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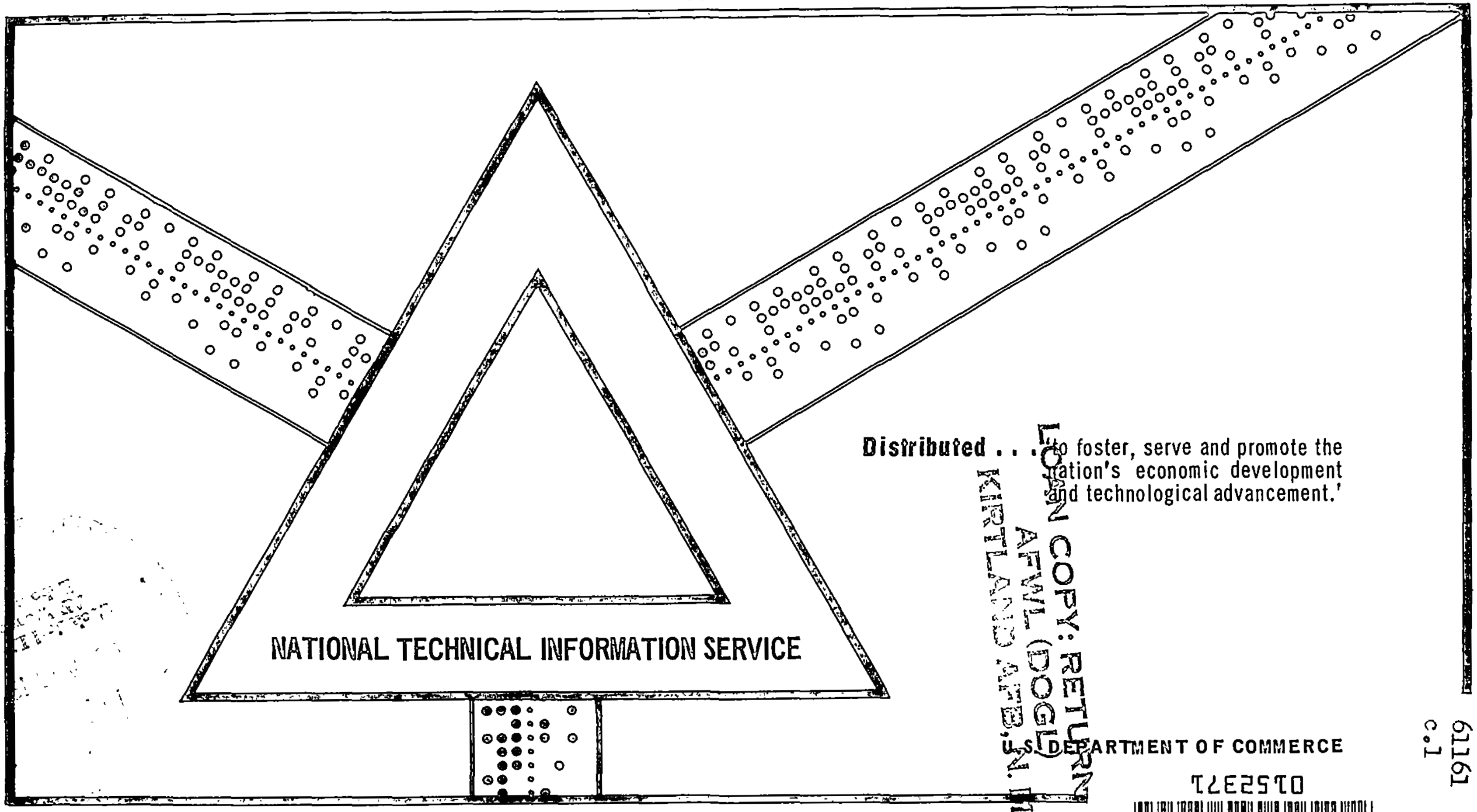

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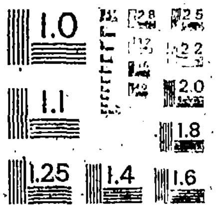

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A SNAP-8 BREADBOARD SYSTEM - OPERATING EXPERIENCE*

by

J. N. Hodgson
Aerojet-General Corporation
Azusa, California

and

R. P. Macosko
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

ABSTRACT

SNAP-8 is a 35 kw nuclear-electric space power system. The system operates on a mercury Rankine cycle using NaK (eutectic sodium-potassium mixture) as the heat-input and heat-rejection working fluids. The test program has evolved from an initial component test phase to testing of complete breadboard systems. Extensive testing has provided information on the relationships between components and the system. Data are presented showing the perturbations, and their consequences, inherent in a dynamic system. Cause and effect relative to boiling instability, system contamination, inventory control, testing mishaps, and transient operation are presented as observed during the test program. The breadboard approach to system testing and design has proven appropriate. A close simulation to flight-configuration testing has been accomplished while maintaining the design flexibility of a breadboard system.

INTRODUCTION

SNAP-8 is a 35 kw nuclear-electric power conversion system for use in space. The system operates on a Rankine cycle and uses four loops and three fluids. The system is shown schematically in Figure 1. The energy source is a nuclear reactor cooled by a pump-driven sodium-potassium (NaK) loop.

The power conversion system uses mercury as a working fluid and is coupled to the reactor cooling loop by a heat exchanger (boiler) where the mercury is preheated, vaporized, and superheated. The superheated vapor drives a turbine-alternator assembly which develops the 400 cps electrical output of the system. The saturated mercury vapor leaving the turbine passes through a condenser and then to a mercury pump to complete its cycle. Cooling for the condenser is provided by a second pump-driven NaK loop which couples the condenser and space radiator. The fourth loop of the SNAP-8 system provides lubrication and cooling using an organic working fluid (polyphenyl ether). Lubrication is provided for the bearings in the turbine-alternator assembly and the mercury pump-motor assembly. Cooling is provided for the alternator, pumps, and electrical controls. The organic loop fluid is pump driven and has its own heat-rejection radiator.

An auxiliary loop connecting the two NaK loops provides a thermal load for the reactor during initial heating prior to startup of the power conversion system.

SNAP-8, in its current configuration, has been under development since 1963. Throughout this period, continuous emphasis has been placed upon effective test programs to obtain data for design improvement and to demonstrate reliability. As a result, the combined hours of testing in various test facilities has continuously risen, particularly as experience and improvements in components and test support equipment have caused an increase in testing efficiency. The testing efficiency of all facilities in the SNAP-8 Program is shown in Figure 2 which defines the percentage of time the facilities have been in operation. The rise of efficiency, particularly during the last year, is indicative of the continual improvement in testing efficiency.

The most significant feature of the test program has been extensive testing with the SNAP-8 components combined into complete power conversion systems. During 1966, testing began on a complete breadboard system known as Power Conversion System 1 (PCS-1). In 1967, a similar test facility (known as W-1) was put into operation by the National Aeronautics and Space Administration at the Lewis Research Center. Both of these systems use all of the SNAP-8 components with the exception of the reactor, radiator, and fluid reservoirs. Testing thus far has used gas or electric heaters in place of the reactor, and air-cooled heat exchangers in place of the radiator. The purpose of these facilities has been to study the

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*The information appearing in this paper is based on the work performed under National Aeronautics and Space Administration Contract NAS 5-417 interrelationships between components and system during both steady-state operation and startup transients.

The PCS-1 and W-1 breadboard systems have been the vehicles by which much information has been gained toward understanding the phenomena to be expected in the final SNAP-8 system. The purpose of this paper is to describe the various system-related phenomena observed during testing of the PCS-1 and W-1 systems.

DESCRIPTION OF BREADBOARD SYSTEM

PCS-1 has been selected here to show the size and configuration of a typical SNAP-8 breadboard system. An overall view of PCS-1 is not possible in one illustration due to the interference of test-cell walls and structure. The best perspective of its size and geometry is gained from photographs of a scale model. Figure 3 shows front and back views of a 1/4-scale model of the facility. The overall floor area occupied by the facility, exclusive of the gas heaters, heat-rejection air cooler, and cell scrubber system, is approximately 950 ft^2. By contrast, the equivalent SNAP-8 flight system might typically be packaged in a conical shape as shown by the model in Figure 4; the cone is approximately 12 feet in diameter and 27 feet high.

The choice of operating with a breadboard system as opposed to the compact system of Figure 4 has been advantageous to the SNAP-8 Program. The breadboard system has allowed the discovery and correction of numerous system problems while retaining the inherent versatility of breadboard design. Consequently, any restrictions that may have resulted from prematurely freezing designs have been avoided. Basically, the breadboard system has the same testing value as a compact system. The primary differences between the two systems are in line lengths, heat losses, and transport delays. During transient testing (startup), a compact system unquestionably has a greater ability to simulate flight conditions. During steady-state testing, however, which has been the predominant mode thus far in the program, the breadboard system is of comparable value to a compact system. The chief area where testing has not simulated flight conditions has been with reactor and radiator simulation. The thermal capacities of the breadboard-system gas heat source and air-cooled heat sink require extrapolation of test data to interpret transient effects. This same problem, however, would be experienced with a compact system unless a reactor and radiator, or their thermal equivalent, were employed. Overall, the breadboard approach has proven highly successful as a testing method.

The test program has been typical in that many subtle areas involving testing methods and equipment have been encountered. A principal problem has been the reliability of test support equipment. Whereas SNAP-8 components are designed for a 10,000-hour life, commercial products generally are not. Difficulties with test support equipment have either directly, or indirectly, been involved with many of the testing problems which have been experienced. One of the significant improvements of the test program has been the evolution to more reliable test support equipment. Changes in pump design, valve design, electrical connections, etc., have been adopted as knowledge was acquired about the requirements and capabilities of test support equipment. It is estimated that through careful product selection and design, the problems directly attributable to test support equipment have been reduced by 50% since the beginning of the test program. The reliability of the overall facility has thereby been increased significantly. Test support equipment problems have generally been eliminated or modified to where they have no effect on the ability to keep the system operating.

Instrumentation accuracy, data reduction, and data analysis have also been stressed throughout the test program. Time and experience have led to significant changes in these areas. Instrumentation redundancy has continually increased to satisfy the need for extensive and reliable data. The quantity of instrumentation has approximately doubled during the test program duration. Coincident with the addition of instrumentation has been a noticeable upgrading of instrument quality and methods of instrument application. The result has been a decrease in instrument failure rate and an incre . .n data accuracy.

Extensive computer use has also evolved from the need for more complete and effective data analysis. Computer programs have been developed which perform functions ranging from instrument calibration to complete system and component analyses. As a result, the data recipients have access to rapidly available and accurate data to evaluate not only past, but also current, performance.

The PCS-1 and W-1 breadboard systems have adequately demonstrated their value as system test facilities. This success is well-illustrated by their records of accrued test time and the value of the system and component data generated. Figure 5 shows the efficiency of breadboard system testing as a function of time. The increase in reliability that had been experienced with time is demonstrated by the significant rise in efficiency (18% to 38%) accomplished during the last year (1967). This testing success, coupled with the system-component performance data which has been generated has made breadboard system testing a highly-successful part of the SNAP-8 program.

TEST RESULTS

The performance of individual SNAP-8 components and some limited system performance were reported earlier(1).*

The great value of the breadboard system testing has come from the acquisition of data regarding the performance of components in a system. Whereas each component

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*Superscript numbers in parentheses refer to similarly numbered references listed at the end of this paper.

worked well in its individual test facility, it remained to be shown that the components were compatible with one another when coupled in a dynamic system. Identification of the various interactions of the components and their effects on system output has been a major accomplishment of the SNAP-8 testing to date. The observed system and component interactions are discussed below.

Boiler

The SNAP-8 boiler is a counter-flow heat exchanger which couples the reactor-coolant NaK loop to the power-conversion-system mercury loop(2). The current design is shown in Figure 6. The heat input consists of 1300°F NaK from the reactor. The NaK flow rate allows the NaK temperature to drop about 170°F in passing through the boiler. On the mercury side of the boiler, the mercury makes a single pass through seven parallel tubes. The mercury enters at 450°F in a subcooled state and leaves the boiler at 1250°F (200°F superheat). Experience with boiler testing has included the testing of four boilers for a total operating time of 2070 hours.

The boiler is a key component with respect to component-system interactions. Since SNAP-8 is a dynamic system, it follows that the system is subject to perturbations in the form of pressure and temperature variations which ultimately affect system electrical output. The boiler is the principal source of the power-conversion-system perturbations because of the extensive change-of-state the mercury undergoes during passage through the boiler. The changing state of the mercury is controlled by the heat-transfer rates and other flow conditions associated with the seven mercury-containment tubes. To an extent, the thermodynamic and hydraulic phenomena in each of the boiler tubes occur independently. Consequently, any process difference between tubes potentially gives rise to system perturbations. One of the foremost objectives in the boiler design has been to achieve uniform tube performance consisting of stable and equivalent mercury liquid-vapor interfaces in each tube.

Conditioning: The boiler, at present, is the most unpredictable component in the system. A boiler is subject to a phenomenon called "deconditioning." The symptoms of a deconditioned boiler are incomplete heat transfer, unusually low pressure drop, low vapor quality, pressure instability, and a large inventory of working fluid retained in the boiler. Deconditioning occurs in degrees varying from slight impairment of performance to the extreme case where the boiler outlet conditions are unacceptable for turbine operation.

The phenomenon causing deconditioned performance is inadequate and poorly distributed surface wetting. The wetting is generally a function of surface cleanliness and materials. Typically the performance of a deconditioned boiler improves with operating time. The scouring action of the flowing working fluid tends to bring about a wetted surface. SNAP-8 experience with boiler testing has involved boilers which conditioned immediately upon startup to boilers which, after several hundred hours, were still not fully conditioned. The time required to condition a boiler simply by operating it is basically unpredictable other than to say that the cleaner the boiler and associated loop, the sooner it will condition. SNAP-8 experience has demonstrated that, once conditioned, a boiler remains conditioned, provided no foreign material (oil, or other mercury-wetting inhibitor) enters the system.

Two methods have been used in SNAP-8 testing to achieve conditioned boiler operation. The foremost, and obvious, method has been to thoroughly clean the boiler. To this end, cleaning methods using repeated flushes of solvents and subsequent drying have been developed and have proven effective. A second method that has been used to achieve conditioning has been the use of additives in the mercury. About 1000 ppm of rubidium added to the mercury has resulted in instantaneous conditioning of the boiler. The conditioned state achieved using rubidium has persisted as long as no oxygen, or other material which could react with the rubidium, entered the loop. Figure 7 shows the instantaneous change in vapor quality resulting from a rubidium injection. Full superheat is achieved in about seven minutes following rubidium injection.

There are, however, potential problems involved with the use of rubidium. Rubidium could accumulate in the space seal area since the mercury would have a more rapid rate of evaporation through the seal and out to space than would the rubidium; eventually, the rubidium concentration might become high enough to form a solid amalgam in the space seal. Also, rubidium oxides might deposit on turbine blades and nozzles, thereby impairing system performance. Because of these potential problems, the use of additives is not being pursued as a conditioning method for SNAP-8. The emphasis is upon material selection and surface preparation.

Liquid Carryover: The many accumulated hours of system testing have provided much data pertinent to boiler-induced system phenomena. One of the primary effects the boiler has on the system is a phenomenon called "liquid carryover." Liquid carryover is minute drops of mercury carried along in the vapor stream in liquid form even though the vapor is superheated. Surface tension effects and inadequate opportunity for the drops to contact the heated boiler tube walls prohibit these liquid droplets from becoming vaporized.

Figure 8 shows test data on the quantity of liquid carryover that has been experienced. At design operation, conditioned boilers show about 2-4% liquid carryover. A less-conditioned boiler has less effective heat transfer and a shorter length of boiler available for superheating and, consequently, has somewhat more carryover. Figure 9 shows the relationship found between liquid carryover and boiler conditioning. There does not appear to be a great change of carryover with changes in conditioning.

The effect of liquid carryover on the system is a change n turbine performance. The lower velocity of the liquid roplets results in a drag effect on the turbine wheels. o data have been generated in SNAP-8 testing to define ie precise magnitude of the effect of carryover. However, xtrapolation from steam data in the literature indicates iat the SNAP-8 system might experience approximately .75 kw loss of output power for each 1.0% of liquid carryver. For design purposes, it is assumed that a 4% quid carryover will always prevail. Future boiler designs re aimed at reducing the carryover content. Turbine rosion damage due to the liquid carryover has not been problem. Over 2000 hours of testing on a single turine, with estimated carryover quantities of 4%, have hown only minor, acceptable, erosion damage to the ucket leading edges.

Stability: Another boiler-induced system phenomenon s pressure fluctuations in the mercury loop. These luctuations are generated within the boiler and are ransmitted throughout the loop. The system sees the luctuations as a cyclic turbine inlet pressure, cyclic ondensing pressure, variable mercury vapor density, nd variable mercury flow rate. The phenomenon is aused by variable heat-transfer conditions within the oiler. Suspected factors within the boiler which lead o the instability are slug-flow boiling, nonuniform heat ransfer of one tube with respect to another, and NaK low stratification.

The boiler design objective is to restrict the pressure luctuation to less than ±2-3%. This objective has been accomplished as is illustrated by a typical pressure race shown in Figure 10. The pressure oscillations ave a maximum magnitude of ±1.6%. A typical frequency f the oscillations is 0.5 cps. The general trend is for he oscillations to be greater for a less-conditioned oiler. However, over a considerable range of conditioning, the test data have indicated that the fluctuations lo not increase appreciably. A boiler sufficiently deconditioned to have excessive (above ±5) fluctuations would already be unacceptable to the system on the grounds of ow vapor quality and, possibly, excessive turbine erosion rates. The pressure fluctuations do not represent hazard to system operation. By their very nature, the luctuations are self-damping: an increase in boiler ressure causes a reduction in flow which results in a ressure-reducing compensation.

The way in which the pressure fluctuations affect the system is in alternator output power. Alternator output power variations occur at the same frequency as the pressure and flow variations. Figure 11 shows a typical trace of alternator output power. The power variations amount to ±0.2% of the total power. The net electrical output of the system, however, does not reflect the power variations seen at the alternator since the SNAP-8 speed-control system absorbs any excess power not required as useful electrical output. Therefore, the useful electrical output remains at a constant level with power fluctuations being absorbed by the speed-control system. Figure 11 also includes a trace of net system electrical output showing the stable nature of the output power. The net power variations are indiscernible even though the alternator power variations are ±0.2%. The penalty imposed by the boiler pressure fluctuations is a reduction in the net output power by an amount equal to the magnitude of the alternator output power dips.

Mercury Inventory: Variations in mercury inventory is another phenomenon characteristic of the boiler. The amount of mercury contained within the boiler is a function of the liquid-vapor interface location. The interface location is a function of heat-transfer conditions and the boiler conditioning status. For a conditioned boiler, the normal mercury inventory is 20-30 lb. For deconditioned boilers, SNAP-8 experience has shown inventories as high as 75 lb. To determine the mercury inventory, the SNAP-8 boilers have been instrumented along the outer shell to record the NaK temperature gradients along the boiler length. Figure 12 shows two such temperature profiles: one for a conditioned boiler, and one for a deconditioned boiler. The beginning of the steep slope of each profile represents the location where boiling begins. The profile for the deconditioned boiler shows the boiling region to have a different location than for the conditioned boiler. Therefore, the two profiles indicate different lengths of boiler filled with liquid mercury. For the two profiles shown, the mercury inventories are approximately 25 lb and 45 lb.

The direct effect of a boiler inventory change is a change in condenser inventory. The subsequent indirect effect is a change in turbine backpressure and alternator output power. Figure 13 presents the relationship between boiler inventory and alternator output power showing that an increase or decrease in boiler inventory results in a corresponding increase or decrease in alternator output.

The specific effect shown in Figure 13 is generally not experienced if the boiler inventory change is the result of boiler conditioning or deconditioning. In this case, the change in boiler liquid carryover associated with the change in boiler conditioning has an approximately equal, and opposite, effect on alternator output. If the boiler inventory change is the result of phenomena other than a change in boiler conditioning, such as boiler erosion or a change in NaK conditions, then the effect defined by Figure 13 can be experienced.

Transient Operation: The above descriptions of boiler-system interactions are based upon steady-state operation. Boiler startup tests have illustrated another interesting boiler phenomenon. The SNAP-8 startup scheme calls for mercury injection into the boiler with the NaK-side of the boiler already at full temperature (1300°F). This naturally gives a potential for higher initial heat-transfer rates than would be experienced during steady-state operation. Therefore, there is the possibility of boiling, and high pressure drops, near the mercury inlet end of the boiler during a startup. This phenomenon has been

observed during some, but not all, startups. A typical plot of boiler pressure drop for a startup involving a pressure-drop surge is given in Figure 14. The boiler pressure drop temporarily reached a peak of about 130 psi and then settled back to a normal value near 35 psi. Other startups have had a smooth pressure-drop ramp with no peak. Presumably, the conditioning status of the boiler affects the extent of a pressure-drop surge.

The effect on the system of the pressure-drop surge is a surge in boiler mercury inlet pressure. The change in boiler inlet pressure changes the pressure drop across the liquid-mercury flow control valve so that the end result is a dip in liquid-mercury flow rate. However, the entire phenomenon is limited to the liquid side of the mercury loop. No effects occur at the boiler outlet and, consequently, the mercury-vapor flow rate and alternator power do not show any response to the pressure surges. The net effect is simply that the mercury liquid and vapor flow rates are temporarily unequal, but the effect is absorbed by a temporary variation in boiler mercury inventory.

Failures: Four types of boiler failure have occurred during testing. The most severe, and frequent, failure mode has been an internal leak between the mercury and NaK. This failure mode has occurred three times. The effect upon the system, besides the natural requirement to shutdown, can be very severe. As a leak develops, the first result is mercury crossing into the NaK loop. Upon shutdown, however, the pressure gradient can easily reverse and allow NaK to enter the mercury loop. Therefore, the potential exists for forming solid amalgams in both the mercury loop and the NaK loop. Just such an occurrence resulted the first time an internal leak occurred in SNAP-8 testing. Solid amalgams formed in both loops and in the rotating components. It was necessary to perform extensive component and loop disassembly to clean the system of amalgams.

As a result of this boiler failure, monitoring methods were established to give early warnings of a leak. The functions selected for monitoring were condenser mercury inventory, NaK pump-motor current, and NaK flow rate. Any decline in condenser inventory represents a possible mercury-to-NaK leak, particularly if there are no indications of an external mercury leak somewhere in the loop, or if there are no indications that the boiler inventory requirement has changed (such as from deconditioning). Confirmation of a suspected NaK leak is obtained by observing the NaK pump-motor current and the indicated NaK flow rate. Both of these functions are sensitive to a fluid density change such as occurs when mercury is in the NaK. By using these monitoring methods it was possible to more readily detect when internal boiler leaks had occurred on two subsequent occasions. The leaks on these latter occasions were detected in time to require only loop cleaning rather than extensive loop and component disassembly.

A second type of boiler failure is an external NaK leak. This type of leak has occurred at the NaK outlet connection, in an area suspected to be subject to high stresses during the startup transient. Tests are being conducted to study the temperature gradients and stress levels in this area.

A third type of failure mode has been mercury corrosion and/or erosion at the mercury inlet end of the boiler. The first few feet of the mercury containment tubes contain plug inserts to increase the liquid-mercury velocity. To achieve a centrifugal action for enhanced heat transfer, each plug was wound with a wire spiral. These wire spirals were subject to heavy corrosion and/or erosion. This undesirable effect was corrected by changing the materials and by machining threads or grooves into the plug rather than winding it with wire.

A fourth failure mode occurred in a boiler which had special plug inserts wound with very tight-pitch wire spirals. The intent was higher liquid mercury velocities with resultant improved boiling characteristics. The effect was that the boiling in this particular region of the boiler was too good. The mercury prematurely boiled in this tight-pitch region with the result that the pressure drop which developed was so high that only about 15% of normal flow could be forced through the boiler. The problem was easily remedied by changing the plug inserts to inserts with increased-pitch wires.

Turbine-Alternator Assembly

The turbine-alternator[3] assembly consists of two subassemblies: a turbine assembly and an alternator assembly. The unit is shown in Figure 15. The turbine is a four-stage, axial impulse machine. The first and second stages are partial admission, the third and fourth are full admission. The alternator is a hermetically sealed radial-air-gap, homopolar inductor with a brushless solid rotor. The electrical output is 3-phase, 120/208 volt, at 400 Hz. Separate ball bearing assemblies are used for the turbine and alternator. The turbine is cantilever-mounted and the alternator is straddle-mounted. The unit operates at 12,000 rpm. The turbine operating condition is a mercury vapor flow of 11,[illegible] lb/hr at 1250 F and 250 psia. The turbine exhaust pressure is 11.0 psia. At these conditions the gross electrical output is about [illegible] kw for a net useful system output of 35 kw. Testing experience has included 8 units for a total accrued time of [illegible] hours.

The turbine-alternator assembly is the heart of the SNAP-8 power conversion system. Every perturbation imposed upon the assembly directly affects the useful electrical output of the overall system. Consequently, the design, operational mode, and system interactions involving the turbine-alternator assembly performance are of paramount importance. Testing experience with the turbine-alternator assembly has demonstrated areas of significant component-system interactions.

Turbine Efficiency: The turbine has an aerothermodynamic efficiency of about [illegible]% when operated at design conditions. Any deviation from design conditions causes an efficiency decrease and resultant decrease in useful system output. On two occasions during turbine operation, internal turbine changes occurred that affected the system output. The first occurrence consisted of a cocking of the first-stage nozzle block which increased the effective nozzle area by about 13%. A cracked second-stage diaphragm, with associated increased leakage paths, was also found. The overall effect was a decrease in efficiency and system output. The majority of the internal change appears to have happened over a period of one hour. Figure 16 shows the changes, during a several-hour time span, in turbine inlet pressure (which is inversely proportional to nozzle area), alternator electrical output, and turbine efficiency. For a few minutes there was an actual improvement in performance due to the initial nozzle-block shifting. The output power and turbine efficiency rose about 10%. Apparently, a more optimum nozzle effective area was temporarily achieved. However, the net effect after the nozzle block had settled into its final position was a decrease of about 10% in alternator output and turbine efficiency.

To correct this, the first-stage nozzle block retention mechanism was redesigned and the second-stage diaphragm material was changed.

A second experience with internal turbine changes was the result of mass-transfer buildups within the turbine. This phenomenon is apparently a function of system materials and boiler operation at low vapor quality. During an extended period of boiler operation at low qualities, a reduction of about 25% in first-stage nozzle area occurred. Reduction of nozzle areas in the other three stages also occurred, but to a lesser degree. As the boiler performance improved, the areas gradually increased. The second, third, and fourth stages regained most of the area they had lost, but the first stage returned to only 85-90% of its original value.

The change with time of the first-stage nozzle effective area and mercury vapor quality are shown in Figure 17. At nominal operating conditions, the area change shown would result in a turbine-efficiency dip of 3-4 percentage points and a system output power dip of 4-5 kw. The remedial action is to maintain the boiler at higher outlet vapor qualities during periods of conditioning.

Space Seals: Within the turbine-alternator assembly, there are two different fluids. Mercury is the turbine working fluid, and a polyphenyl ether is used as a bearing lubricant. It is important to prevent intermixing of these two fluids.

To provide a barrier against intermixing, the assembly has a space seal(1,6). The space seal operates on the principle of dynamically holding the two fluids apart, and then venting to space those portions of the fluids which evaporate and thereby succeed in crossing the dynamic barrier. Space simulation is accomplished in the breadboard system testing with vacuum pumping. Some loss of mercury and lubricant-coolant is expected, and allowed for, in the system design. A general design objective has been to restrict the loss per 10,000 hours to about 10 lb of mercury and one pound of lubricant-coolant. With regard to restricting the interdiffusion of fluids, the objective has been to limit the interdiffusion to about 1-2% of the total leakage. The evaluation of the space seal has been one of the important accomplishments during SNAP-8 testing.

The effect on the system of space-seal leakage is shown in Figure 18. The effect is actually one of improved performance. A loss of mercury decreases the condenser inventory, which increases the condensing area and decreases the turbine backpressure. Therefore, the system electrical output is increased as a result of the inventory loss. However, this would only be true up to the point where the condenser is empty. Beyond this point, there is the danger of mercury-pump cavitation. Certainly, it is more desirable to minimize inventory loss so as to not approach the critical point of complete condenser inventory depletion. Lubricant-coolant loss has no effect on system performance unless, here again, the inventory is depleted to the point of causing lubricant-coolant pump cavitation.

System testing to date has not been designed to accurately measure the long-term space-seal leakage and interdiffusion. Such measurements in other test facilities have, however, demonstrated that space-seal leakage and interdiffusion rates are within the design objectives. The contribution of the system testing to space-seal evaluation has been, rather, in the realm of system startup and shutdown leakage evaluation. Since the space seal depends on dynamic action to cause sealing, the startup and shutdown conditions require special static seals to restrict leakage. During a startup, rubbing-contact face seals are kept in contact until a minimum speed has been reached. When the minimum speed has been reached, the seals are pneumatically lifted. System testing has demonstrated that the startup and shutdown leakages can be effectively restricted. On isolated occasions, when the start seals were not properly engaged, startup and shutdown leakages have been observed. But with properly functioning start seals, no visible leakage of mercury or lubricant-coolant has been detected. Design work is continuing on the start seals to improve their actuation methods.

Provisions have been made in the breadboard system testing to handle any gross contamination of the mercury by the oil. The liquid mercury passes through a gravity oil separator which has been effective in separating any oil inadvertently allowed into the mercury loop. On some shutdowns, oil has been found in the separator, apparently the result of improper start-seal actuation or sealing. The oil separator has been a valuable system addition by eliminating at least gross oil entrance into the boiler which could result in boiler deconditioning.

Failures: Three turbine-alternator assemblies have failed for one reason or another during the breadboard system testing. One failure involved the disintegration of the first-stage wheel. The other two failures were much less severe, consisting of visco-seal seizures in the alternator.

The disintegration of the first-stage wheel is a good example of the possible severity of component-system interactions. The failure was the indirect result of a NaK-loop pump failure. The system was operating normally when an open circuit on the primary NaK loop pump-motor caused a loss of NaK flow to the boiler. The loss of NaK flow very rapidly resulted in a loss of mercury superheat followed by a decreasing mercury vapor quality. The decrease in mercury vapor flow reduced the boiler outlet mercury pressure which, in turn, lowered the mercury temperature since the mercury vapor was saturated. The overall effect on the turbine was a very rapid change of inlet mercury temperature. A maximum gradient of about 800°F per minute was recorded. It is considered likely that the temperature gradient and liquid slugs in the saturated vapor precipitated the failure. The system has since had a safety feature added to avoid a reoccurrence of this type of shutdown. An automatic transfer mechanism now starts an auxiliary electromagnetic pump in the event of a loss of primary NaK flow. In the W-1 facility, loss of the primary loop flow automatically shuts down the mercury loop.

The alternator visco-seal seizures were both the result of alternator overspeeds. The first overspeed resulted when the mercury flow rate was changed to reduce the system operating power level. The external load on the alternator was accidentally left too high and the alternator was unable to supply both its external load and the speed-control power requirements. The excess load on the alternator pulled the voltage down and an undervoltage safety mechanism (to protect the alternator against a short circuit) removed the external alternator load. The turbine-alternator assembly then went into a runaway acceleration to about 17,000 rpm and an alternator visco-seal seized. The system operational mode was subsequently changed so that an undervoltage condition stops mercury flow and then removes alternator load several seconds later. This remedial action eliminated the possibility of a reoccurrence of the overspeed.

The second alternator overspeed and seizure occurred during off-design performance tests. The particular test in progress required operating the turbine-alternator assembly at 13,500 rpm as opposed to the normal 12,000 rpm. To operate off-speed, all alternator output, including power normally used for pumps and speed control, was being delivered to an external load bank. The resultant load on the bank was 60 kw as opposed to the usual 35 kw. The excess load tripped the load bank thermal-overload protective switch and disconnected the entire alternator load. The result was an overspeed to about 10,000 rpm and a visco-seal seizure. The corrective action consisted of changing the thermal switch to give a warning signal rather than disconnecting the load.

Condenser

The SNAP-8 condenser consists of 73 parallel tapered tubes enclosed in a shell(6,7). The mercury condensation occurs in the tubes and the heat-rejection-loop NaK flows in the outer shell. The taper of the tubes provides a decreasing vapor-flow area so that vapor velocity is maintained even though the mass flow of vapor is decreasing. This feature provides a stable liquid-vapor-interface location under conditions of zero-gravity operation. The condenser is shown in Figure 19.

The purposes of the condenser are to condense the mercury vapor, to subcool the liquid to provide adequate NPSH for the liquid mercury pump, and to provide the proper backpressure for the turbine. At the nominal operating condition, the condenser operates at a mercury vapor inlet temperature of 670°F (14.0 psia). The mercury condenses at 670°F and then is subcooled to about 462°F. The NaK side of the condenser operates with an inlet temperature of 169°F. A typical liquid mercury inventory in the condenser is 45 lb which occupies about 22 inches of the total tube length of 70 inches. Experience with testing has included the testing of 3 units for a total operating time of 7690 hours.

By virtue of its function of establishing the turbine backpressure, the condenser can have a considerable effect on system overall performance. System testing has demonstrated two main areas of important component-system interactions.

Noncondensibles: The condenser provides a natural barrier to the passage of any gas that cannot be condensed at the temperature and pressure of the condenser. The velocity of the condensed liquid leaving the condenser is not sufficient to move a gas bubble against the floating action of 1g operation. During zero-g operation, the gas could move on through the condenser. Consequently, during ground testing, any noncondensible gas in the system is trapped in the condenser. The mercury-vapor velocity entering the condenser is sufficiently high that it is thought that the noncondensibles occupy a volume adjacent to the liquid-vapor interface. The size of this volume is dependent upon the amount of noncondensibles. The effect then, is that the condenser has a decreased area available for heat transfer. The effect on the system is the same as if the condenser had shorter tubes. Consequently, noncondensibles result in an increase in turbine backpressure and a decrease in system electrical output.

The effect of noncondensibles on system performance is shown in Figure 20 where system electrical output is shown as a function of the magnitude of noncondensibles. Because of the considerable effect of noncondensibles on system performance, it is important to restrict their entrance into the system.

Two basic sources of noncondensibles exist. The first source is incomplete outgassing and loop evacuation prior to startup. This problem has been handled in SNAP-8 testing by establishing minimum acceptable vacuum-retention requirements prior to startup. Prior to a startup, the vacuum system is valved off and the vacuum decay rate is monitored. The acceptable decay rate is established at a minimum that assures no potential noncondensible problems. Loop outgassing is assisted by pumping on the system with the boiler heated to full operating temperature by the primary NaK loop. The second source of noncondensibles is in-leakage following startup. With the exception of the area from the turbine exhaust to the condenser, the mercury loop always operates above atmospheric pressure. Therefore, there is ordinarily only a limited portion of the loop where a leak could permit gas entry. However, turbine interstage pressure instrumentation has provided an additional region where a leak could result in gas in-leakage. The interstage pressure instrumentation lines pass through an internal turbine cavity which is vented to the turbine exhaust. On several occasions in the test program, leakage has occurred at the location where these instrumentation lines pass through the internal turbine cavity. The result was a significant ingestion of noncondensibles (air). This source of noncondensibles has now been eliminated by changing from brazed to welded instrumentation connections.

The question naturally arises concerning removal of noncondensibles during testing. This has not been attempted to date in the test program. One problem is the question of how to accomplish the removal. To vent the condenser inlet would probably be ineffective. If the postulate holds that the noncondensibles are located inside the mercury tubes, then venting the condenser would only remove mercury vapor. It appears likely that the noncondensibles are indeed inside the tubes, because during one test period when the noncondensibles were so extensive that they had doubled the condensing pressure, readings of pressure and temperature at the condenser inlet were still on the mercury vapor saturation line. Assuming, then, that the noncondensibles are located within the tubes, removal of the noncondensibles from the top of the condenser would require raising the liquid-vapor interface to push the noncondensibles out the top. To remove all the noncondensibles by such a procedure would be impractical since the turbine backpressure would simultaneously rise, probably to unacceptable levels. Possibly the opposite approach, of removing the noncondensibles from the bottom of the condenser, could be used. This latter method would require lowering the liquid-vapor interface out of the condenser. Provided that the mercury-pump NPSH was maintained, this approach might prove acceptable. No plans are presently in effect to attempt to vent the condenser. Except for the problem of turbine instrumentation tap leaks, which is correctable, there appears to be no problem of noncondensible buildup, even over long operating periods.

Stability: The condensing pressure (turbine backpressure) fluctuates in a manner similar to the boiler outlet pressure. These pressure fluctuations at the condenser affect alternator output power just as do boiler outlet (turbine inlet) fluctuations. Therefore, an important consideration is whether the condenser pressure fluctuations are self-generated due to the condensing process or are simply reflections of the boiler outlet pressure fluctuations. If the pressure-rises at the turbine inlet and outlet coincide, the torque developed by the turbine would not vary as greatly as it would if the pressure fluctuations were 180° out of phase so that a peak at the turbine inlet matched a dip at the turbine outlet, and vice versa. Thus, the ultimate power delivered by the system is a function of the source and phase relationship of the condensing pressure fluctuations.

Test data have provided the answer to the question on the relationship between the condenser and the boiler pressure variations. Figure 21 shows traces of boiler outlet pressure and condensing pressure. The variations are exactly in-phase and are of the same frequency. Therefore, it is concluded that the system output power variations are as small as possible for the turbine inlet and outlet pressure variations that exist. There are no out-of-phase relationships to further reduce the net system output.

Electrical Controls

The function of the electrical-control system is to maintain the turbine-alternator assembly speed constant at 12,000 rpm within ±2% while delivering any required vehicle load (system net output) between 0 and 35 kwe, and to control the vehicle load voltage to 120/208 volts within ±5%. An additional requirement of the electrical controls is to program the sequence of events during the period of system startup. This startup phase of operation is not included here since system startup tests have not yet been conducted; however, system startup tests are planned for the near future, and component testing has indicated that the start system should operate successfully.

The electrical controls consist of two basic units: a voltage regulating unit and a speed control unit. The voltage regulating unit is of the solid-state magnetic type. The unit senses volts/frequency and adjusts voltage to maintain a constant ratio of volts to frequency. The speed control unit operates by sensing frequency and changing alternator load to correct any change in frequency. A parasitic load is used by the speed control unit to change the alternator load. The parasitic load consists of a set of resistors located in the heat-rejection loop. A total of 7505 hours of testing has been accumulated on the electrical controls.

The interactions between the electrical controls and the system fall into two main categories: the control required because of normal system perturbations and the control required because of sudden changes in vehicle load. Each of these phenomena has been evaluated during system testing.

Normal System Perturbations: Normal system perturbations comprise the fluctuations in flow and pressure caused by the boiler. These fluctuations result in variable torque development in the turbine. The requirement of the electrical controls is to vary the load to the parasitic load resistor in a manner that compensates for the variable alternator output. Consequently, the parasitic load is variable, thereby providing a constant vehicle voltage. Test experience has included operation with boilers with performance varying from a relatively stable, conditioned state to operation at a deconditioned state giving rise to alternator output power variations of ±8%. Under all conditions, the testing has demonstrated that the electrical controls can and do maintain speed and voltage within the design requirements.

Sudden Change of Vehicle Load: The most extreme operating condition of the electrical controls is during a sudden application or removal of full vehicle load. This operating condition requires a sudden transfer of 35 kw either from, or to, the parasitic load resistor. A load transfer of this magnitude inevitably causes a perturbation in alternator speed and voltage. The objective, which was successfully met, was to make the transfer with a frequency transient of no more than ±20 Hz and with a damping time of not more than five oscillations. Figure 22 shows a trace of frequency and voltage during a typical application and removal of a 35 kw vehicle load. The perturbation magnitude and damping time are approximately equal to the design objective.

Pump-Motor Assemblies

A pump-motor assembly is used in each of the four loops of SNAP-8. Since the pump working fluids are liquid, the magnitudes of component-system interactions are small by comparison with the interactions for the components discussed thus far. For the pump-motor assemblies, the experience has been more one of observing the effects on the components of factors such as system cleanliness and operational methods. The pump-motor assemblies for the mercury and NaK loops are discussed individually below. The lubricant-coolant pump-motor assembly has been virtually trouble-free and is not discussed.

Mercury Pump-Motor Assembly: The mercury pump-motor assembly[6] is shown in Figure 23. The unit is hermetically sealed and comprises a centrifugal pump, dynamic seals, induction motor, and angular-contact ball bearings. A jet booster pump is integral with the unit to suppress cavitation during the startup phase when the system-developed net positive suction head is low. Bearing lubrication and spacer-seal and motor cooling are provided by the polyphenyl ether lubricant-coolant fluid. The unit operates with 460°F mercury and 210°F lubricant-coolant fluid. Testing on 10 units has occurred for a total of 11,150 operating hours.

The primary component-system interaction observed has been associated with the spacer seal. Functionally, the mercury pump-motor assembly spacer seal is the same as in the turbine-alternator assembly. With respect to leakage and interdiffusion, the discussion of the turbine-alternator assembly spacer seal applies here also. In addition, two specific [illegible] phenomena unique to the mercury pump-motor assembly have been [illegible] during testing. On one occasion, the lubricant-coolant pressure at the discharge of the pump-motor assembly was set too high. As a result, the dynamic slingers were unable to scavenge the bearing [illegible] lubricant-coolant [illegible] over [illegible] into the motor cavity.

The effect of flooding the motor cavity is an increase in motor power of as much as 1 kw, depending on the degree of flooding. The increase in motor power must be supplied by a decrease in vehicle load unless the parasitic load has excess power available. The problem was corrected by operating with normal lubricant-coolant discharge pressures so that bearing scavenging is effective.

The second incident involving the spacer seal was a burned-out motor caused by mercury in the motor. Disassembly disclosed mercury droplets coating the windings and other interior surfaces. Considerable corrosion damage had also occurred. Possibly the spacer seals had worn out during a previous period when they were engaged during operation. With worn spacer seals, mercury could cross into the oil-side of the pump-motor assembly during system startup or shutdown.

NaK Pump-Motor Assembly: The NaK pump-motor assembly[9] is shown in Figure 24. Identical units are used in both the primary and the heat-rejection loops. The pump-motor assembly is hermetically sealed, incorporating a centrifugal pump, hermetically sealed motor, an internal NaK lubricant-coolant recirculation pump, and NaK-lubricated bearings. Integral with the assembly is an external recirculation loop containing a cold-trap system, heat exchangers, and a filter. No seals or dynamic seals are used in the assembly. Isolation of the main loop NaK and the recirculation loop NaK is accomplished by a close-clearance annulus around the shaft between the pump and the motor. The recirculation loop NaK cools the motor and supplies the bearings with clean NaK. Any oxide migrating through the annulus from the main loop, where the oxide level may be unacceptable for the bearings, is trapped by the recirculation loop cold trap. The normal operating temperatures of the pumps are [illegible]°F for the primary loop pump and [illegible]°F for the heat-rejection loop pump. The motor temperatures are about [illegible]°F. Testing has included 16 units for a total of 29,230 hours.

Two primary component-system interactions have been experienced with the NaK pump-motor assemblies

The first type of interaction is the result of improper "bleeding" of the assembly. Before a pump-motor assembly is filled with NaK, the recirculation loop contains an inert gas. The recirculation loop must be carefully bled to remove all the gas to complete the loop fill. Incomplete bleeding has resulted in erratic recirculation loop flow rates and high motor temperatures. On one occasion, gas entrapment in the recirculation loop caused flow variations of ±2% in the main NaK loop. The gas in the recirculation loop had caused variations in recirculation loop flow which resulted in a heating and cooling cycle of the main pump-motor shaft. The temperature variation of the shaft caused a variation of impeller-to-housing clearance which changed the pumping characteristics of the pump. The bleed problem is avoided by adequately bleeding the assembly initially. In the event of an incomplete bleed, experience has shown that stopping and starting the pump several times sufficiently clears the loop of gas.

A second basic component-system interaction has been the result of mass transfer and NaK oxide deposits within the pump. Under normal operating conditions, the loop oxide level is maintained below 30 ppm by a NaK purification system which cold-traps NaK oxides and mass-transfer products. However, on many occasions in the test program it was necessary to operate for periods without the NaK pump-motor assemblies. During these periods, electromagnetic pumps were used and the pump-motor assemblies were bypassed. When bypassed and sitting idle, the pumps were cold relative to the loop. Consequently, the pumps tended to collect oxides and mass transfer products. These deposits were the cause, at least once, of a pump completely freezing so that it could not be started normally. The pump was finally started by rotating alternately forwards and backwards.

FUTURE TESTING

The SNAP-8 Test Program to date has primarily been involved in steady-state testing with the basic objective of defining component performance and component-system interactions. The program has been successful. More than 100,000 component-hours of testing were accrued by the end of 1967, and the interrelationships between components and the system have been well defined. As has been discussed, the perturbations and other phenomena characteristic of SNAP-8 have been identified and the system has been shown to be stable.

Future testing will apply more emphasis to the areas of long-term reliability demonstrations and transient testing as it relates to system startup. The objective of SNAP-8 is to run continuously for 10,000 hours, and the testing goal is to demonstrate this 10,000-hour capability. Any component or system degradation which is life-related will be identified and corrective measures will be applied. The area of transient testing will be a significant contribution toward development of a flight-rated SNAP-8 system. Analytical work has provided the groundwork on which to base the startup procedure for the system. The prime consideration is to avoid adverse temperature gradients at the reactor during the transient performance of the power conversion system as the rotating components start and the system output is raised to full-power operation. Planned testing will include various startup modes to identify the most appropriate scheme consistent with a reliable power-conversion-system startup and acceptable reactor transients.

The breadboard approach to testing has been adequate during the steady-state testing of the program thus far. As the testing proceeds into transient performance, the deviations of a breadboard system from a flight configuration become more significant. Now, transport delays, heat losses, and the like, become important. Even here, though, the present breadboard configurations are expected to be amenable to valuable extrapolation. By applying the analytical work which has been performed regarding startup phenomena, it will be possible to obtain data that can be translated to define startup conditions for a flight system. It is anticipated that much valuable test data relative to endurance testing, reliability, and transient performance will be obtained in forthcoming tests using breadboard SNAP-8 systems.

REFERENCES

1. J.N. Hodgson, R.G. Oelmer, A.H. Kreeger, "SNAP-8 - A Technical Assessment", Report No. 3387, 13 August 1967.

2. A.H. Kreeger, J.N. Hodgson, and A.J. Sellers, "Development of the SNAP-8 Boiler", paper presented at AIAA First Rankine-Cycle Space Power Systems Specialist Conference, 26-28 October 1965.

3. M.G. Cherry and G. Otte, "Design and Development of a Turbine-Alternator Assembly for the SNAP-8 System", paper presented at AIAA First Rankine-Cycle Space Power Systems Specialist Conference, 26-28 October 1965.

4. R.L. Lessley and J.N. Hodgson, "Low-Leakage Dynamic Seal to Space", ASME Paper No. 65-GTP-14, 15 January 1965.

5. J.N. Hodgson, "Designing a Molecular Pump as a Seal-to-Space", ASME Paper No. 65-GTP-15, 15 January 1965.

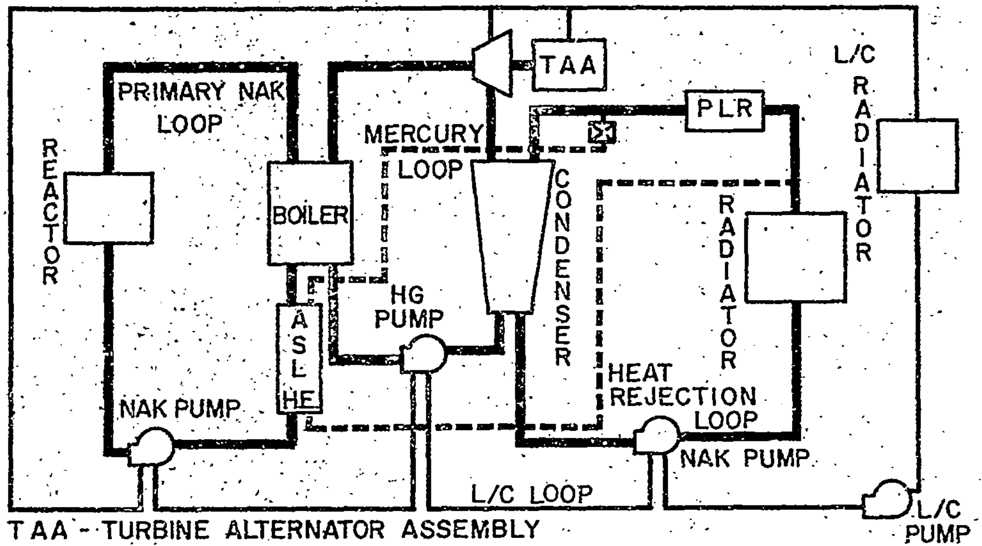
6. A.H. Kreeger, and J.N. Hodgson, "Design and Development of the SNAP-8 Multi-tube Condenser", AIAA Specialists Conference on Rankine Space Power, Volume I, 26-28 October 1965.

7. R.A. Lottig, R.W. Vernon, W.D. Kennes, "Experimental Heat Transfer Investigation of Non-wetting, Condensing Mercury Flow in Horizontal, Sodium-Potassium-Cooled Tubes", NASA TN D-3993, May 1967.

8. E.S. Chalpin, J.R. Pope, C.L. Foss, "Development of a SNAP-8 Pump for Mercury Service", paper presented at AIAA First Rankine-Cycle Space Power Systems Specialist Conference, 26-28 October 1965.

9. E.S. Chalpin, C.P. Colker, C.L. Foss, "Design and Development of Pumps for High-Temperature NaK Service", paper presented at AIAA First Rankine-Cycle Space Power Systems Specialist Conference, 26-28 October 1965.

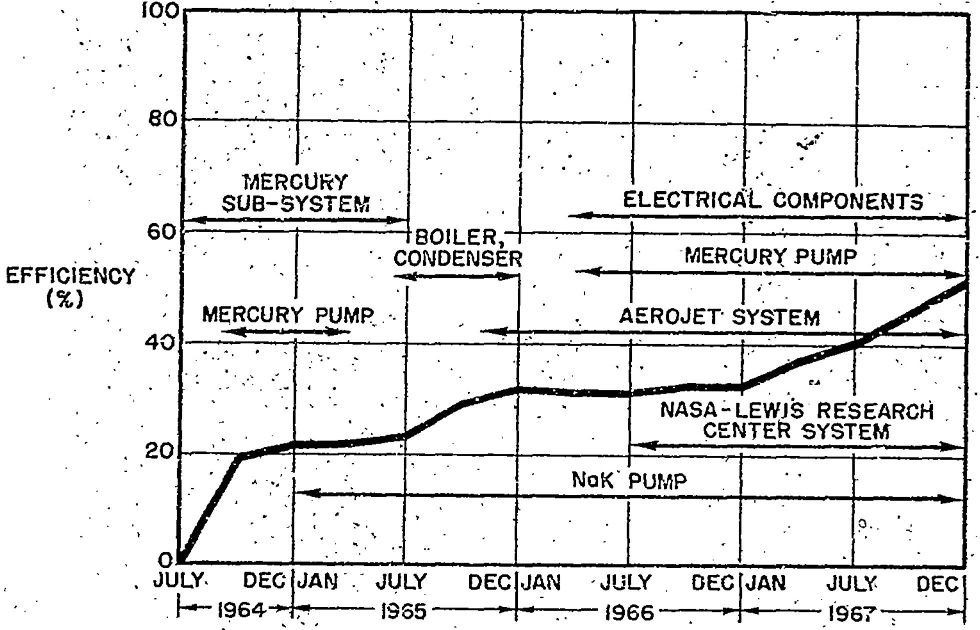
668-156



TAA - TURBINE ALTERNATOR ASSEMBLY
PLR - PARASITIC LOAD RESISTOR
ASL H.E. - AUXILIARY START LOOP HEAT EXCHANGER
L/C - LUBRICANT - COOLANT

FIG. I SNAP-8 SYSTEM SCHEMATIC

668-154



NOTE:
$*\text{EFFICIENCY} = \frac{\text{CUMULATIVE TEST TIME}}{\text{AVAILABLE TEST TIME}}$

TOTAL TEST TIME = 25,940 HOURS

FIG. 2. SNAP-8 COMPONENT & SYSTEM TEST FACILITY EFFICIENCY*

668-185

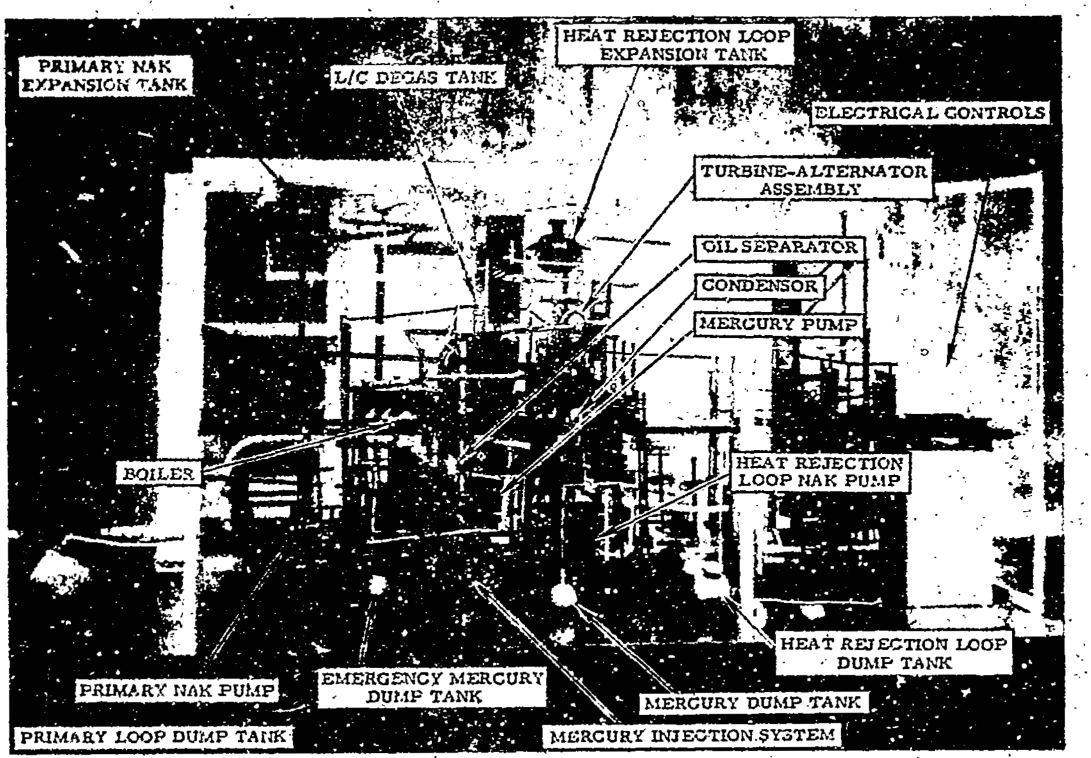


FIG. 3a. 1/4 SCALE MODEL OF SNAP-8 TEST CONFIGURATION (FRONT)

668-190

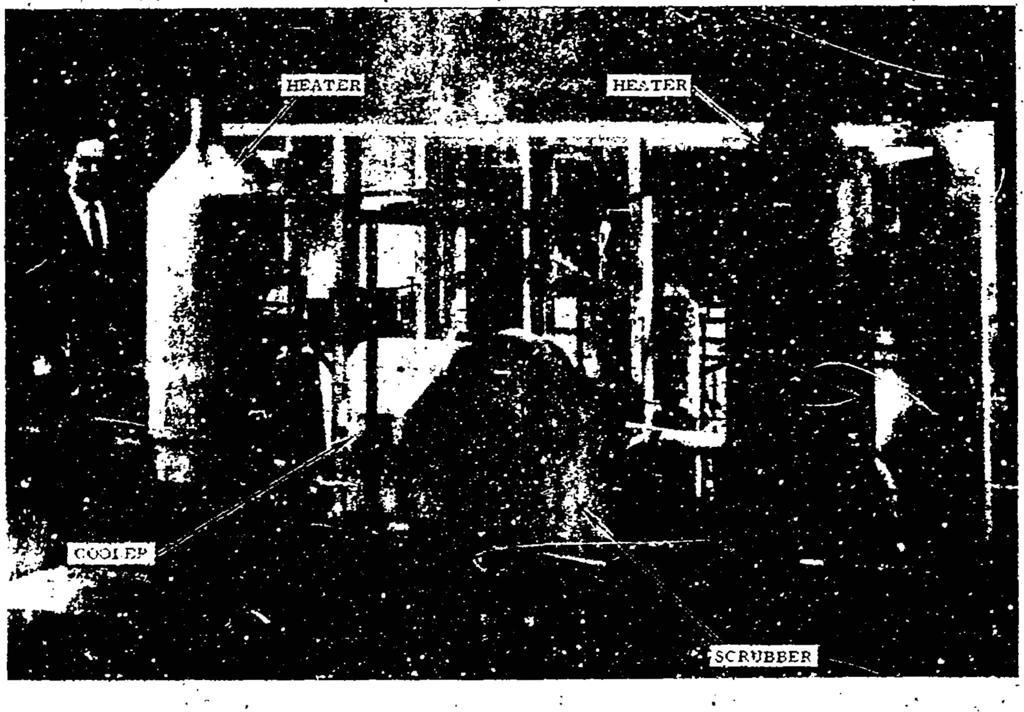


FIG. 3b. 1/4 SCALE MODEL OF SNAP-8 TEST CONFIGURATION (REAR)

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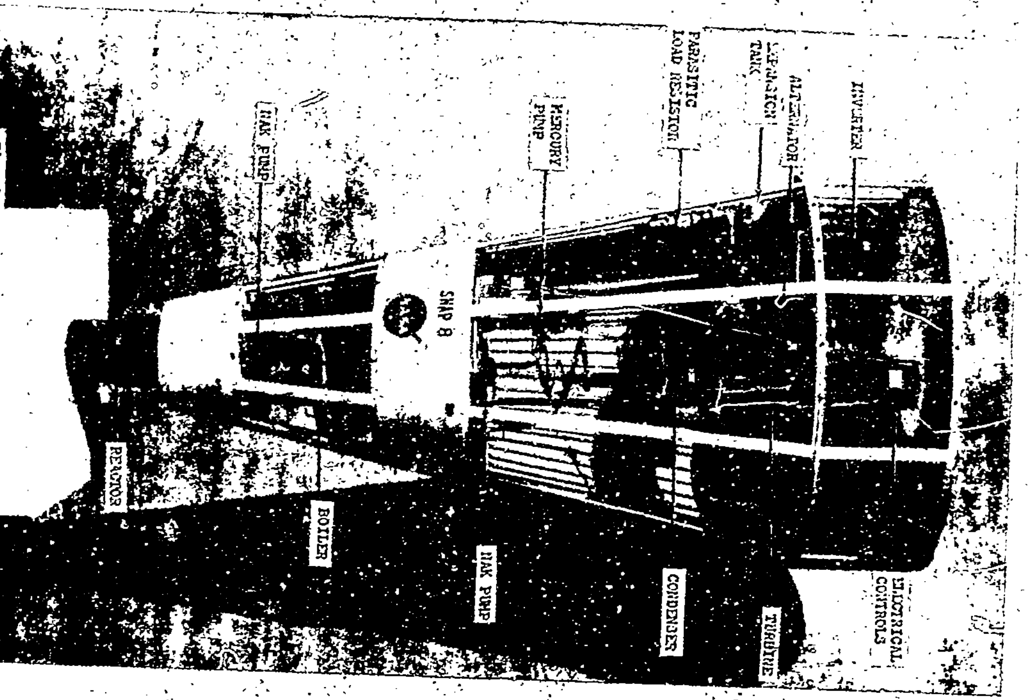

Fig. 4 Possible SNAP-8 Flight Configuration

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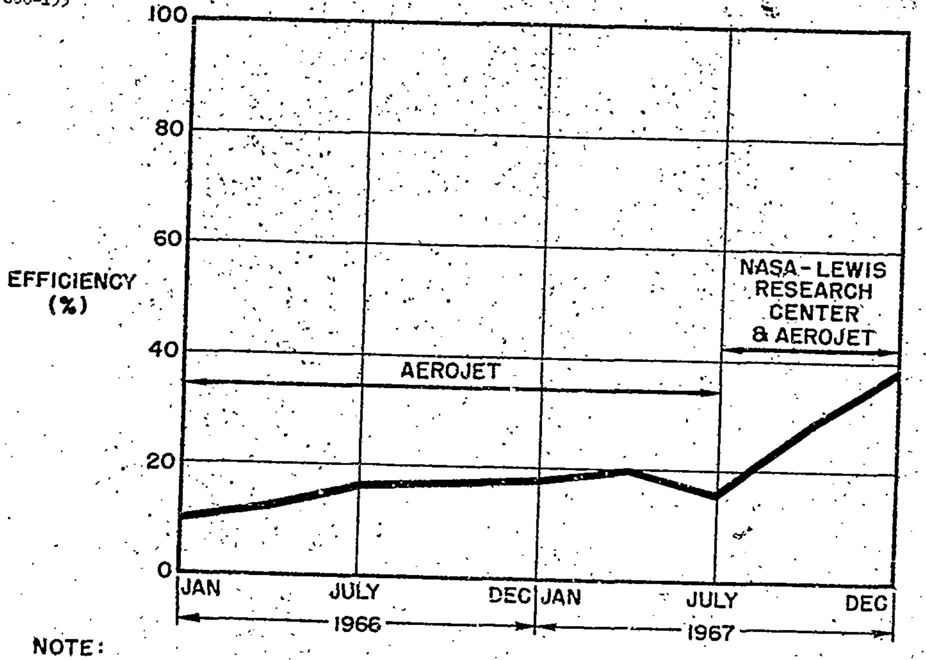


NOTE:
*EFFICIENCY = $\frac{\text{CUMULATIVE TEST TIME}}{\text{AVAILABLE TEST TIME}}$

FIG. 5 SNAP-8 POWER CONVERSION SYSTEMS OPERATION EFFICIENCY*

668-186

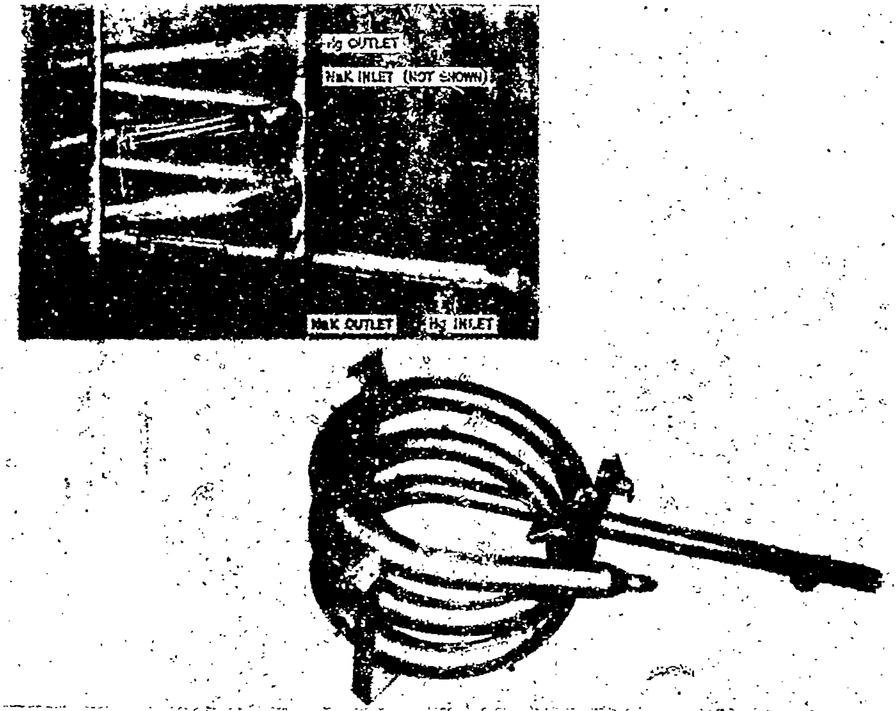


Fig. 6 Tube-in-Tube Boiler and Cutaway Showing Cross-Counter Flow

668-161

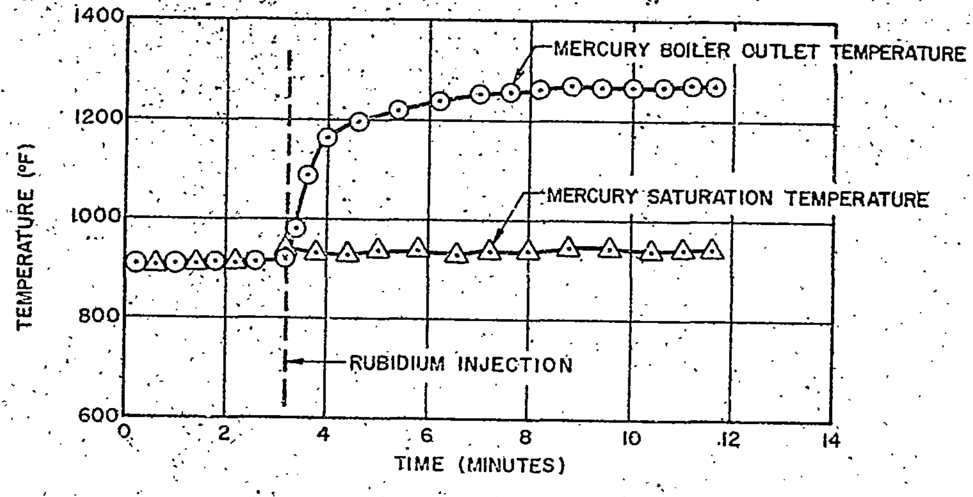


FIG. 7 EFFECT OF RUBIDIUM INJECTION ON BOILER CONDITIONING

668-162

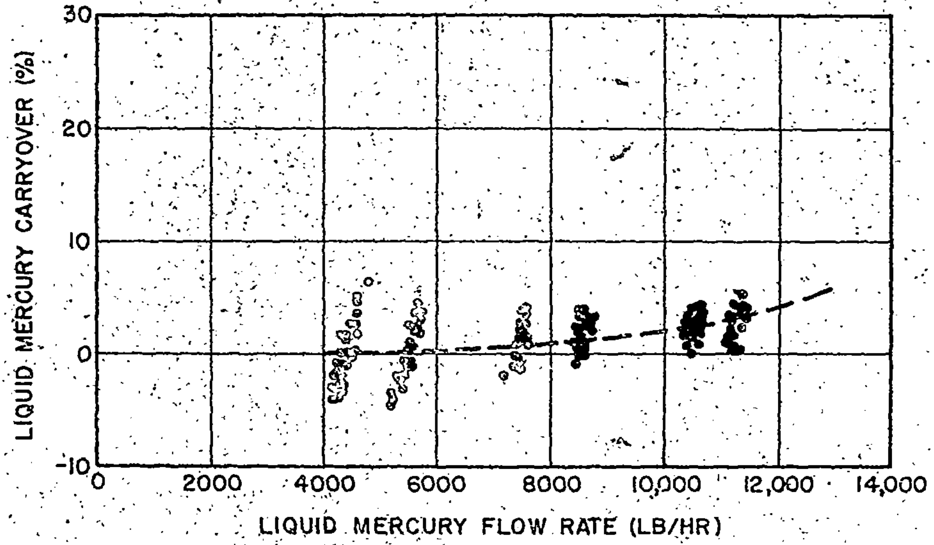
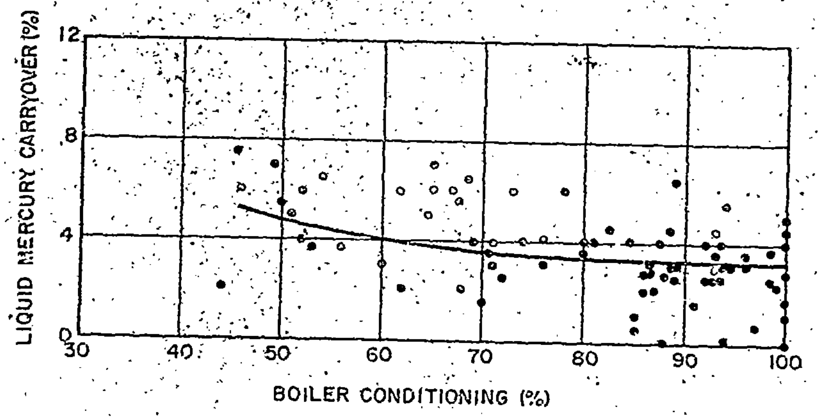


FIG. 8 LIQUID MERCURY CARRYOVER IN VAPOR STREAM

668-165



NOTE: PERCENT CONDITIONED IS ARBITRARILY DEFINED AS ZERO AT A TERMINAL TEMPERATURE DIFFERENCE OF 400°F AND 100% AT A TERMINAL TEMPERATURE DIFFERENCE OF 20°F

FIG. 9 EFFECT OF BOILER CONDITIONING ON LIQUID MERCURY CARRYOVER

668-164

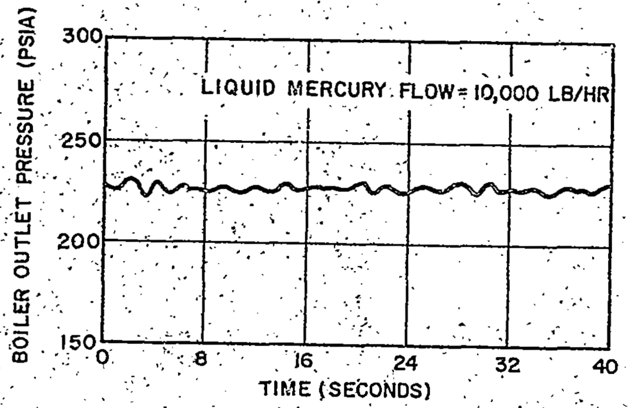


FIG. 10 BOILER OUTLET PRESSURE FLUCTUATIONS

668-170

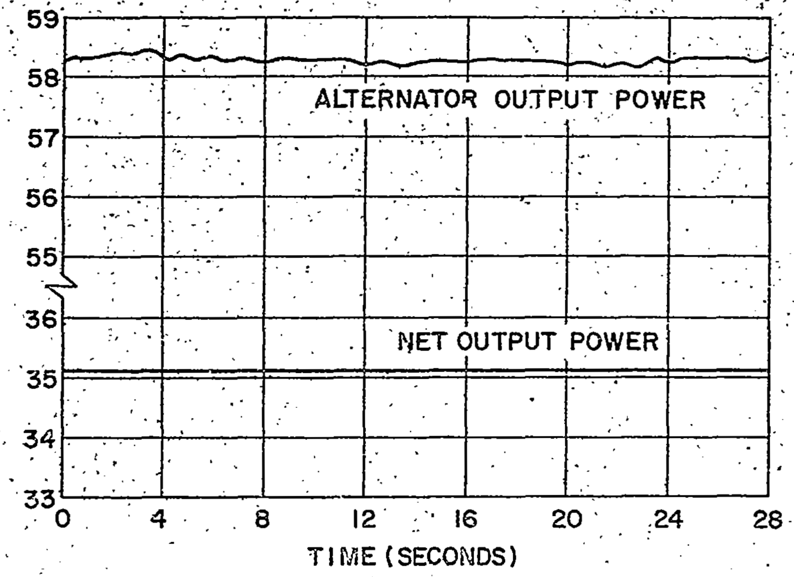


FIG. 11 SYSTEM NET OUTPUT STABILITY

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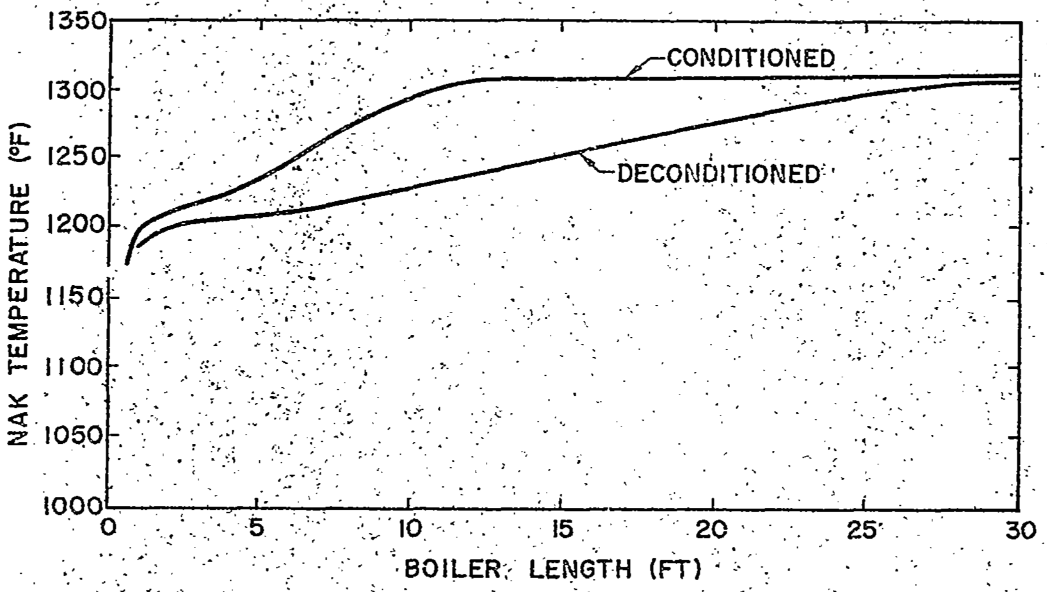

FIG. 12 BOILER TEMPERATURE PROFILES

668-160

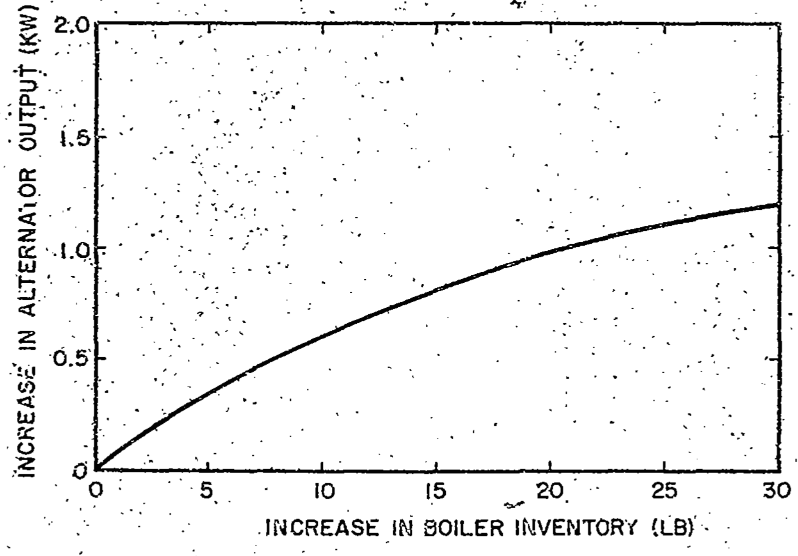

FIG. 13 EFFECT OF BOILER MERCURY INVENTORY ON ALTERNATOR OUTPUT

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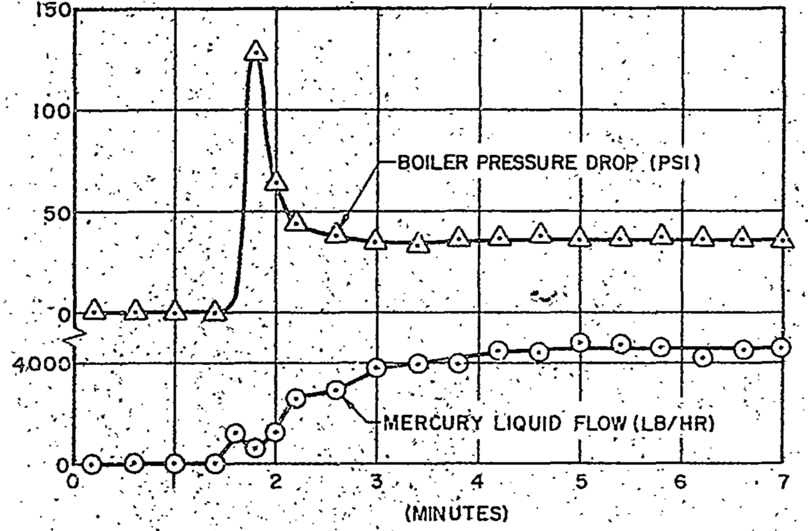

FIG. 14 BOILER PRESSURE SURGE DURING STARTUP

1065-500

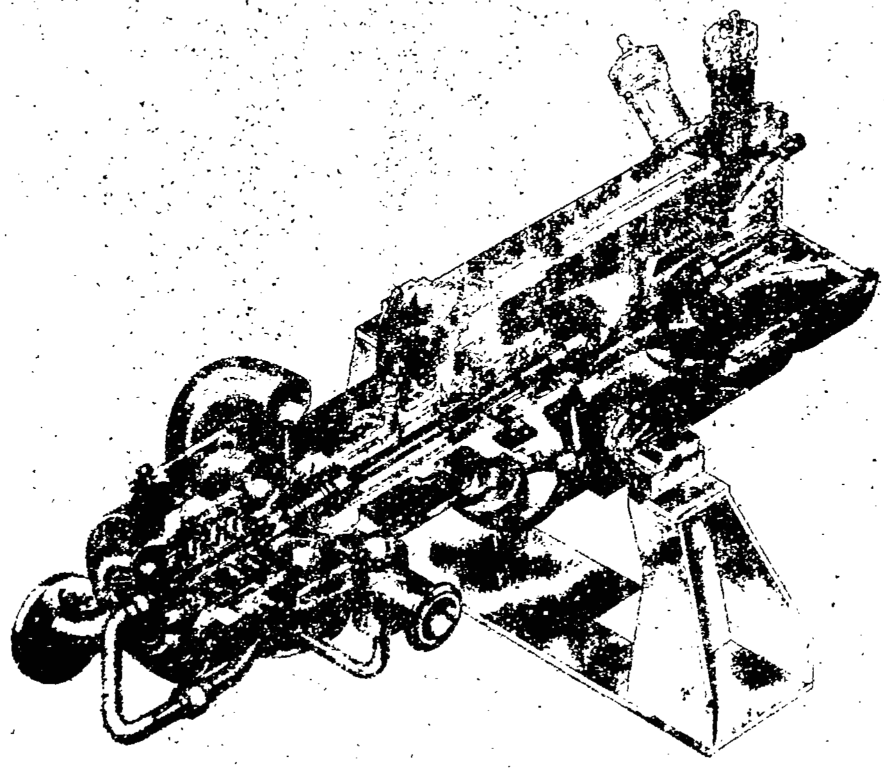

Fig. 15 SNAP-8 Turbine-Alternator Assembly

668-158

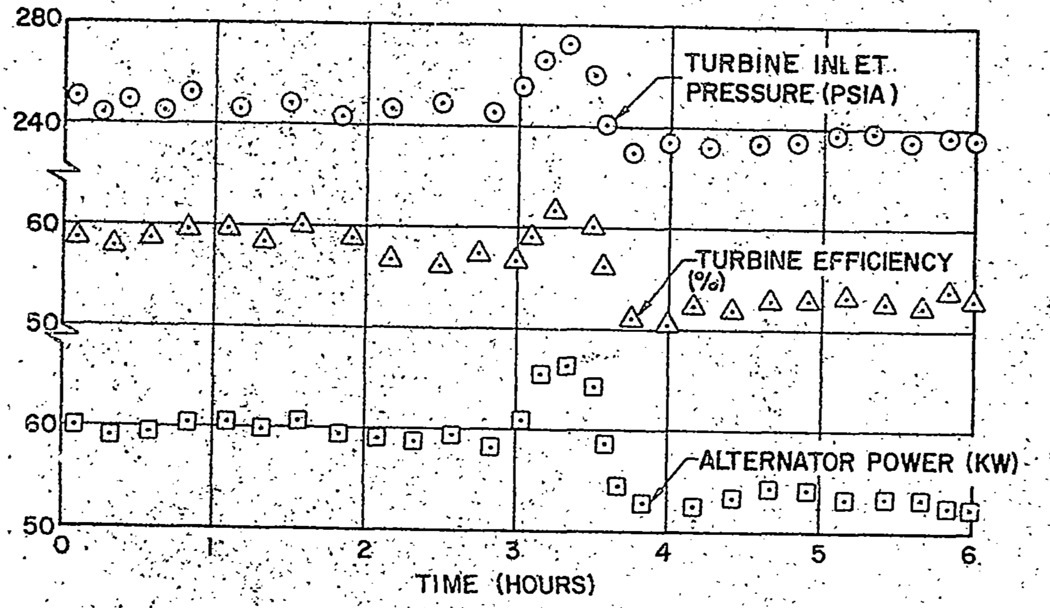

FIG. 16 EFFECT OF TURBINE NOZZLE BLOCK SHIFT

668-168

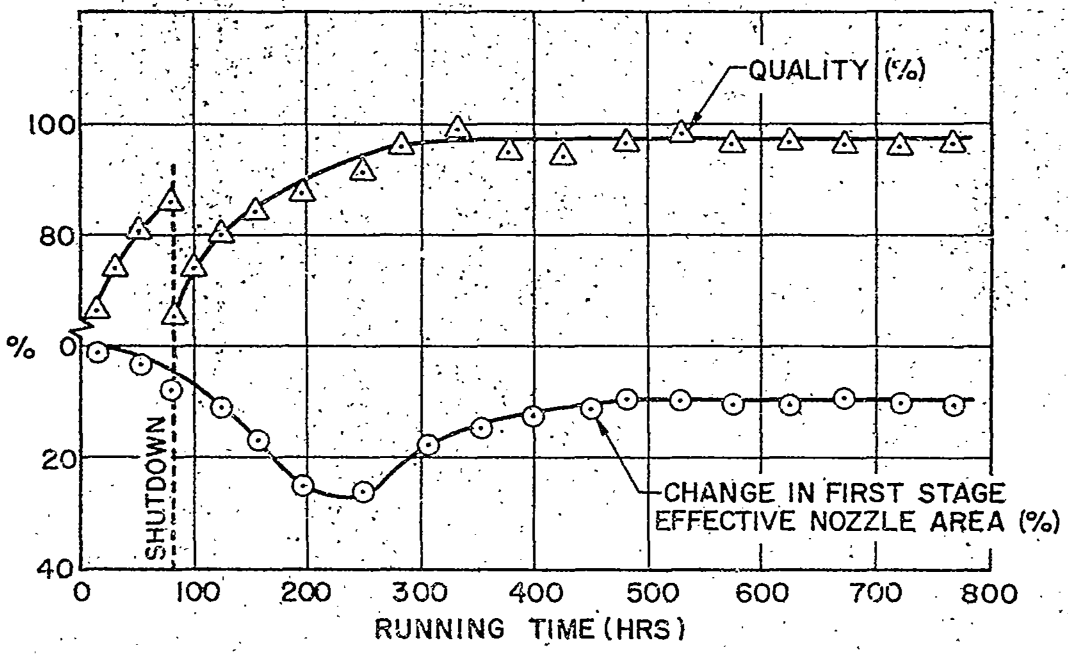

FIG. 17 EFFECT OF MASS-TRANSFER ON TURBINE FIRST STAGE EFFECTIVE NOZZLE AREA

668-159

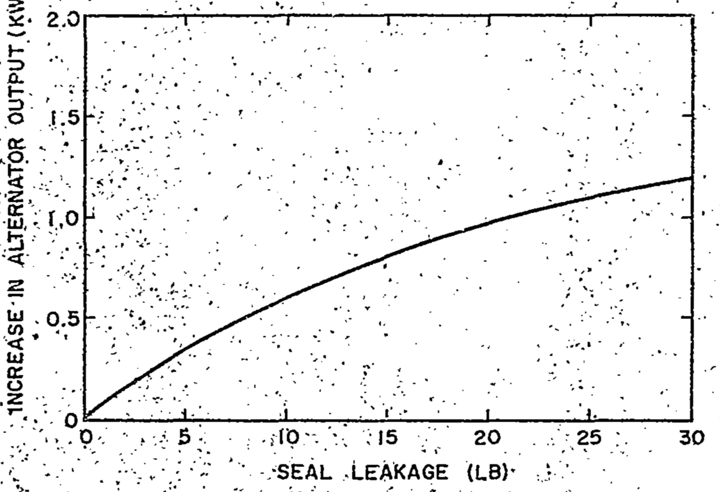

FIG. 18 EFFECT OF SPACE SEAL LEAKAGE ON ALTERNATOR OUTPUT

668-187

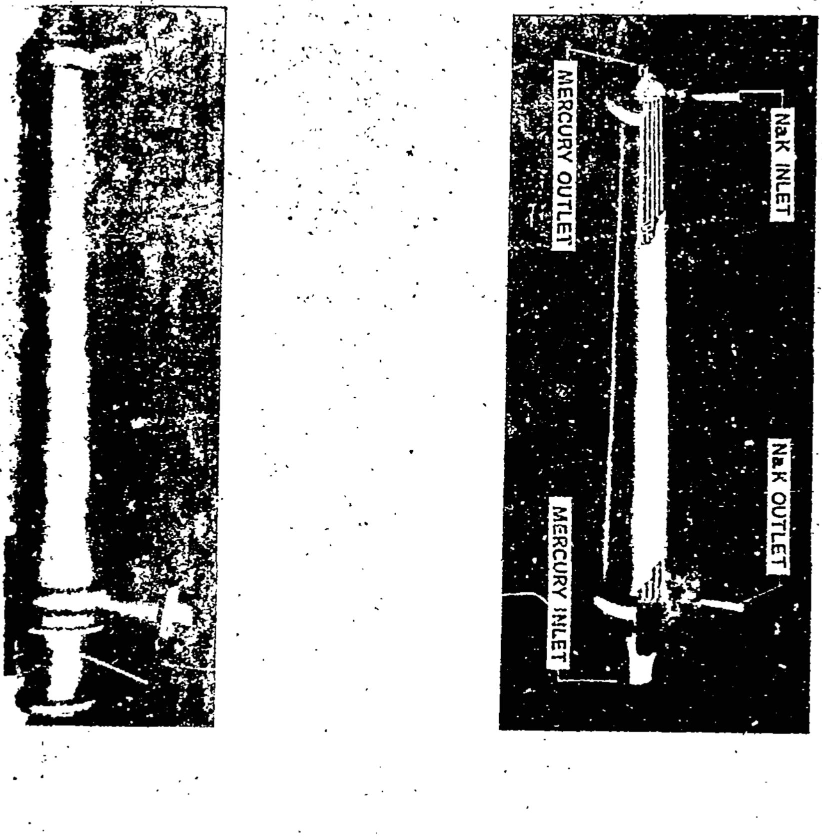

Fig. 19 SNAP-8 Condenser and Cutaway Drawing Showing Cross-Counter Flow

668-167

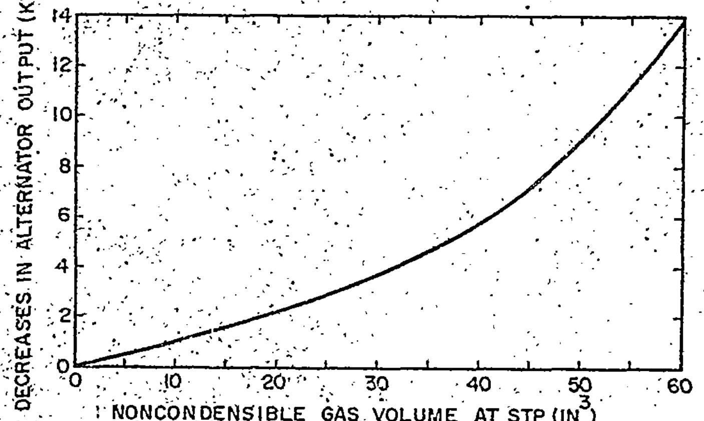

FIG. 20 EFFECT OF NONCONDENSIBLES ON ALTERNATOR OUTPUT

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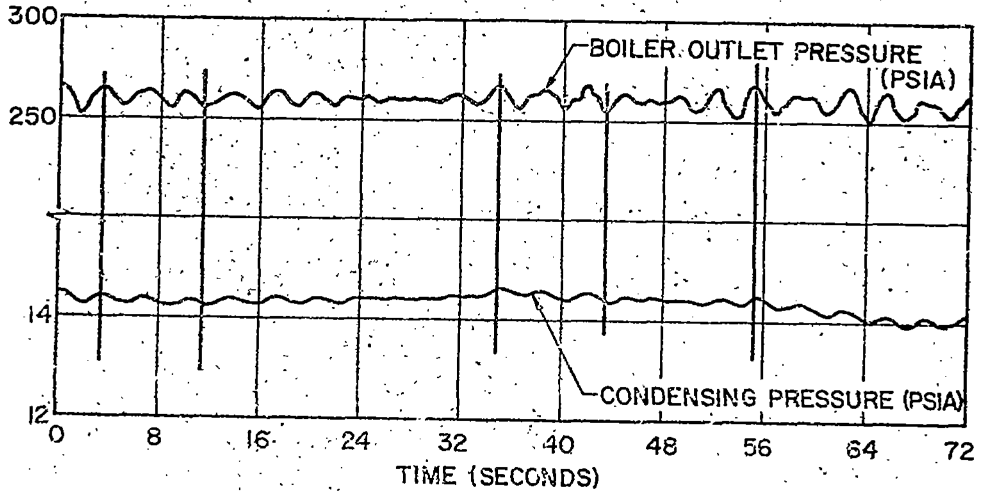

FIG. 21 IN-PHASE RELATIONSHIP OF BOILER OUTLET PRESSURE AND CONDENSING PRESSURE