VI. SNAP-8 DEVELOPMENT STATUS

Henry O. Slone

INTRODUCTION

The SNAP-8 is a turboelectric nuclear space power system using a mercury Rankine cycle. It is being developed jointly by the NASA and the AEC to produce a minimum electrical power of 35 kilowatts, to have high reliability, and to be capable of unattended full-power operation for 10 000 hours.

The SNAP-8 electrical generating system comprises three major subsystems, as shown in figure VI-1: a nuclear system consisting of a reactor, reactor controls, and a shield; a power conversion system consisting of a boiler, a turbine-alternator assembly, mercury- and sodium-potassium-pump-motor assemblies, a condenser, and the necessary electrical controls, piping, and structure; and a flight radiator assembly consisting of radiator heat exchangers required to remove heat from the liquid cooling loops and reject it to space. As indicated, Atomics International under AEC contract is responsible for developing the nuclear system, and Aerojet-General under NASA contract is responsible for developing the power conversion system. Since SNAP-8 is not being designed for a specific space mission at this time, the development of the flight radiator assembly and flight shielding is not a part of the current SNAP-8 program. The prime objective of the SNAP-8 development effort at this time 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 NASA Lewis Research Center has project management responsibilities for the development of the power conversion system and for the integration of the nuclear system and the power conversion system. In addition, Lewis is engaged in experimental and analytical programs which are an integral part of the SNAP-8 development program. The project management responsibilities for the nuclear system are within the AEC Space Nuclear Systems Division.

This paper discusses the current status of the technical development of the SNAP-8 reactor and the power conversion system. Both technical accomplishments and difficulties are included.

SNAP-8 SYSTEM DESCRIPTION

The SNAP-8 program was started by NASA and AEC in 1960. The initial design, based on the technology existing at that time, included two loops and a direct-condensing radiator. After a thorough technical evaluation by NASA, the AEC, and their respective contractors in late 1962, the SNAP-8 system was redesigned in January 1963 in order to separate and to simplify the development problems being experienced. The resulting four-loop concept is shown in figure VI-2. Also shown in figure VI-2 are typical temperatures, pressures, and flow rates required to produce a minimum net electrical power of 35 kilowatts. The systems operate as follows.

A liquid sodium-potassium alloy (NaK 78) flowing at about 46 000 pounds per hour is used in the primary loop to transfer heat from the reactor to the boiler; the alloy enters the boiler at about 1300° F. Mercury is used as the Rankine cycle working fluid in the second loop, wherein thermal energy is converted to mechanical energy. The mercury, flowing at about 11 600 pounds per hour, is boiled and superheated in the boiler. The superheated mercury vapor enters the turbine at 1250° F and 265 pounds per square inch absolute, is expanded through the turbine, condensed, and pumped back to the boiler. The turbine drives the alternator and thus provides the desired electrical power. All the pumps are motor driven, and they are powered by the alternator. A third loop, the heat-rejection loop, uses NaK to transport waste heat from the mercury condenser to a radiator from which it is rejected to space. The fourth loop in the SNAP-8 system, the lubricant-coolant loop, uses an organic fluid, a mixture of polyphenol ethers, at about 210° F to cool the pump motors, the alternator, the space seals in the turbine-alternator assembly and the mercury pump, and the electrical controls; this loop also lubricates the turbine-alternator and mercury pump bearings. The heat from this fluid is disposed of through a separate space radiator. As mentioned previously, development of the radiators is not part of the current development program.

The SNAP-8 electrical controls, not shown in figure VI-2, can be divided into two areas: the start system and those components that operate for 10 000 hours. The start system includes a 28-volt chemical battery, a start programer, and an inverter which provides alternating-current starting power to the pump motors. The 10 000-hour electrical components, which are hermetically sealed, include a voltage regulator, a speed controller, and a parasitic load resistor. The SNAP-8 control system is based on constant-power-level operation independent of the electrical load supplied to the space vehicle. The parasitic load resistor, located in the heat-rejection loop, is capable of absorbing the entire net electrical output of the power conversion system.

Much progress has been made in the SNAP-8 program since January 1963. All the components and subsystems which comprise the SNAP-8 system have undergone testing. In February 1966, the first power conversion system went on test, and it has operated for over 400 hours to date. During operation of this system, 35-kilowatt net electrical power was delivered to a dummy space vehicle load. Thus, the SNAP-8 program has finished its preliminary phases and is now ready for intensive performance and endurance tests.

In the following sections all the major components shown in figure VI-2, are described and their test results discussed. In addition, there is a discussion of the mercury loop containment material, 9-percent chromium - 1-percent-molybdenum (9 Cr - 1 Mo) steel, since mercury corrosion is considered to be a potential problem for 10 000-hour operation.

Reactor

The SNAP-8 reactor, shown in figure VI-3, is designed to produce 600 kilowatts of thermal power at a NaK coolant outlet temperature of 1300° F for 10 000 hours. This compactly designed reactor utilizes hydrided zirconium-uranium fuel-moderator rods clad with Hastelloy N. There are 211 fuel elements in the reactor core vessel. The reactor is controlled by movable beryllium reflector control drums, which by their position control the amount of neutron leakage. There are 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 overall reactor dimensions are a diameter of about 27 inches and a height of about 30 inches; the reactor weight is about 600 pounds.

The SNAP-8 experimental reactor (S8ER), which was developed to demonstrate and measure performance of the reactor core at design conditions of 600 kilowatts of thermal power and a 1300° F NaK coolant outlet temperature, went on test in May 1963. Figure VI-4 shows the S8ER reactor core, control drum assembly, and test shield being lowered into the test facility containment vessel.

The reactor went critical in May 1963, and testing continued until April 15, 1965. The energy output during this period was 5 154 332 kilowatt-hours out of a possible design output of 6 000 000 kilowatt-hours. A total of 11 990 hours of operating time was accumulated, of which 8800 hours were at the design temperature of 1300° F and thermal powers between 400 and 600 kilowatts (table VI-1). The remaining operating hours were obtained at lower NaK outlet temperatures and/or thermal powers less than 400 kilowatts. The longest continuous run was about 5000 hours, and about 2400 hours were accumulated at 600 kilowatts and 1300° F.

The results of the S8ER test program were generally satisfactory; and they showed that the reactor core had sustained power operation capability. However, upon disassembly of the core, it was discovered that about 80 percent of the 211 fuel elements had cladding cracks. A critical technical evaluation of the fuel-element cracking has been completed, and corrections will be made in the design of the next reactor, which will be mated with a power conversion system.

Boiler

The SNAP-8 mercury boiler is the interface between the nuclear and nonnuclear systems and is subject to the most significant perturbation that occurs in operation, a variation in NaK inlet temperature as the nuclear reactor responds to its temperature control system. The boiler must continually maintain vapor superheat, an acceptable fluid inventory variation, and minimal outlet pressure fluctuations over a 50° F band of NaK inlet temperature.

The boiler, shown in figure VI-5, is a second-generation design. The boiler is a single-pass counterflow tube-in-tube heat exchanger wound into a helix with a protruding inlet and outlet. The mercury flows through seven parallel 0.652-inch-inside-diameter tubes 30 feet long. The NaK flows, in the opposite direction, through the annulus passage between the mercury tubes and the outside tubular shell which has an outside diameter of 4.25 inches. Spacers are used to center the seven mercury tubes in the NaK annulus. The mercury tubes are made of 9 Cr - 1 Mo steel, and the shell is made of type 321 stainless steel. The boiler weight, including the mercury and NaK inventories, is about 480 pounds.

Boiler operation is shown schematically in figure VI-6. Here the NaK and mercury temperature profiles are plotted against boiler length. Also shown in figure VI-6 is a cross section of a mercury tube. An inlet plug is inserted into each of the seven mercury tubes. The inlet plug is a solid rod spaced from the inside of the tube by a wire spring forming a spiral flow path for the mercury. This insert continues through the boiler tube for about 5 feet. Downstream of the plug, the spiral flow is maintained by another wire spring (spring turbulator) that is wound at a larger pitch to reduce the pressure drop. The inlet plug is inserted to increase the liquid-mercury and low-quality velocity, while the spring turbulator serves to separate the high-density liquid from the vapor, and makes boiler operation insensitive to gravitational field forces and increasing heat-transfer rates.

Since the boiler is a once-through heat exchanger, four regions are ideally defined on the mercury side of the boiler. The first region, called the preheat region, is where the sensible heat is added to the liquid mercury and the mercury temperature is heated to the saturation temperature which corresponds to the pressure at the liquid-vapor interface. The second region is where the majority of evaporation occurs and is termed the boiling region. The mercury vapor from the boiling region is superheated in the third region to a temperature approaching the NaK temperature. The fourth region, called the excess superheat length, exists to dry the vapor, and represents the surface area margin in the boiler design. Note that the liquid region occurs in the plug insert, as does a portion of the boiling. On the NaK side, a minimum of heat is transferred in the excess superheat region. There is a slight drop in NaK temperature through the superheat region followed by a relatively steep drop through the boiling region. A final drop in NaK temperature represents the sensible heat addition. Another parameter of importance in defining boiler performance is the "pinch point ΔT," which is the temperature difference between the NaK and the mercury at the boiling or liquid-vapor interface. As the pinch point ΔT approaches 0° F, little or no heat is transferred, and test data have shown undesirable variations in boiler pressure and an increase in liquid carryover from the boiler.

Five full-scale SNAP-8 boilers have been tested for a total accumulated operating time of over 3600 hours. In addition, over 6000 hours have been accumulated on subscale SNAP-8 single-tube boilers. During this testing a phenomenon termed boiler "conditioning" has been observed. The term "conditioning" is defined as a time-dependent change in boiler performance. Three modes or regimes of boiler conditioning have been observed. These are (1) fully conditioned operation as typified by the NaK temperature profile shown in figure VI-6, (2) partially conditioned operation, and (3) deconditioned operation.

Figure VI-7 illustrates the three conditioning regimes obtained during a particular test of a SNAP-8 boiler. Temperature of NaK is plotted against boiler length. The NaK temperature profile is used to determine the conditioning regime, because the derivative of the profile (temperature plotted against length) is proportional to the heat flux. After 35 hours of boiler operation, the lower NaK temperature profile indicates the deconditioned operation. The extended flat portion in the first 15 feet of the boiler represents a region of low heat flux. With continued operation, note that the local heat-transfer rates increase, as shown by the increase in the slope of the profile. Also, the region of excess superheat length becomes apparent. Finally, after 51 hours of boiler operation, the fully conditioned NaK temperature profile obtained. Continued operation results in no further improvement in performance. The amount of time required to fully condition a boiler has varied from a few hours to a few hundred hours.

The curves shown in figure VI-7 indicate the effects of conditioning on boiler performance.

Other performance parameters found sensitive to conditioning are boiler outlet pressure stability, boiler exit temperature, and boiler pressure drop. For example, a deconditioned boiler shows outlet pressure fluctuations of ±10 percent compared to pressure fluctuations of ±2 percent in a conditioned boiler.

Thus far, boiler conditioning has been defined and its effec. on the boiler has been noted. Two logical questions are

(1) What causes this phenomenon?

(2) What can be done to minimize its effect?

Dr. L. Rosenblum of the Lewis Research Center has demonstrated that small amounts of oil contamination on an otherwise clean surface can prevent mercury droplets from wetting the surface. Tests at Aerojet-General have verified that oil contamination of forced-convection mercury boilers can cause boiler deconditioning. Boilers can be contaminated because of oil exposure during fabrication and/or installation in a test loop, or because of turbine and mercury pump ball-bearing lubricant entering into the mercury during abnormal system operation.

Thus far, three methods have been successfully employed to obtain fully conditioned boilers. These are (1) the chemical cleaning of the boiler prior to operation, (2) continued operation or "wear-in" of the boiler such as illustrated in figure VI-7, and (3) the use of the additive rubidium in the mercury. All boilers tested were fully conditioned by one of these methods. In addition, once a boiler was fully conditioned, it did not decondition during continued operation.

The boiler tests have shown that the boiler can meet SNAP-8 system requirements and that the conditioning problem is not limiting. However, in order to understand, minimize, or, hopefully, eliminate the conditioning phenomenon, heat-transfer and materials programs have been recently initiated.

Condenser

The SNAP-8 condenser, shown in figure VI-8, is a NaK-cooled tube-in-shell counterflow heat exchanger in which the mercury vapor discharging from the turbine is condensed and subcooled. The mercury flows axially through 72 tubes with inside diameters tapered from 0.44 to 0.20 inch, while the NaK flows through the tapered shell in the opposite direction to the mercury. The tubes and shell are tapered to maintain vapor velocity and provide a continual movement of condensate to the liquid-vapor interface in zero-gravity operation by the drag of the vapor on the condensate droplets. The overall length of the condenser is about 61 inches, and its wet weight is 120 pounds. The tubing and headers are made of 9 Cr - 1 Mo steel, and the shell is made of type 410 stainless steel. Since the thermal expansion coefficients of both materials are compatible, the thermal stresses between tubes and shell are minimized, and fixed header design is possible.

The operational requirements of the condenser in the SNAP-8 system are threefold:

(1) To provide a back pressure (condensing pressure) on the turbine commensurate with system power requirements

(2) To provide subcooling to assure adequate net positive suction head to the mercury pump

(3) To provide mercury inventory storage capacity to make up for space-seal leakage from the turbine-alternator assembly and the mercury-pump - motor assembly

(The space seal is discussed later.)

Over 3600 test hours have been accumulated on three SNAP-8 condensers, and the test results have been very satisfactory. A typical NaK and mercury temperature profile plotted against condenser tube length is shown in figure VI-9 for a particular test condition. The mercury temperature profile was calculated; the NaK profile was measured. The NaK enters from the right, and the initial relatively flat slope moving from right to left represents the subcooling area of the condenser with relatively low heat-transfer rates. The steep gradient represents the high-heat-transfer-rate area characteristic of condensing. The flat portion of the profile at the left represents an area of no heat transfer. The tube schematic indicates the relative tube lengths for the saturated mercury vapor, the mercury condensate, and liquid mercury.

Data obtained from single tapered tube condensing experiments conducted at the Lewis Research Center were used in the design of the SNAP-8 multitube condenser.

In testing to date, the performance of the condenser has been good, and it has met all its operational requirements.

Turbine-Alternator Assembly

The heart of the SNAP-8 power conversion system is the turbine-alternator assembly. A simple schematic of the turbine-alternator assembly is shown in figure VI-10, and a photograph of the actual assembly in the clean room at Aerojet-General is shown in figure VI-11 to give some idea of its size.

Two major assemblies comprise the turbine-alternator assembly: a turbine assembly and an alternator assembly. The two assemblies are bolted together with the turbine rotor shaft directly coupled to the alternator rotor by means of a splined quill. Both the turbine and the alternator assembly use conventional design ball bearings which are lubricated by polyphenol ether.

The turbine assembly, which is cantilevered, is a four-stage impulse turbine with the first two stages operating with partial admission and the last two stages with full admission.

The alternator, supplied by General Electric, is a four-pole, brushless, radial-air-gap, homopolar-inductor machine. There are no rotating windings, the rotor being a one-piece steel forging mounted on ball bearings. A cooling jacket surrounds the electrical windings.

To prevent intermixing of the turbine working fluid (mercury) and the bearing lubricant (polyphenol ether), a low-leakage seal to space was designed and developed. Intercontamination of the two fluids is avoided by venting a section of the shaft to space and permitting limited leakage of mercury and polyphenol ether to space. Leakage rates are controlled by creating a liquid-vapor interface in each seal, through which liquid cannot pass. The interfaces are established by a screw pump on the mercury side and a disk slinger on the polyphenol ether side. Loss of vapors emanating from the liquid-vapor interfaces is further restricted by molecular screw pumps on each side. In the mercury seal, a heat exchanger built into the housing serves the dual function of cooling the liquid-vapor interface and assuring that mercury condensate, instead of vapor, fills the adjacent seal section.

The turbine design conditions are output, 63 kilowatts; efficiency, 60 percent; speed, 12 000 rpm. The alternator design conditions are output, 80 kilovolt-ampere at a power factor of

0.75; efficiency, 87 percent; frequency, 400 cps. The turbine assembly weighs about 151 pounds, and the alternator weight is about 430 pounds.

The first turbine-alternator assembly went on test in a mercury test loop in November 1964. Since then, four other units have been operated. Figure VI-12 shows a performance comparison of the first four turbine assemblies tested to date. Also shown in figure VI-12 are the accumulated test hours obtained for each turbine-alternator assembly and the number of starts made on each unit.

Tests on turbine-alternator assembly 1 were terminated after 820 hours of operation because of a mechanical failure which occurred when a locking device from the floating shaft seals escaped from its location. Posttest examination indicated a number of other mechanical deficiencies and a materials problem. The cobalt base material Stellite 6B, chosen as the turbine wheel and diaphragm material because of its excellent mercury erosion resistance, went through a metallurgical transformation which caused extreme reduction in ductility and increased notch sensitivity.

Subsequent turbines that went on test were modified in varying degrees to correct for the minor difficulties encountered in turbine-alternator assembly 1. Also, some design changes were made to accommodate the notch sensitivity of Stellite 6B. About 400 hours of test time were accumulated on turbine-alternator assemblies 2, 3, and 4, and although some mechanical problems were encountered with these units, no testing was terminated because of a turbine failure as in the case of turbine-alternator assembly 1.

As indicated, none of the turbines met the design efficiency goal of 60 percent. The variations in efficiency among the four units are due mainly to interstage leakages and the fact that the first-stage nozzle areas were different for each unit. The performance degradation shown for turbine-alternator assembly 2 was due to a movement of the first-stage nozzle block insert that effectively increased the nozzle area, which caused a loss in efficiency. At present, a new turbine aerodynamic and mechanical design is under way in order to improve the performance and mechanical integrity of the turbine assembly. It is anticipated that these improvements will allow the turbine efficiency to approach the design level of 60 percent. The new turbine will be available for testing early in 1967.

Four alternators have been tested, and a performance map of alternator capability has been generated. Some results of the alternator tests are shown in figure VI-13. Alternator efficiency is plotted against power at the alternator terminals for three power factors. The data show an alternator efficiency of about 87.8 percent at the design power factor of 0.75, compared to the design efficiency of 87.0 percent. In general, no problems have been encountered with the SNAP-8 alternator.

The space-seal configuration which is used in the turbine-alternator assembly and the mercury-pump - motor assembly are the result of a separate development effort in which extensive theoretical and experimental work was done. Testing during this effort revealed that the total leakage of mercury and polyphenol ether to space can be expected to be less than the design goal of 10 pounds over the 10 000-hour life of the system. This is illustrated in figure VI-14, which shows data obtained for the mercury seal operating in a simulator test rig. Mercury leakage in pounds per 10 000 hours is plotted against heat-exchanger coolant inlet temperature. The data were obtained during a 1000-hour run by taking leakage samples in 1- to 20-hour runs and in 100- to 200-hour runs and extrapolating to 10 000 hours. Note the reasonably good agreement with the theoretical leakage curve. Also, note that the data indicate a leakage of less than 1 pound in 10 000 hours at the design operating temperature, which is considerably less than the design goal of 10 pounds in 10 000 hours.

Lubricant-Coolant-Pump - Motor Assembly

The lubricant-coolant-pump - motor assembly, provided by TRW and shown in figure VI-15, consists of a single shaft with a straddle-mounted motor rotor and an overhung, single-stage impeller. The assembly is self-cooled and lubricated by the polyphenol ether which bleeds from the pump discharge, flows through the motor and bearing area, and returns to the eye of the impeller through the hollow shaft. The pump-motor assembly dimensions are mean diameter, about 6 inches, and length, about 12 inches. The weight is about 25 pounds.

Seven units have been built and tested and have accumulated over 7700 test hours. One unit has accumulated over 4500 test hours. A typical test performance curve is shown in figure VI-16. Note that the pump has exceeded its SNAP-8 design requirements and its mechanical integrity has been demonstrated during over 7700 hours of operation.

Mercury-Pump - Motor Assembly

The mercury-pump - motor assembly, shown in figure VI-17, consists basically of a one-piece solid shaft supported by two ball bearings mounted in a central transmission housing. The bearings are lubricated with polyphenol ether, and mercury sealing is effected by pump seals similar to the sealing configuration used in the turbine-alternator assembly discussed previously. A 400-cycle, three-phase induction motor is overhung from the bearing housing at one end, and a combination jet and centrifugal pump is overhung on the other end. The jet pump is incorporated upstream of the centrifugal pump to provide positive suction head to the centrifugal impeller at very-low-flow starting conditions. The pump-motor assembly dimensions are mean diameter, about 8 inches, and length, about $2\frac{1}{2}$ feet. The weight is about 150 pounds.

Six units have been built, and four of these units have been tested and have accumulated about 2000 hours. A test performance curve is shown in figure VI-18. As can be seen from the curve, the mercury-pump - motor assembly has met or exceeded SNAP-8 design requirements. In general, no difficulties have been encountered in testing.

Sodium-Potassium-Pump - Motor Assemblies

As discussed previously, the SNAP-8 system requires two NaK-pump - motor assemblies, one for the primary loop and one for the heat-rejection loop. Because of the similarity of requirements, one design is used in both loops.

The NaK-pump - motor assembly, shown in figure VI-19, is a self-contained hermetically sealed unit. It incorporates on a single shaft a centrifugal pump, a hermetically sealed 400-cycle, three-phase induction drive motor, an internal lubricant-coolant circulating pump, and NaK-lubricated hydrodynamic bearings. Included with the pump-motor assembly, but not shown in figure VI-19, are heat exchangers, a cold trap, and a NaK filter for the circulating NaK. Polyphenol ether is used as the coolant in the heat exchanger. The NaK lubricant-coolant circuit is independent of the process pumping circuit. The pump-motor assembly dimensions are mean diameter, about 8 inches, and length, about $1\frac{1}{2}$ feet. The weight is about 200 pounds.

A total of 10 NaK-pump - motor assemblies have been tested and have accumulated over 4000 hours of test time. One unit has operated for 3028 hours. A test performance curve is shown in figure VI-20 for a NaK-pump - motor assembly operating at 1170° F, the operating temperature of the primary loop. As shown by the curves, the NaK-pump - motor assembly meets SNAP-8 design requirements. It should be noted that the SNAP-8 NaK-pump - motor assembly design is the first of its kind, and the results of the test program have been most satisfactory.

Mercury Containment Material

A potential problem in a mercury system is that of mercury corrosion of the containment material. Of the current materials, low-additive iron-base alloys exhibit minimum corrosion potential in mercury. This is illustrated in figure VI-21, where the corrosion rates of an iron-base alloy, 9 Cr - 1 Mo steel, and a cobalt-base alloy, HS-25, are shown. These data were obtained at the Lewis Research Center in refluxing mercury capsules operating at 1100° F. Individual capsules fabricated from the two materials were operated for time increments of 300, 1000, 2000, and 5000 hours. After testing of each capsule was completed, it was metallurgically examined to determine its resistance to mercury corrosion, expressed as corrosion penetration. The data curves were then extrapolated to 10 000 hours. On the basis of these data, 9 Cr - 1 Mo steel was selected in early 1963 as the SNAP-8 mercury containment material. The predicted penetration in 10 000 hours is about 3 to 4 mils for 9 Cr - 1 Mo and about 17 mils for HS-25. It should be noted that the stainless steels exhibit a higher corrosion penetration than HS-25 and that the refractory metals such as columbium and tantalum exhibit no mercury corrosion. A refractory material was not selected for SNAP-8 in 1963 because of the difficulties encountered in handling the material.

Since the selection of 9 Cr - 1 Mo steel was made in early 1963, three subscale corrosion loops and five boilers fabricated from 9 Cr - 1 Mo have been operated. Figure VI-22 shows the results obtained after metallurgical examination of a first-generation-design SNAP-8 boiler which operated for 1425 hours. The NaK temperature profile is plotted against length of one of the mercury tubes in the boiler. The two profiles shown indicate the change from partial conditioning to full conditioning with test time. Also plotted is the maximum pit depth observed in the tube wall at various locations along the tube. The maximum depth observed was about 5 mils, which occurred in the liquid section of the boiler tube. The test results from the subscale corrosion loops indicate pit depths greater than 5 mils.

Based on the test data, the following observations are made:

(1) The maximum attack which occurs is apparently associated with the liquid-mercury section and high-heat-flux area of the boiler tube.

(2) The attack pattern seems to depend on the conditioned state of the boiler during operation.

(3) It is not clear whether the pits observed in the tube wall are due to corrosion or cavitation-erosion or both.

In summary, the current test data do not allow an accurate prediction of the life of 9 Cr - 1 Mo steel as a mercury containment material in the SNAP-8 system. The life could be greater or less than 10 000 hours. As a result, tests are continuing in order to establish the life capability of 9 Cr - 1 Mo steel. In addition, work is under way to establish the feasibility of using a bimetal refractory material, such as tantalum clad with a stainless steel, or a bare refractory material for the mercury containment material.

SUMMARY

The major technical accomplishments and problem areas of the SNAP-8 program are summarized in table VI-2.

Test times, as of August 1, 1966, are tabulated for the major power-conversion-system components. Listed are the number of units tested, the accumulated test time for all units, and the longest test time accumulated on a single unit. Only one unit, the turbine-alternator assembly, has had a failure, and its performance has been somewhat lower than expected.

The results obtained on SNAP-8 components and subsystems have been most encouraging in that no fundamental problems have been encountered which might prevent development of the SNAP-8 system. However, much effort is required before it can be said that the SNAP-8 is ready to be selected for a given mission. The endurance and reliability of SNAP-8 for 10 000 hours must be demonstrated. For example, the 10 000-hour life of the boiler material (9 Cr - 1 Mo steel) is uncertain. The first power conversion system, which began tests in February 1966, has accumulated a total operating time of only about 400 hours. In addition, the three major subsystems which comprise the SNAP-8, that is, the nuclear system, the power conversion system, and the flight radiator assemblies, must be integrated and operated. Currently, testing is continuing on the first power conversion system and on components. In the future, a second power conversion system and a combined system (i.e., a reactor mated with a power conversion system) will be tested. All systems will be operated for 10 000 hours.

TABLE VI-1. - OPERATING TIME OF SNAP-8

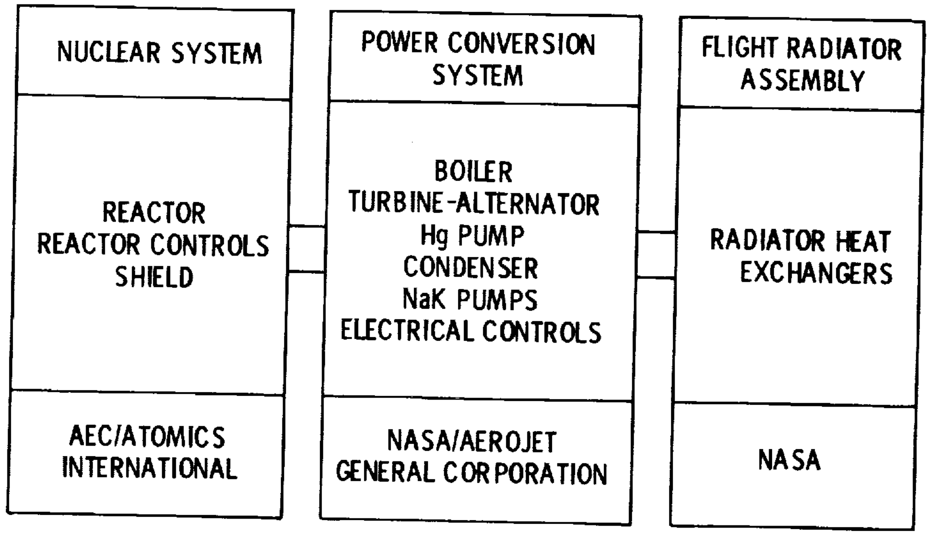
REACTOR AS OF APRIL 15, 1965

Temperature, °F	Thermal power, kW		Total operating time, hr
	400 to 600	Other than 400 to 600	
	Operating time, hr		
1300	8 800	470	9 270
1300 and other	10 320	1670	11 990

TABLE VI-2. - SUMMARY OF SNAP-8 PROGRAM AS OF AUGUST 1966

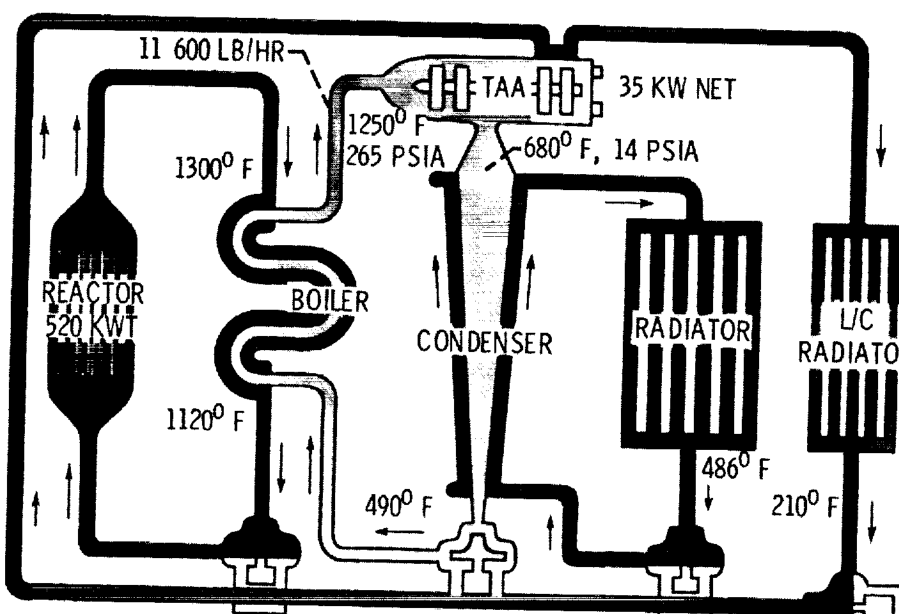
Component	Number of units tested	Test time for all units, hr (a)	Longest single-unit test time, hr
Turbine-alternator assembly	4	1122	820
Sodium-potassium-pump - motor assembly	10	4157	3028
Mercury-pump - motor assembly	3	1975	1099
Lubricant-coolant-pump - motor assembly	4	7727	4552
Boiler	5	3694	1429
Condenser	3	3694	1851

[a]Power conversion system delivered 35 kW net electric power with all pumps on alternator power during 1966 testing.



CS-40215

Figure VI-1. - SNAP-8 electrical generating system. Electrical power, 35 kilowatts; life, 10 000 hours.



CS-40234

Figure VI-2. - Schematic drawing of SNAP-8 system.

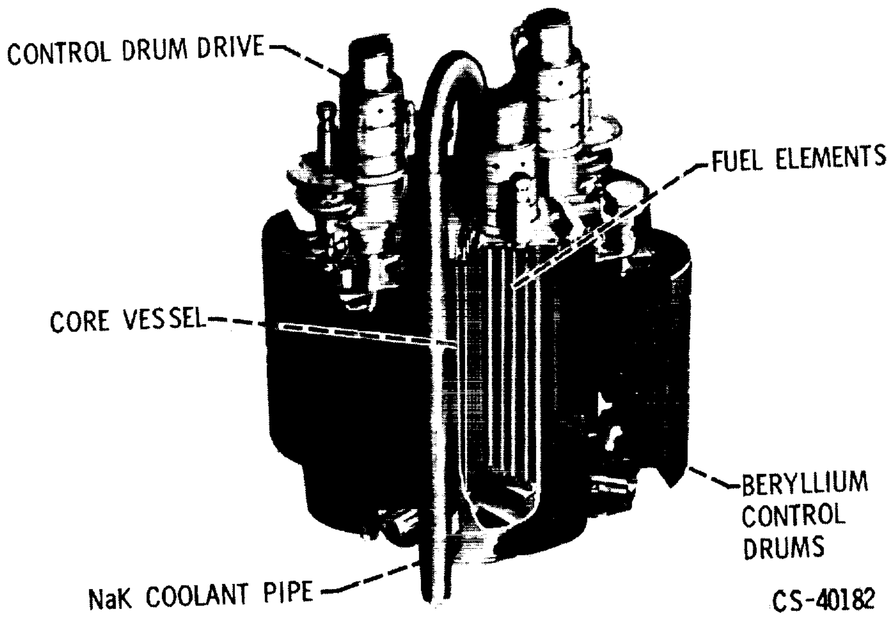
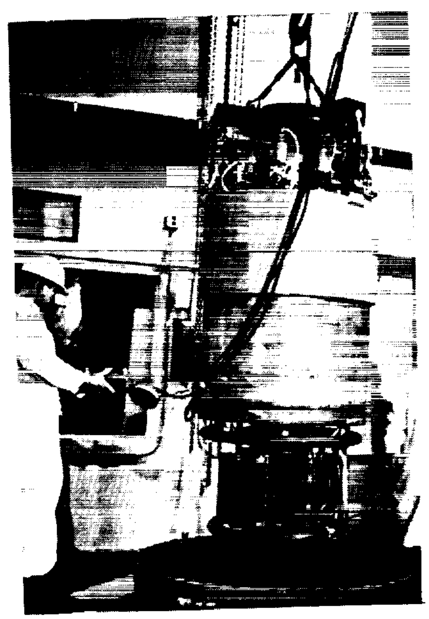


Figure VI-3. - SNAP-8 reactor assembly.



CS-40220

Figure VI-4. - SNAP-8 experimental reactor. Critical operation reached in May 1963; thermal power, 600 kilowatts; sodium-potassium outlet temperature, 1300° F; energy output through April 15, 1965, 5 154 332 kilowatt-hours.

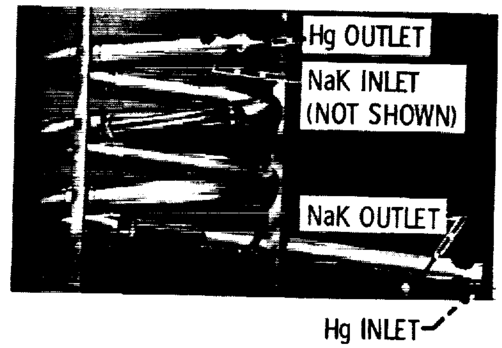


Figure VI-5. - SNAP-8 tube-in-tube boiler. Sodium-potassium and mercury flow in opposite directions; shell dimensions: outside diameter, 4.25 inches; wall thickness, 0.125 inch; length, 30 feet; tube dimensions (seven tubes): inside diameter, 0.652 inch; wall thickness, 0.09 inch; length, 30 feet; wet weight, 480 pounds.

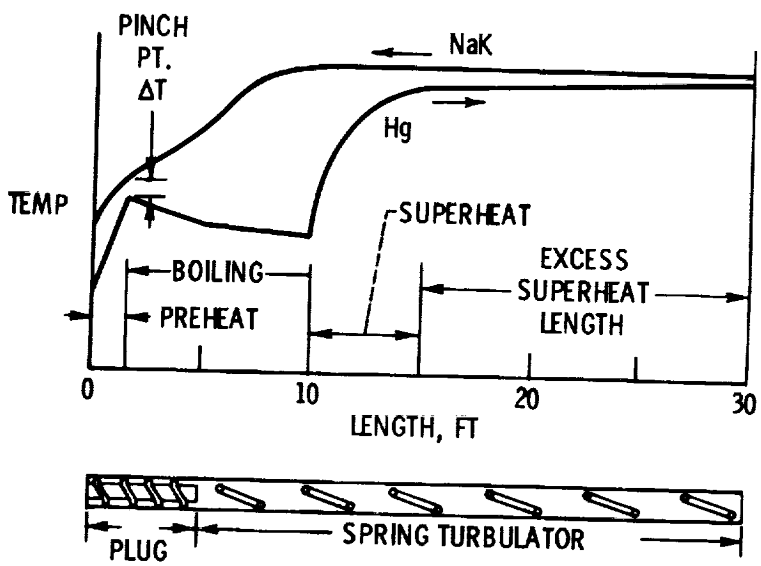
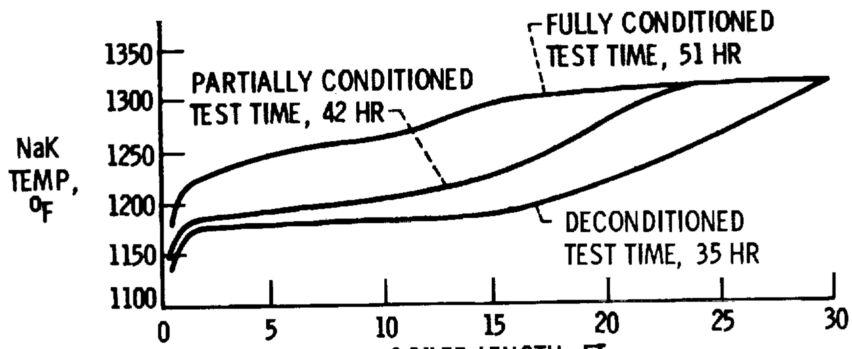
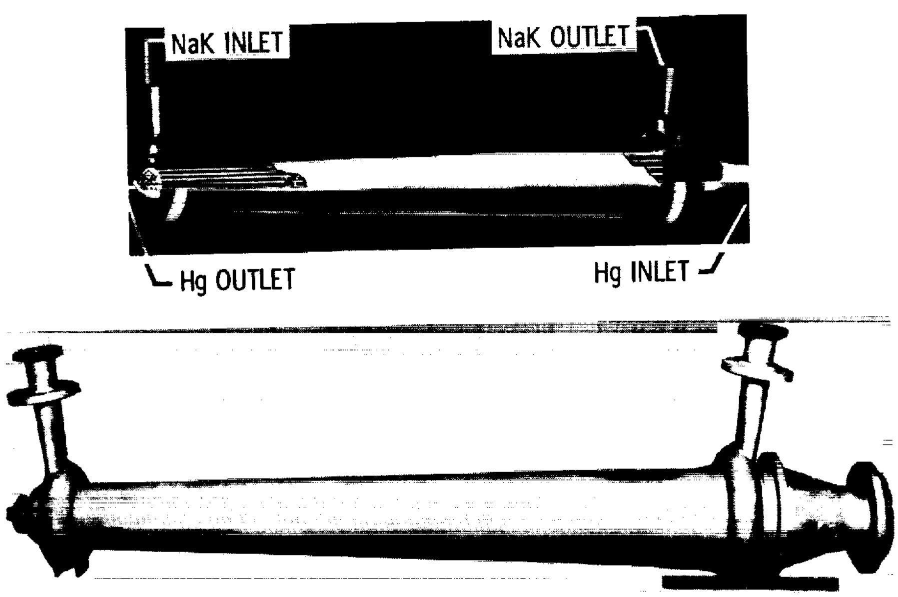


Figure VI-6. - Temperature profile of SNAP-8 tube-in-tube boiler.



CS-40174

Figure VI-7. - Conditioning history of SNAP-8 tube-in-tube boiler. Mercury flow rate, 11 500 pounds per hour; mercury exit pressure, 265 pounds per square inch absolute; mercury inlet temperature, 450° F; sodium-potassium flow rate, 45 000 pounds per hour; sodium-potassium inlet temperature, 1310° F.



CS-40221

Figure VI-8. - SNAP-8 condenser. Sodium-potassium and mercury flow in opposite directions; shell dimensions: outside diameter, 4.4 to 7 inches; length, 52 inches; tube dimensions: inside diameter, 0.44 to 0.20 inch; length, 51.5 inches; wet weight, 120 pounds.

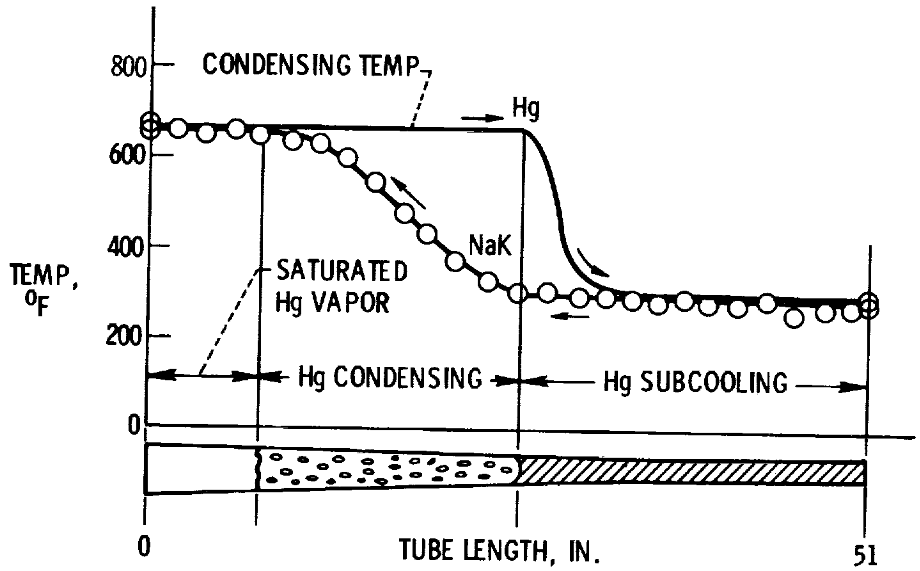


Figure VI-9. - Temperature profile of SNAP-8 condenser. Mercury flow rate, 12 500 pounds per hour; sodium-potassium flow rate, 41 500 pounds per hour; mercury inlet temperature, 678° F; mercury outlet temperature, 490° F; sodium-potassium inlet temperature, 486° F; sodium-potassium outlet temperature, 672° F.

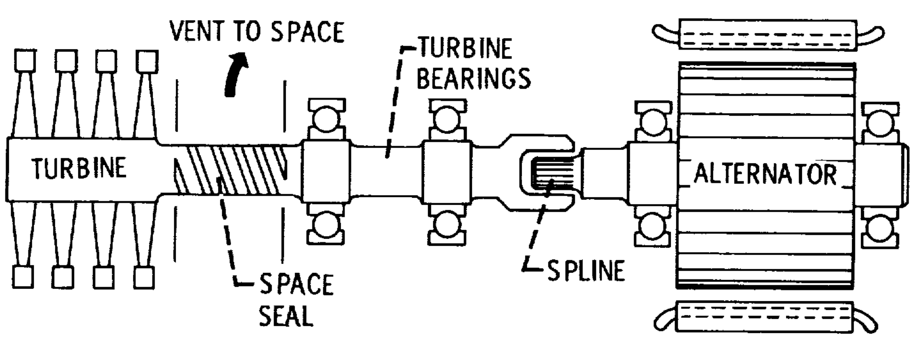


Figure VI-10. - Schematic drawing of turbine-alternator assembly. Turbine design conditions: output, 63 kilowatts; efficiency, 60 percent; weight, 151 pounds; speed, 12 000 rpm; alternator design conditions: output, 80 kilovolt-amperes; power factor, 0.75; efficiency, 87 percent; frequency, 400 cps; weight, 430 pounds.

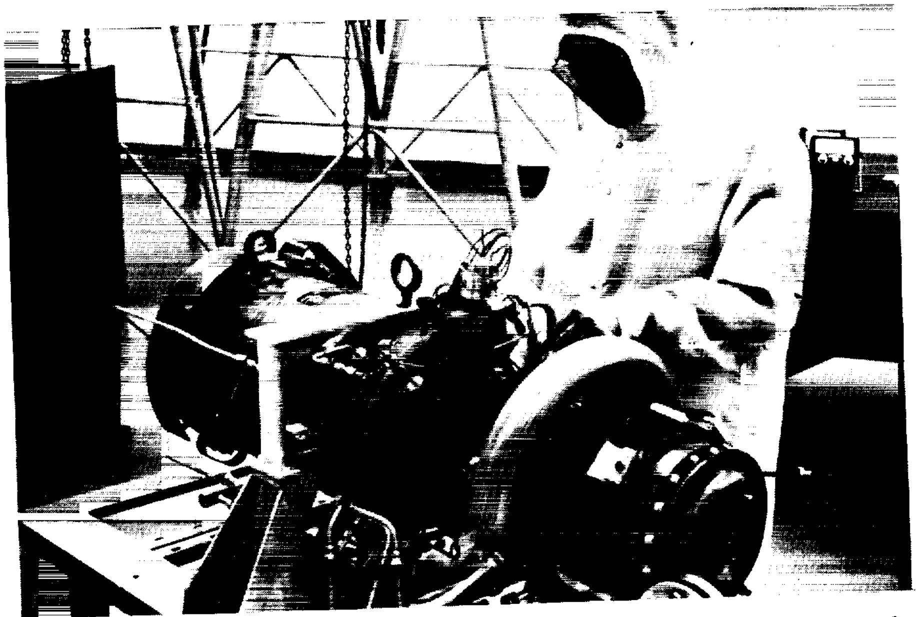
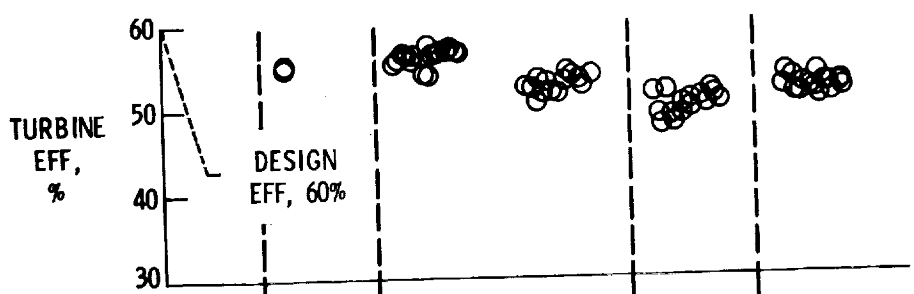


Figure VI-11. - Turbine-alternator assembly in clean room.



TAA UNIT	1	2	3	4
TOTAL TEST TIME, HR	820	141	42	117
NO. OF STARTS	43	3	2	3

CS-40178

Figure VI-12. - Performance comparison of SNAP-8 turbine assemblies.

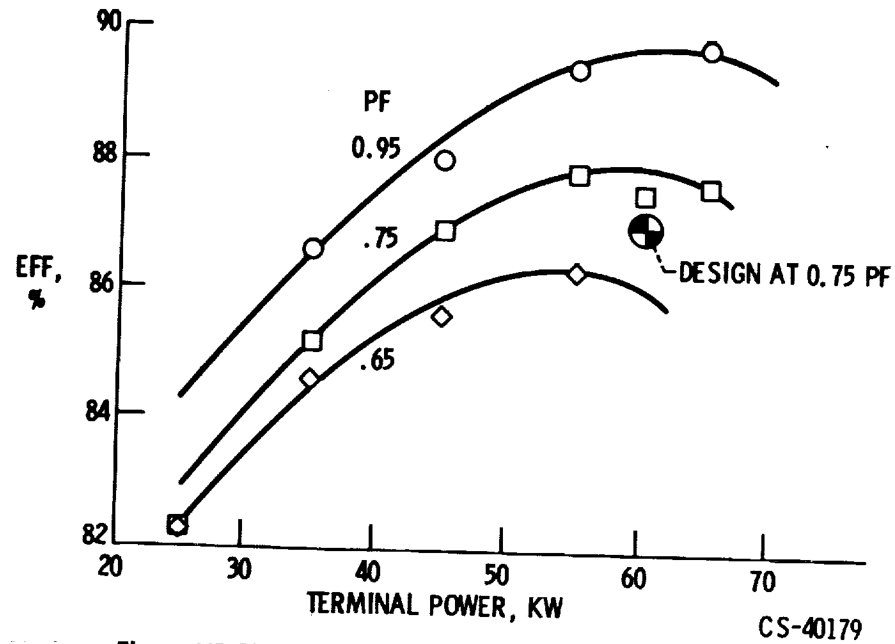


Figure VI-13. - SNAP-8 alternator efficiency as function of power.

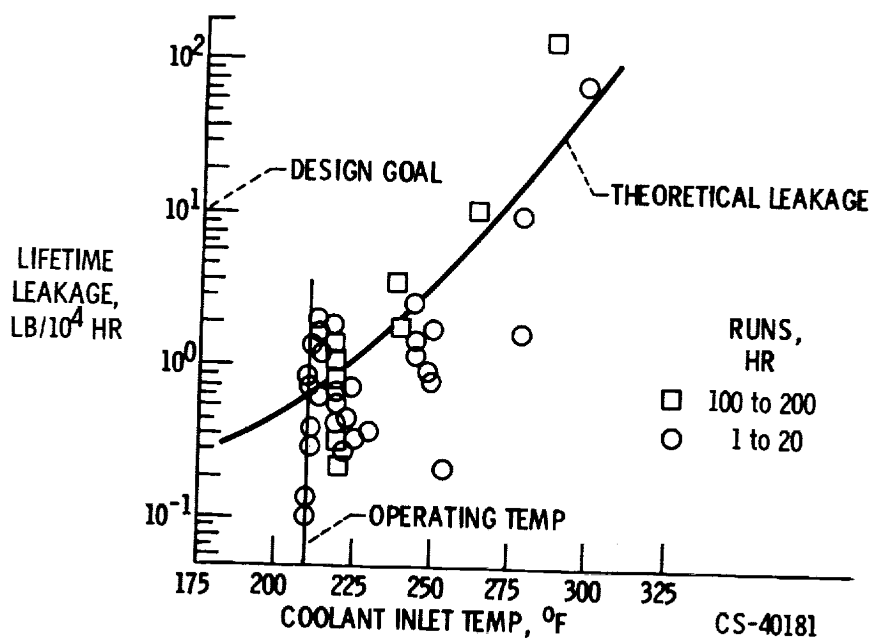
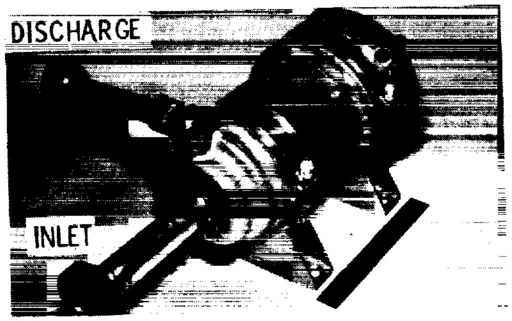
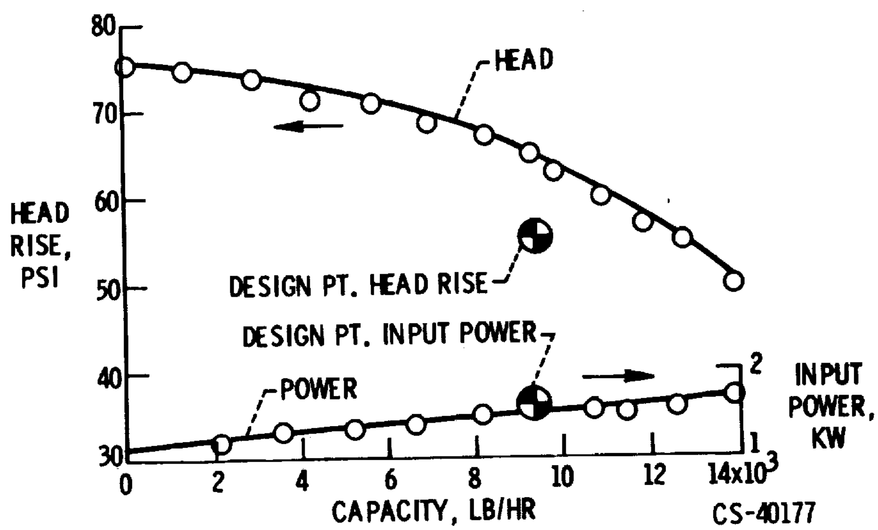


Figure VI-14. - SNAP-8 seal-to-space leakage.



CS-40219

Figure VI-15. - Lubricant-coolant-pump - motor assembly. Design conditions: speed, 7800 rpm; head rise, 57 pounds per square inch; flow, 9400 pounds per hour; input power, 1.6 kilowatts; overall efficiency, 27 percent; carbon journal and thrust bearings lubricated with polyphenyl ether.



CS-40177

Figure VI-16. - Performance of lubricant-coolant-pump - motor assembly. Fluid, polyphenyl ether.

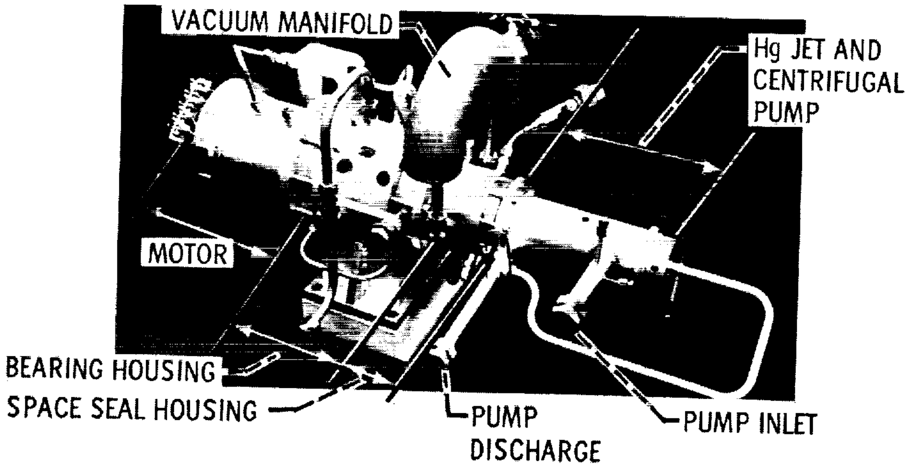


Figure VI-17. - Mercury-pump - motor assembly. Design conditions: speed, 7800 rpm; head rise, 394 pounds per square inch; flow, 11 500 pounds per hour; input power, 2.8 kilowatts; overall efficiency, 14 percent; ball bearings lubricated with polyphenyl ether.

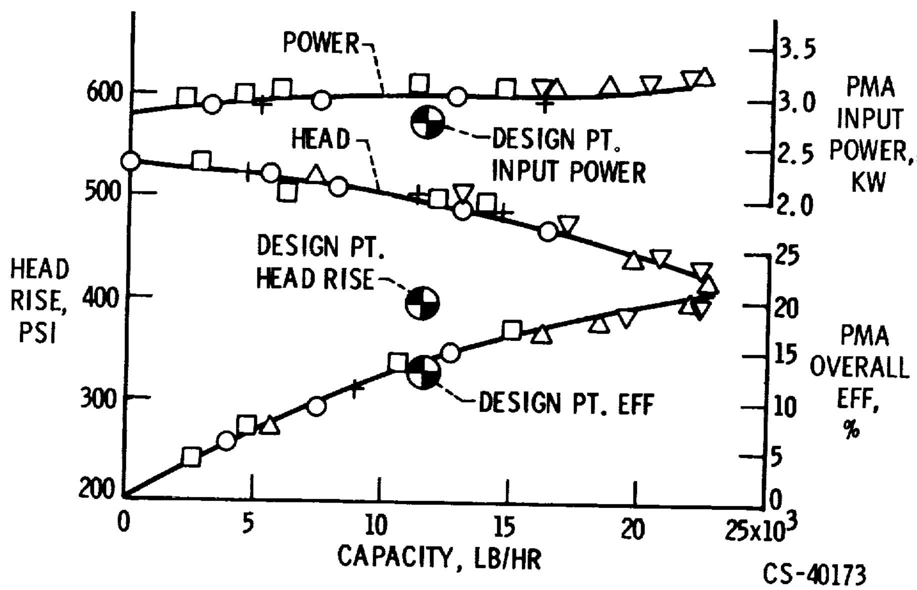


Figure VI-18. - Performance of mercury-pump - motor assembly.

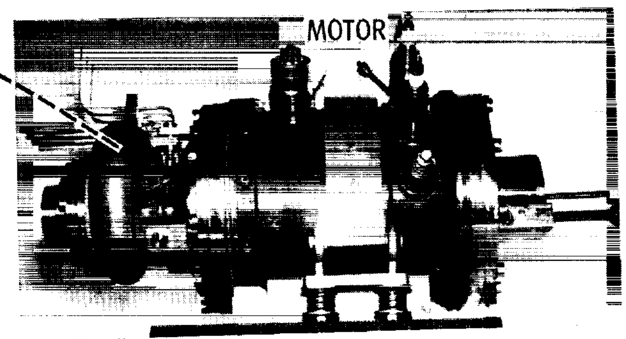


Figure VI-19. - Sodium-potassium-pump - motor assembly. Design conditions: speed, 5800 rpm; head rise, 35 pounds per square inch; flow, 35 300 pounds per hour; input power, 4.6 kilowatts; overall efficiency, 35 percent; sodium-potassium-lubricated, tilting-pad journal and thrust bearings.

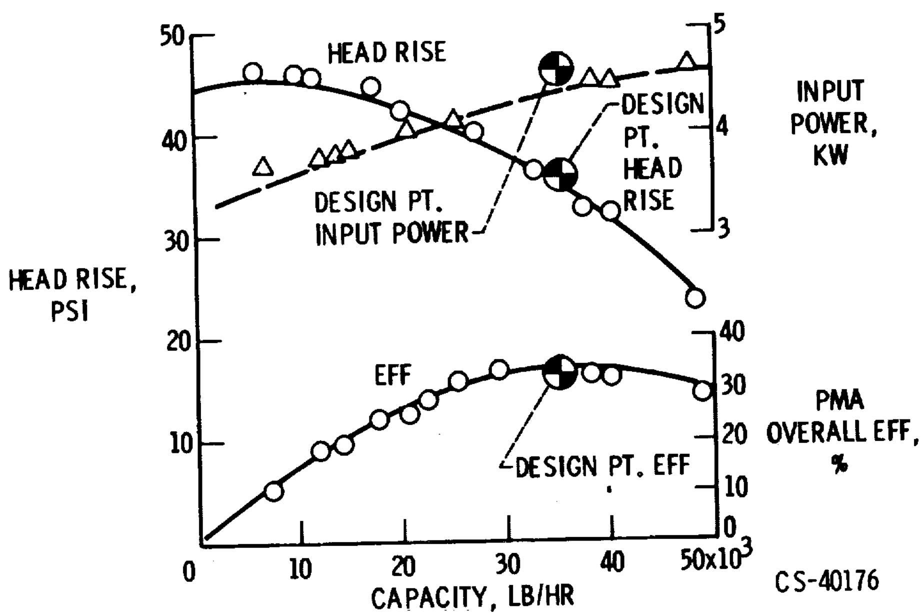


Figure VI-20. - Performance of sodium-potassium-pump - motor assembly operating at 1170° F.

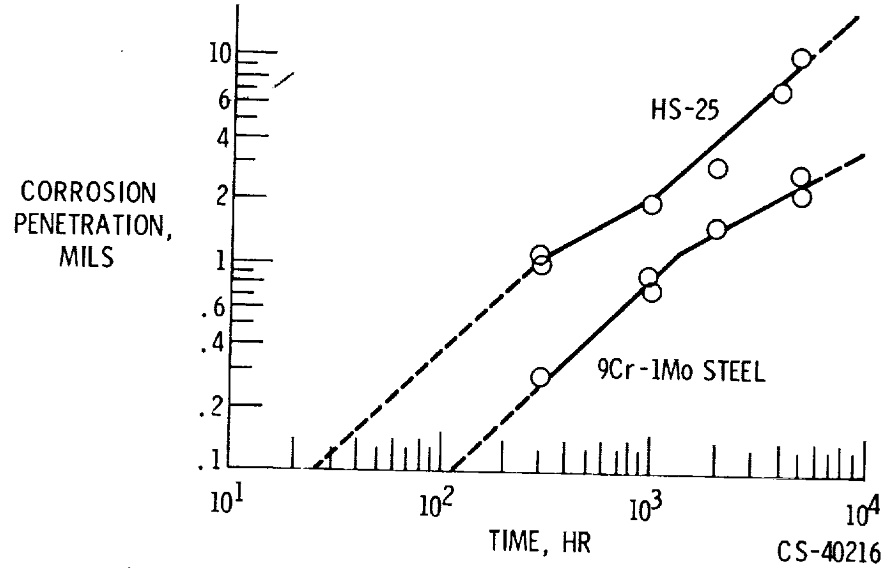


Figure VI-21. - Corrosion rate of selected materials in refluxing mercury capsules at 1100° F.

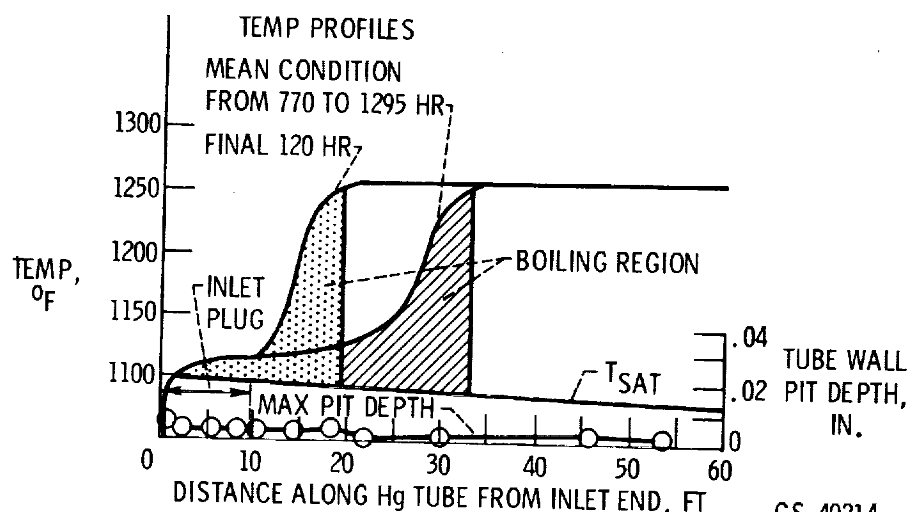


Figure VI-22. - Temperature rise and pitting in mercury tubes during 1425-hour test of full-scale boiler.