Of the three units tested to date, one has operated in excess of 5,000 hours. A nondestructive examination has revealed no life-limiting factors. The second unit is installed in the W-1 facility at Lewis Research Center and has operated for 2400 hours. A third unit has accumulated 760 hours in an inactive system-test loop where it remains at this time. There is no current plan for modifications of the condenser.

VII. OVERALL ASSESSMENT OF THE POWER CONVERSION SYSTEM

The assessments of the major components just made were based on component and subsystem testing. It would be impractical for SNAP-8 to achieve technology readiness (all performance and endurance uncertainties understood and satisfactorily resolved) without additional tests of the power conversion system and the combined reactor and power conversion system. A meaningful technology-readiness demonstration requires that the system assume a configuration that meets the design criteria.

Known areas which require such a test to insure that they are satisfactorily resolved include:

- Startup, shutdown, and restart
- Reactor deadband oscillations
- Hydrogen effects
- Component drift interactions
- Thermal-vacuum effects
- Radiation effects
- Corrosion
- Transient interactions

It is planned to run a combined-system test for the next phase of development to verify the above.

A realistic assessment of the power conversion system (excluding the reactor and its effects) can be made only by using the experience obtained from some 4906 hours of operation on two power conversion systems that were tested at Aerojet General Corporation and the NASA Lewis Research Center. These systems are in configurations that were dictated by early test requirements and do not resemble a flight configuration in any geometric sense. These system tests have demonstrated:

- the capability of generating 35 kW of electrical power within the power rating of the reactor
- the capability of running for extended periods of time on a single set of components

- hydraulic stability
- predicted performance
- no major interaction among components
- manual startup and shutdown (in a few cases automatic startups have been made)
- margin capability of the components
- the criticality of contaminants in the mercury loop
- the effects of liquid carryover on turbine performance and erosion
- the effects of mass-transfer products and how they are transported around the loop
- the required cleanliness levels in critical clearance areas
- liquid-metal-oxide control
- component replaceability
- off-design capability
- vacuum control

A general conclusion can be drawn that states that there are no fundamental problems associated with meeting the power conversion system operational objectives and life requirements of 10,000 hours or more. The problems that do exist have, in most cases, solutions that will yield to further development. Characteristics basic to this type of mercury rankine system such as turbine blade erosion, mass transfer, oil diffusion into the mercury loop, etc., have to be carefully monitored and understood to the point that allows a final determination of their effects on the maximum life potential of the SNAP-8 system.

VIII. GROWTH POTENTIAL OF THE POWER CONVERSION SYSTEM

Because the initial designs of the major components placed more emphasis on reliability and life than on performance, a sizeable performance growth potential of the Power Conversion System is possible by refining the cycle conditions, upgrading component performance, and optimizing the integration of components. An intermediate growth potential can be realized by making minor modifications to the present components. Another substantial growth potential is possible by improving the specific speed of the turbine; this, however, requires a major modification to the turbine-alternator and therefore would be accomplished during a product-improvement phase and after the intermediate performance gains are verified.

The following table reflects the growth potential for SNAP-8 for the next two logical evolutionary steps of development:

	Current SNAP-8	1st Upgrading (1)	2nd Upgrading (2)
Power rating, kWe	35	50	70
Specific weight (unshielded, nonredundant)(3), lb/kWe	283	174	110
Specific radiator area, sq ft/kWe	40	30	20
Overall system efficiency, μ, %(4)	7.8	9.2	12.2
Gross reactor power, kWt	515	600	600

(1) The intermediate-performance growth potential can be obtained by increasing turbine-inlet pressure from 240 to 300 psia, decreasing turbine-exit pressure from 14 to 8 psia, adjusting turbine-nozzle and turbine-rotor passage areas to the new pressures and flows, raising alternator power factor to 0.90, and running the NaK pumps at higher coolant temperature.

(2) By increasing the turbine shaft speed from the present level of 12,000 rpm to 24,000 rpm and by going to a larger number of full-admission stages, turbine efficiency can be increased from the present level of 58 percent to approximately 75 percent. In addition, parasitic losses can be reduced by 2 to 3 kW by going to a solid-state speed-control system.

(3) The man-rated SNAP-8 is designed to have redundant power conversion systems. As a result, the specific weights will increase by approximately 40 percent when this configuration is used.

(4) Degradation allowance of 5 kW removed from listed power level.

IX. CONCLUSIONS

The major components of the SNAP-8 system are now reaching a level of maturity to permit a meaningful assessment of life potential. Furthermore, each of the long-time components was thoroughly inspected after 2000 or more hours of operation, and the inspection did not reveal any serious deterioration which would preclude operation for over 10,000 hours. A number of the major components such as the NaK, mercury, and lube/coolant pumps are approaching or have exceeded 10,000 hours of operation on a single unit and will shortly be removed from the test facility for the 10,000-hour inspection. If no failure modes are discovered during these inspections, the components will be reassembled and put back on test for accumulation of additional endurance hours.

It appears that the boiler and turbine problems have been solved; however, more testing in the current phase of the program is required to verify this tentative conclusion. Boiler conditioning, which has plagued boiler performance for all mercury-Rankine cycles, is finally being quantitatively understood.

It is clear that the SNAP-8 program is continuing to pursue its two primary and important objectives: (1) the development of a reliable, long-endurance power system in the 35 kW range, and (2) the advancement and, if possible, the establishment of the total technology required for the realistic and economical development of long-endurance power systems. Included in this total technology are such processes and procedures as methods of testing, methods of evaluating test results, development of instrumentation techniques, development of analysis methods, and the gradual accumulation of experience of personnel appropriate to the complex and difficult task of building long-endurance mechanical equipment.

Although continued reference in this report has been made to 10,000 hours as the design endurance goal for SNAP-8, it is understood, and in fact inherent, in the development philosophy of SNAP-8 to push and extend the technology limits of endurance. As a result, it is very possible that after the present phase of development, new life goals will be established that will extend the present life goal of 10,000 hours to 20,000 hours and more.

Finally, a power conversion system has been designed, Fig. 5, that incorporates the latest mission requirements and is flight configured using components discussed in this report.

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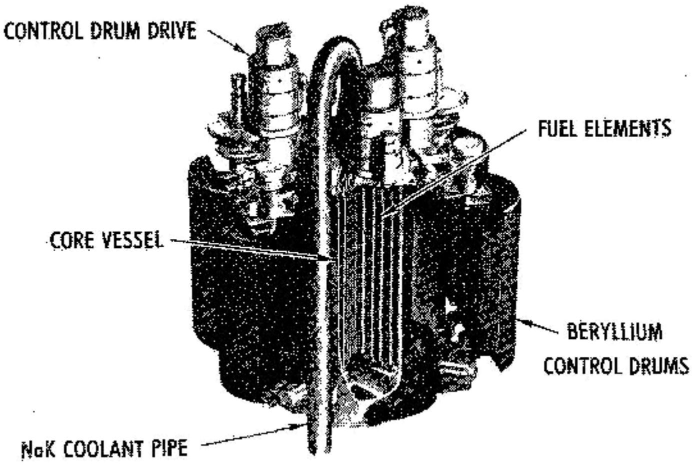

Figure 1. - 600-SNAP-8 reactor assembly.

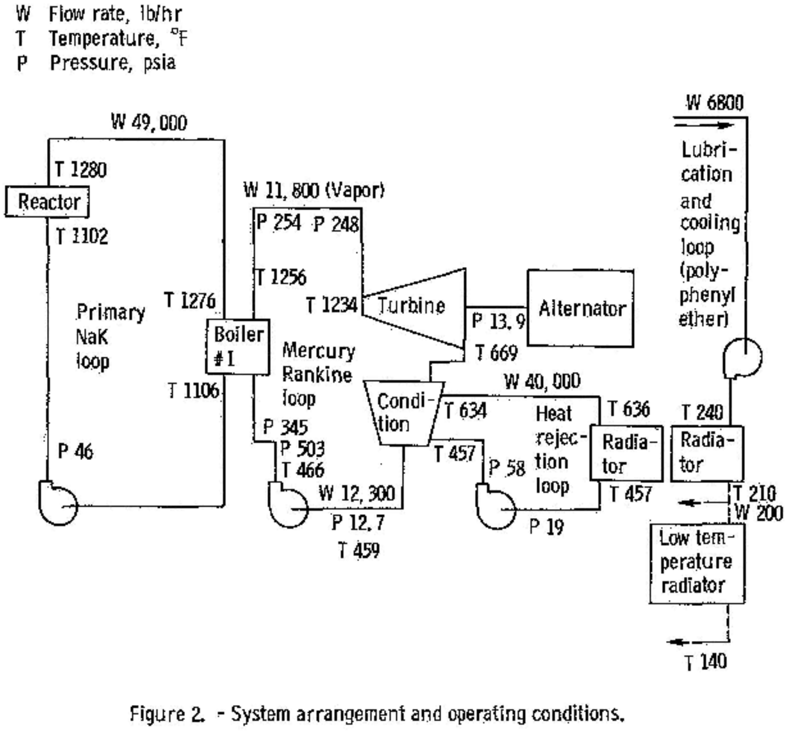

Figure 2. - System arrangement and operating conditions.

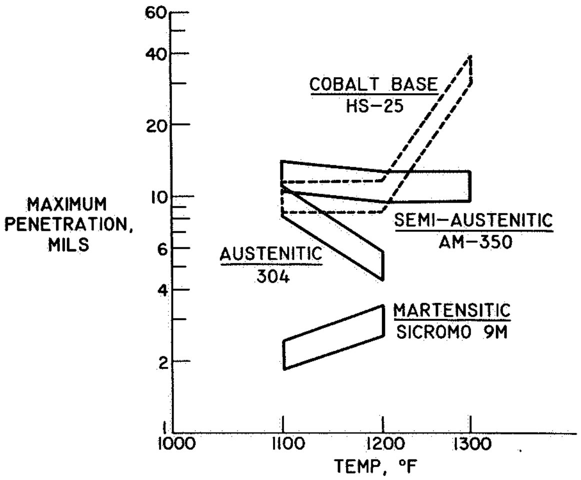

Figure 3. - Mercury corrosion penetration of selected materials (5000 hour tests).

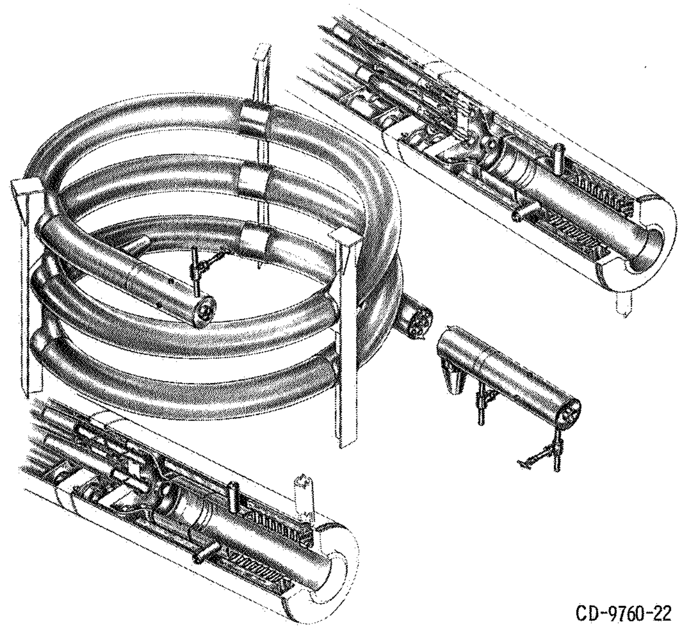

Figure 4. - Boiler bare refractory double containment.

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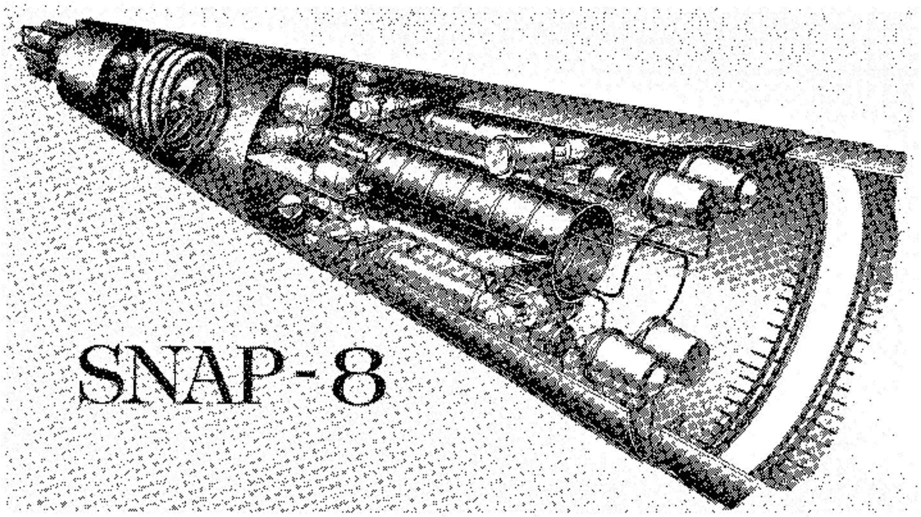

Figure 5. - National Aeronautics and Space Administration's 35 kw electrical generating system for manned space missions.