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THE SNAP II POWER CONVERSION SYSTEM

TOPICAL REPORT No. 14

MERCURY MATERIAL EVALUATION AND SELECTION

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Thompson Ramo Wooldridge Inc.
CLEVELAND, OHIO

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SELECTION

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ABSTRACT

SNAP II is the designation for a 3 kilowatt nuclear auxiliary power unit to be used in a satellite vehicle. The SNAP II System consists of a reactor heat source, a boiler, a mercury Rankine engine, an alternator, and a condenser. The corrosion and subsequent mass transfer resulting from the use of mercury as the thermodynamic working fluid are important considerations in the selection of materials for the SNAP II System. Consequently, corrosion and mass transfer behavior have been under study for the past three years. This report presents the recent results of this study and discusses the corrosion mechanisms involved. The program was performed under a sub-contract to Atomics International as part of the Atomic Energy Commission Contract AT(11-1)-GEN-8.

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1.0 INTRODUCTION

Space power systems involving conversion of nuclear energy to electrical energy are acknowledged presently to be the best method for supplying large amounts of power at a low system weight for long periods of time. Of these, the turboelectric system appears to be the most promising (1).^{*} Efficient operation requires high operating temperatures and high heat flux, which implies the utilization of liquid metals as working fluids. The need for unattended operation of a power conversion system for a year or more has added severe requirements, since such systems are subjected to corrosion and mass transfer of corrosion products. These can result in fouling of bearings, orifices and other critical components. It is apparent, therefore, that material choices for such systems must be made on the basis of corrosion resistance with an understanding of corrosion mechanisms. Separation or handling techniques for corrosion products may also have to be developed to neutralize deleterious effects caused by crud.

One of such systems is the SNAP II Power Conversion System which uses mercury as the thermodynamic working fluid to drive an axial-flow, impulse turbine-generator. The mercury is converted to vapor in a boiler heated by a sodium or sodium-potassium alloy heat transfer loop, which in turn is heated with a reactor heat source. This vapor is then condensed in a condenser and returned to the boiler by a pump.

The SNAP II materials program, under contract to Atomics International, is concerned with the screening of materials and determination of corrosion rates and mechanisms so that effective selection of materials may be made to insure satisfactory system performance. The program was initiated in 1958 and results presented herein are a summary to date of corrosion data obtained since the last published report in 1960 (2).

2.0 SUMMARY

An important factor in the selection of materials for the SNAP II Power Conversion System is the corrosion and subsequent mass transfer resulting from use of mercury as the working fluid. Consequently, this materials program, conducted under a subcontract to Atomics International as part of the Atomic Energy Commission Contract AT (11-1) GEN-8, is concerned with material evaluation and selection, and developing a working knowledge or understanding of mechanisms and mass transfer behavior so that satisfactory performance may be obtained for an unattended system.

In order to determine material suitability, screening tests were performed at 600 to 1000°F, and classifications based on corrosion resistance are presented herein.

The inhibitors, titanium and zirconium, were investigated in capsule tests. Effect of time and temperature was determined on the effectiveness of titanium as an inhibitor with and without magnesium-deoxidized mercury. Wettability with the additives titanium and magnesium and effects of mercury purity were investigated and are discussed.

^{*}Numbers in parentheses pertain to references listed in the Bibliography.

The temperature dependence of corrosion rate for Haynes alloy No. 25, PH15-7Mo, AISI 1010, Type 410 and Sicromo 58 was determined and results are presented herein. These results suggested slight temperature dependence to at least 700°F with a calculated energy of activation of 5,400 calories. An activation energy of 38,000 calories was determined for temperatures over 700°F. Mechanisms of corrosion were suggested and are discussed.

Loop test results are presented for Haynes alloy No. 25, and Haynes alloy No. 25-PH15-7Mo at a boiling temperature of about 1000°F. These showed that pretreatment with 40 ppm titanium and 80 ppm magnesium and addition of 11 ppm titanium to the test mercury were ineffective in inhibiting corrosion at 1000°F. PH15-7Mo steel was found to be unsatisfactory in combination with Haynes alloy No. 25 because of excessive weld attack and nature of debris generation.

Penetration data from 1000 hour Haynes alloy No. 25 loop tests were shown to be threefold greater than penetrations interpolated from bent reflux tube tests. The general level of attack or crud generation, of course, was dependent upon the boiling temperature. However, Haynes alloy No. 25 penetration by mercury was found to have slight temperature dependence between at least 500°F to 1000°F under 5000 hours. These results indicate that low temperature regions of a system cannot be ignored. A mechanism of attack was suggested.

3.0 PROGRAM OBJECTIVES

Mercury corrosion is a consequence of the fact that most metals have a slight but finite solubility in liquid metals. Corrosion severity, therefore, is simply a question of solubility rate and extent, barring chemical interaction, and is dependent exponentially on temperature. Thermal gradient mass transfer can occur when a temperature gradient of 10°F or less exists in a liquid metal system. Dissolution usually takes place in the sections where the mercury is subjected to a temperature increase and fouling usually, though not always, results in areas subjected to a temperature drop. Fouling is caused by precipitation of corrosion products dissolved in the mercury in the form of scale, crystalline growths or surface deposits, or dispersed solids in the liquid metal. Corrosion may also be influenced by presence of a second metal. This phenomenon is called dissimilar metal mass transfer and may result in corrosion even under isothermal conditions. Electrolytic action may be a factor in this type of corrosion (2).

The primary objective of the Mercury Materials Evaluation and Selection Program is to select optimum materials for the SNAP II Power Conversion System, considering minimum corrosion products, appropriate strength, and other special property requirements. Information considered essential in the pursuit of this objective during this reporting period was the determination of the following:

1. Screening of materials to liquid mercury corrosion at 600 to 1200°F.

2. The corrosion rate as a function of time and temperature to 1200°F for a number of selected materials. These materials are:
 - a. Type 410
 - b. Haynes alloy No. 25
 - c. Columbium
 - d. AISI 1010
 - e. PH15-7Mo
3. Bimetallic effects of Haynes alloy No. 25 and other materials.
4. Effect of time and temperature on the effectiveness of inhibitor additives.
5. Conducting the following corrosion loop tests:
 - a. Haynes alloy No. 25 with inhibitor for 5000 hours at 1000°F.
 - b. Type 410 with inhibitor for 1000 hours at 1000°F.
 - c. Bimetallic combination Haynes alloy No. 25-PH15-7Mo for 1000 hours at 1000°F.
 - d. Bimetallic combination Columbium-Haynes alloy No. 25 for at least 2000 hours at 1200°F.

All commercially available standard alloys of construction are corroded by liquid mercury to varying degrees (2). Only some refractory metals such as tantalum, columbium, molybdenum and tungsten appear to have adequate resistance, yielding practically no corrosion products at 900°F (2). However, these materials are difficult to fabricate and, in addition, special requirements of power conversion packages such as magnetic properties, thermal expansion, etc. presently preclude the exclusive use of refractory metals.

Consequently, it is apparent that the most important problem is that of material selection, since this may be the deciding factor for successful operation of a power conversion system. Furthermore, since some corrosion product generation may be expected, separation procedures may have to be developed.

4.0 EXPERIMENTAL METHODS

Materials have been screened and effects of time and temperature have been investigated by means of the "Bent Reflux Tube" (BRT) capsule test developed at TRW. In essence, dynamic contact is maintained between the sample and liquid mercury by an evaporation-condensation process in a Pyrex or Vycor inverted "L" shaped tube. The average flow rate is about 0.5 pounds of mercury per hour. This simple glass apparatus, along with sample preparation and other test procedures, has been adequately described elsewhere (2). Accuracy and reproducibility of test results have also been previously discussed (2). Pyrex glass has been used to 1000°F without any special precautions. However, for temperatures in excess of this value, a pressurized furnace was designed and built in which the pressure generated inside the

Vycor capsule could be balanced by introduction of argon into the furnace (see Figure 1).

For a simulation of conditions as found in a PCS system, the Loop Test, previously described (2), probably yields sufficient information concerning dissolution and deposition of corrosion products. In essence, the loop consists of tubing arranged in a parallelogram. On one lower vertical leg the mercury is boiled, superheated in a nearly horizontal leg, condensed in an upper vertical leg and subcooled in a nearly horizontal leg. The mercury is circulated by natural, two-phase circulation. Flow rate at 1000°F is on the order of about 12 pounds of mercury per hour.

4.1 Bent Reflux Tube Results

4.1.1 Material Screening

Compositions of materials screened at 900°F are listed in Table 1 and heat treatments utilized are presented in Table 2. Results are tabulated in Table 3.

A plot of weight loss versus time is presented in Figure 2 on log-log paper. Classification bands according to penetration calculated from weight losses are also shown. Material classification is apparent from an examination of the graph.

Previous work (2) has shown that corrosion may proceed according to an accelerated rate (slope > 1), decelerated rate (slope of $\frac{1}{2}$) or linear rate (slope of 1) according to the equation

$$-W^n = kt$$

where W is the weight loss, n is the reciprocal of the slope, k is the rate constant and t is the elapsed time at a given temperature. Most of the materials tested appeared to follow a decelerating rate of corrosion since the slope was about one-half. Vicalloy and tool steels T15 and M36 showed an accelerated rate initially. Tenelon and the Hastelloys also appeared to show accelerated attack.

Some composition effects may be noted. Cobalt containing alloys show generally decreasing resistance with increases in chromium and nickel or reduction in cobalt content, i.e., in order of decreasing resistance Vicalloy, Haynes Stellite 151, 31, 21, Nivco and Haynes Stellite 56. The same behavior may be noted for Ferrotic S45 with about 2% more chromium and nickel than S55 and for 440 C with 2% more chromium than BG41. Also, the high manganese (Tenelon) and nickel base (Hastelloys) materials showed poor resistance.

4.1.2 Bimetallic Effects

Haynes alloy No. 25 brazed with J8400, and Hyperco 27 and Haynes alloy No. 25 brazed with J8400 did not appear to show any accelerated corrosion effects up to 30 and 60 days at 900°F, respectively (Table 7).

Haynes alloy No. 25 in combination with Type 410, PH15-7Mo, Type 347 and 17-4PH showed no excessive weight losses (Table 7) at 900°F in 30 day tests. Microscopic examination indicated accelerated penetration for the Haynes alloy No. 25 with the PH15-7Mo and 17-4PH, and for Type 410. Deposition was observed in all cases indicating that weight losses would not be an adequate guide since a mutual exchange of materials probably occurred.

The same tests at 600°F showed no certain synergistic influences in regards to weight losses. However, penetration observed on one Haynes alloy No. 25 coupon in combination with PH15-7Mo showed accelerated penetration (Table 8). Deposition was again noted similar to the run at 900°F.

A Haynes alloy No. 25 and Type 410 coupon each showed greater weight losses in 30-day tests at 600°F in contaminated mercury than in clean mercury (Tables 4 and 8). This suggests that corrosion products which may flow through a lower temperature region may accelerate or cause corrosion.

On the other hand, corrosion of Haynes alloy No. 25 for 30 days and Type 347 stainless steel for 14 days at 900°F in Metasalts Corporation high purity mercury yielded weight losses and penetrations lower than for the customarily used (triple distilled) mercury (Table 3). Spectrographic analysis showed that the Metasalts mercury contained only a trace of silicon. The triple distilled mercury contained a minor amount of silver and a trace of silicon and copper (as per spectrographic analysis). The data suggest that impurities normally found in mercury increase corrosion by reducing the induction period preceding corrosive attack. In addition, these corrosion reactions may be autocatalytic, which can explain this longer induction period with ultra-pure mercury. Once initiated the corrosion rate may eventually reach the same value as with triple distilled mercury. Tests in progress should determine the relative importance of this effect in conjunction with the time element more clearly.

4.1.3 Inhibitors

The additives zirconium, titanium and magnesium were tried with Type 347 and Haynes alloy No. 25 (Table 3) at 900°F. In the case of the Type 347 stainless steel and Haynes alloy No. 25, titanium appeared to be consistently more effective (Table 3) than zirconium when added at a concentration of 2 ppm. The titanium was added to the mercury at its 900°F solubility limit, whereas the zirconium was added well below its solubility limit. The solubility of titanium in 900°F mercury is about 2 ppm, and that of zirconium about 10 ppm. Also, after a vacuum anneal at 500-700°F following immersion with inhibitor, a run in clean mercury appeared to show maximum benefit of inhibitor pretreatment as shown by the low weight losses (Table 3). Generally, for a specimen which suffered low weight loss, an inhibitor layer could be seen microscopically. For specimens which yielded high weight losses, the inhibitor, in part, appeared to form in clumps on the surface. Evidence of corrosion could be seen although penetrations were slight. In other cases penetrations appeared large where a breakdown in the protective film occurred.

The Haynes alloy No. 25 appeared to lose protection prior to 120 days (Table 3) with 2 ppm titanium and 20 ppm magnesium additives. Penetration

and weight loss after 120 days exposure appeared to be equivalent to untreated corrosion results. One test result with only 2 ppm titanium additive yielded no weight loss after 112 days exposure. Titanium additions with PH15-7Mo and Type M4 tool steel appeared to be inadequate in inhibiting corrosion (Table 3).

The titanium and magnesium additives appeared to be effective in the concentrations used at 600°F and at 700°F (Tables 4 and 5) in reducing weight losses up to 90 days, although some penetrations were observed with about the same magnitude as without inhibitors. On the other hand, results at 1000°F indicated that the same amount of inhibitor was ineffective in 30 day tests (Table 6).

4.1.4 Wetting

Specimen wetting was observed to occur within one day at 900°F on Haynes alloy No. 25, PH15-7Mo and Type M4 tool steel (Table 3) with addition of 2 ppm titanium to the mercury, and within 4 days at 600°F. The magnesium (20 ppm) and titanium (2 ppm) combination caused specimen wetting at room temperature within one day.

4.1.5 Coatings

A spinal type oxide coat, developed on Type 347 stainless steel by exposure to moist hydrogen at 1400°F, appeared to reduce corrosion severity by 50 fold (Table 3). Some penetration of this coat as manifested by corrosion was evident in a few areas after 30 and 60 days exposure at 900°F.

4.1.6 Effect of Time and Temperature on Select Materials

Additional tests on Sicromo 55 and AlSl 1010 at 900°F have shown that the corrosion rate changes from a linear to probably a decelerating rate after 90 days (Table 3), indicating diffusion controlled attack (2).

Weight losses at 600°F and 700°F showed considerable scatter (Tables 4 and 5). Weight losses for all materials appeared to be of about the same magnitude at each temperature, although the weight losses at 700°F were generally of somewhat higher magnitude than at 600°F. Some weight gains were experienced; for example, PH15-7Mo, probably because of amalgam formation. However, penetrations at 600°F and 700°F were greater than anticipated, and ranged approximately between one-half to three-quarters of the penetration depth observed typically at 900°F for these materials. Penetration was predominantly of the crevice type as contrasted to the layer or depleted zone type usually found at 900°F and above. Heavy deposition always appeared to accompany dissolution at these temperatures, which may account along with amalgamation for some of the scatter observed. This also suggests that these temperatures tend to be favorable for deposition.

Variation of rate constants with temperature can be expressed according to the Arrhenius equation

$$\frac{d \ln k}{dT} = \frac{\Delta E}{RT^2}$$

where k is the reaction rate constant, T is the absolute temperature, ΔE is the energy of activation (in calories) and R is the gas constant. On the supposition that ΔE is a constant, integration of the above equation yields

$$\ln k = \frac{\Delta E}{RT} + C$$

where C is a constant of integration. According to this equation, a plot of $\ln k$ again $\frac{1}{T}$ should be a straight line with

$$\text{slope} = \frac{\Delta E}{-4.58}$$

When the corrosion process changes, the temperature dependence also changes and the Arrhenius plot does not consist of a single straight line.

In Figures 3 through 7 are shown tentative plots of $\ln k$ vs $\frac{1}{T}$ for the select materials. The values for rate constants were obtained by extrapolation from maximum and minimum weight losses at each temperature in accord with diffusion controlled corrosion. As predicted by the Arrhenius equation, satisfactory straight lines were obtained with what appeared to be a suggested break in the curves at approximately 700°F. All of the materials appeared to have the same slopes. Plot of average parabolic rate constants is presented in Figure 8. AISI 1010, Sicromo 5S and PH15-7Mo constants are about 1.5 fold greater than those for Type 410, Haynes alloy No. 25 about 3 fold greater than Type 410, and type 300 series stainless steels about 300 fold greater.

The activation energy of the first low temperature branch was calculated to be about 5,400 calories and for the second branch--about 38,000 calories. The first value corresponds approximately to the energy of activation for diffusion in liquid metals, whereas the second value corresponds approximately to the energy of activation for the diffusion of vacancies (3) (4). The shallow slope to about 700°F suggests a low temperature dependence to at least this temperature and possibly higher, since the diffusion coefficients of metals in mercury vary with temperature only slightly. Prediction of a low temperature dependence for corrosion in mercury has also been made by Epstein (3) and Horsley (12).

The patterns or mechanisms of corrosion are suggested by the above information and other observations presented previously (2). The crevice type attack usually discernible as contrasted to the somewhat more infrequently observed leached layer, and the high diffusion rate possible in the liquid as contrasted to the relatively low rate of vacancy diffusion in the solid suggest that diffusion of elements in the liquid found in the crevice tend to control the corrosion process at relatively low temperatures. At higher temperatures the diffusion rate of vacancies becomes more pronounced since it is temperature sensitive, and it begins to compete with diffusion in the liquid metal. The diffusion rate in liquid metals is relatively insensitive to temperature (3). Therefore, a depleted layer is more often observed to form after a period of time through which the susceptible elements diffuse with a counter flow of vacancies. These elements may also

find their way into the channels filled with liquid mercury. Thus, although both processes occur simultaneously regardless of temperature, each one tends to be more predominant depending upon temperature and, therefore, rate controlling. The break at 700°F is probably a minimum temperature value, and for a maximum value as suggested by the parabolic rate constant value of about $0.01 \text{ mg}^2 \text{ in}^{-4} \text{ day}^{-1}$ calculated for Type 410 and Haynes alloy No. 25 run in "contaminated" mercury at 600°F (Table 8), this temperature may reach at least 900°F.

At higher temperatures interstitial or direct interchange diffusion may be expected to compete with liquid and vacancy diffusion; and consequently, another break in the Arrhenius plot may be anticipated resulting in all probability in a serious increase in corrosion. The composition of the corrosion products may also be expected to change somewhat with change in process. This consideration is theoretical and substantiations have not as yet been obtained experimentally. However, if there is another break it probably occurs over 1200°F.

4.1.7 Comparison of Bent Reflux Tube Data with Other Investigations

Extrapolating the rate constant data obtained from bent reflux tube tests to 1200°F for Type 304 (average $k = 1000 \text{ mg}^2 \text{ in}^{-4} \text{ day}^{-1}$) and Type 310 (maximum $k = 10,000 \text{ mg}^2 \text{ in}^{-4} \text{ day}^{-1}$) in Figure 7, the weight losses are evaluated to be $26 \text{ mg cm}^{-2} \text{ mo}^{-1}$ and $78 \text{ mg cm}^{-2} \text{ mo}^{-1}$, respectively. These data compare favorably with Nerad's all-liquid loop data at 1200°F of $32 \text{ mg cm}^{-2} \text{ mo}^{-1}$ for Type 304 and $77 \text{ mg cm}^{-2} \text{ mo}^{-1}$ for Type 310 (11).

The maximum weight loss data obtained from Figure 4 for Sicromo 5S at 900°F and at the 1200°F extrapolation of $0.45 \text{ mg cm}^{-2} \text{ mo}^{-1}$ and $4.5 \text{ mg cm}^{-2} \text{ mo}^{-1}$, respectively, also compare favorably with Nerad's loop data of $0.3 \text{ mg cm}^{-2} \text{ mo}^{-1}$ and $4 \text{ mg cm}^{-2} \text{ mo}^{-1}$ at 900°F and 1200°F, respectively. However, the AISI 1010 maximum weight loss of $0.45 \text{ mg cm}^{-2} \text{ mo}^{-1}$ at 900°F from bent reflux tube data presented in Figure 6 is low compared to the value of $7 \text{ mg cm}^{-2} \text{ mo}^{-1}$ reported for Nerad's loop data in the Liquid Metals Handbook (11). The value of $88 \text{ mg cm}^{-2} \text{ mo}^{-1}$ reported at 1200°F (11) appears to be much too high for AISI 1010, since this value is higher than that reported for the Type 300 series stainless steels at this temperature. The Type 300 series have been found to be generally less resistant to mercury attack than AISI 1010. The equivalent penetrations reported for Types 304 and 310 for one year (11) are based on a linear rate of attack. Since both loop (2) and bent reflux tube data indicate a parabolic or a decelerating rate of attack, these values are too high and should be 6 mils year^{-1} for Type 304 and 14 mils year^{-1} for Type 310 ($\sqrt{12}$ time factor instead of 12). Actually, the observed penetrations would be on the order of 45 and 80 mils, respectively.

4.2 Loop Test Results

4.2.1 Haynes Alloy No. 25-PH15-7Mo Stainless Steel (5)

The precipitation hardening stainless steel PH15-7Mo appeared in material screening tests to have satisfactory resistance to mercury corrosion at 900°F (2). In addition, the material has adequate resistance to

atmospheric corrosion. Since the material has potential use in the lower temperature piping of the SNAP II Power Conversion System, Atomics International requested testing of this material in combination with Haynes alloy No. 25 to determine existence of bimetallic effects. This information is essential since some bimetallic combinations have demonstrated adverse corrosion behavior (2). Therefore, a 1000 hour corrosion test was conducted on a Haynes alloy No. 25-PH15-7Mo stainless steel loop containing boiling mercury at 1029°F with superheat temperature of 1090°F and a subcooler temperature of 435°F. The boiler and superheater were made of Haynes alloy No. 25 and the condenser and subcooler were made of PH15-7Mo.

The mercury removed from the system was clean but developed a scum after standing. Spectrographic analysis of this scum after removal by filtering through filter paper showed that chromium, cobalt, nickel and iron were the major constituents (Table 9), while the mercury filtrate was reasonably free of contaminants. The deposit removed from the loop consisted of cobalt, iron, chromium and tungsten as dissolution elements (Table 9).

Microscopic examination of various sections removed from the loop showed that Haynes alloy No. 25 corrosion occurred with progressively greater penetration from the first boiler heater midpoint to boiler outlet, 0.0005 inches to 0.0023 inches, respectively. Of interest was the fact that corrosion was observed in the unheated section between the two boiler heaters. This indicates that moderate variations of heat flux have no influence on corrosion. The boiler inlet region, on the other hand, showed crystal deposits as did the lineheat section following the boiler and the superheat area. Some of the lineheat midsection deposits appeared to be grains of material removed from the system container walls, whereas the lineheat outlet and superheater deposits consisted of nucleation and growth type deposits.

The PH15-7Mo material in the condenser from inlet to outlet showed a corrosion layer of 0.0005 inches with grains of material being removed. This corrosion was severe in the liquid-contacted, post-condenser midsection where 0.0008 inches of penetration was observed. The corrosion in the post-condenser outlet and subcooler sections was insignificant, with less than 0.00028 inches of penetration. Some deposition also occurred in the post-condenser and subcooler sections.

The weld interface between the Haynes alloy No. 25 and PH15-7Mo was seriously attacked with penetration measured to 0.013 inches in the condenser area. The weld attack and the fact that metal "chunks" or grains may be found in the mercury system would probably make use of this material questionable in a power conversion system. The deposits in the lineheat and post condenser sections appeared to be in part made of debris from the condenser. Also, the observation that a depth of penetration about equivalent to that observed in a 5000 hour run on Haynes alloy No. 25 in mercury at 1000°F was achieved, suggests that the PH15-7Mo steel may have some influence on the Haynes corrosion rate at 1000°F. The effect, however, is not catastrophic with exception of the attack on the weld interface. (6)

4.2.2 Haynes Alloy No. 25 (6)

A 5000 hour corrosion test was conducted on a Haynes alloy No. 25 loop containing boiling mercury at 998°F with superheater temperature of 1098°F and the subcooler temperature of 360°F. The mercury contained 11 ppm of titanium additive as an inhibitor. The loop system was pretreated with a temperature variation of 360°F to 900°F for a total of 84 hours prior to the test run with mercury containing 24 ppm each of magnesium and titanium additive to build up a protective layer. This mercury was drained under a nitrogen cover. The titanium, added as a powder entrained in the mercury, undoubtedly should have floated to the top of the mercury in the hottest liquid areas of both the condenser and boiler. The solubility of titanium in 998°F mercury is about 2.6 ppm.

Bent reflux tube screening tests have suggested that Haynes alloy No. 25 has a higher degree of resistance to mercury corrosion than any other of the high temperature materials of construction (2); consequently, a 1000 hour loop corrosion test was conducted on this material at 900°F which showed that some dissolution did occur (7). However, capsule tests with titanium and magnesium additives indicated that mercury corrosion was drastically reduced with the utilization of these inhibitors. Therefore, this test was run to determine the effectiveness of an inhibitor additive in a dynamic system by a method described below that could be applied safely in a mercury power conversion system. Since the presence of any contaminants may be undesirable due to fouling of bearings, orifices, etc., it was thought best to build up a protective layer by a relatively heavy additive pretreatment which would treat all loop surfaces. The system would then be drained and replaced with mercury containing only a relatively small amount of titanium, thus reducing the contaminant content of the system to a safe level.

The mercury drained from the system after pretreatment contained a heavy scum which was removed by filtering. This scum consisted principally of magnesium, titanium, and mercury as shown by analysis in Table 10. The filtrate did not appear to contain any titanium but did contain an appreciable amount of magnesium.

The mercury removed at completion of the 5000 hour run contained only a slight surface film which thickened slightly upon exposure to air. The scum was found to consist of magnesium, titanium, chromium, cobalt and tungsten (Table 10). The filtrate contained a trace of magnesium, and no titanium.

An amalgam-like deposit was found in the subcooler as a mass and as a sheath which clung to the tubing wall and was easily removed. Although 13 grams of deposit was removed from this area, actually according to analysis only one gram of actual elements dissolved from the container walls was incorporated in this mixture, while the balance was mercury. See Table 11. The deposit consisted of 16.5% cobalt, and 12% chromium. Magnesium, tungsten, iron, nickel and titanium also were present in minor amounts.

The loosely adherent deposit removed from the boiler through superheater

sections analyzed 22% cobalt and 2% chromium, while the deposit from the post condenser analyzed 19.5% cobalt and 5% chromium. The interesting feature was the lack of copious nickel and titanium insufficient for wet analysis, although spectrographic analysis demonstrated their presence. However, nickel appeared to be selectively deposited in the superheater as shown by spectrographic analysis in Table 11, while cobalt was found deposited in about equal concentration over the loop, and chromium appeared to be selectively deposited primarily in the subcooler, and secondly in the post condenser area.

The mercury removed after pretreatment showed the beginnings of container wall dissolution. The mercury analysis at completion of 5000 hours of operation suggested that most of the dissolved elements were probably in some combined form which permitted separation to occur, since these elements were found only in the residue and not in the filtrate.

The fact that titanium was found in the pretreat mercury residue only and not in the filtrate, while the magnesium was found in both, suggests that the titanium was consumed and combined with other elements. The magnesium is protective and would prevent combination of titanium with oxygen. The mercury filtrate at completion of the test run was also devoid of titanium, which suggested that the addition of titanium made after the pretreatment was inadequate to maintain a small concentration of titanium in the mercury.

Metallographic observations of various loop sections showed that corrosion occurred to a depth of about 0.0025 inches in the boiler, the condenser and post condenser. On the other hand, deposition occurred in the lineheat section, boiler midsection and superheat area.

The pretreatment with magnesium and titanium and the titanium addition to the test run mercury did not inhibit corrosion. In order to have protection, it has been reported that the titanium level must be maintained at least at $3/4$ ppm (8) with magnesium-deoxidized mercury to satisfy metal surfaces and to replace any titanium removed by reaction. Also, an adequate titanium layer must be built-up on the metal surface, probably on the order of 200A (9) to 2.0 to 2.6 mg per sq. in. (8). This apparently was not accomplished since titanium metal was absent from the mercury filtrate. For example, in a commercial boiler power installation operating at a mercury boiling temperature of about 1050°F, the titanium concentration in the mercury was maintained at between $3/4$ to 8 ppm and the magnesium concentration was maintained at 50 to 100 ppm (8). The initial additions consisted of 80 ppm of titanium and 160 ppm of magnesium (8). The true solubility of titanium at 1050°F is on the order of 3 ppm. Obviously, the titanium was added in concentrations above true solubility. Moreover, titanium values of 10 ppm reported necessary to give protection at 1200°F (11) are also in excess of true solubility by about 4 ppm. Another factor to consider is the titanium solubility ratio (ratio of solubility at the highest and lowest system temperatures). The solubility ratio in commercial boilers using inhibitors was on the order of 4, whereas the solubility ratio in the loop was about 8. When the solubility ratio exceeded about 5 in bismuth systems, inhibitor effectiveness apparently deteriorated (13).

The depth of penetration of the Haynes alloy No. 25 by mercury attack at

998°F was not as great as anticipated (0.004 in.) from data obtained at 900°F on the untreated loop (12), and extrapolated with help of penetration data obtained from capsule tests at 900 and 1100°F (2).

However, the corrosion penetration which occurred over the loop from a low temperature region of about 500°F to the high temperature region of 998°F was of about the same severity. In other words, the corrosion rate was accelerated for the low temperature regions and decelerated for the high temperature regions to yield a reasonably constant penetration over the loop system.

The penetration for 10,000 hours of operation would probably be on the order of an estimated 0.0033 inches, which certainly would not in itself be detrimental to container life if the corrosion products would not be objectionable.

The Haynes alloy No. 25 was embrittled in the superheater region as manifested by (a) brittle fracture during sectioning of the loop, and (b) increase in hardness to Rockwell C 39 from a base hardness of Rockwell C 20, indicating that aging occurred. This effect was most noticeable in the area where a temperature of at least 1000°F was experienced. The boiler, lineheat and condenser sections also indicated that some aging occurred which resulted in a hardness of about Rockwell C 27, but this increase did not result in any apparent loss of ductility. Microstructure of the affected area showed excessive carbide precipitation in the grains and grain boundaries which accounted for the brittleness displayed. This heavy precipitation was absent in other areas.

The actual amount of leached materials found, including the adherent deposits, was probably less than 7 grams total. Considering the length of operation and temperature of boiling and condensing, this amount was probably not excessive. However, the 13 grams of amalgam which was found in the subcooler area could possibly lead to plugging eventually, unless a trap of some sort is designed into the low temperature region of the system.

4.2.3 Type 410 Stainless Steel

This loop is being tested for 5000 hours with a mercury boiling temperature of 1000°F. The loop system was pretreated with mercury containing 40 ppm each of titanium and magnesium. The mercury used in testing contains 67 ppm of titanium additive.

4.2.4 Columbium-Haynes Alloy No. 25

This loop is being tested for 5000 hours with a boiling temperature of 1200°F. The boiler and condenser are made of columbium tubing protected by an outer tube of Type 347 stainless steel. The superheater and subcooler are made from Haynes alloy No. 25,

4.3 Comparison of Loop and Bent Reflux Tube Results

Penetrations observed in 1000 hours corrosion loop tests and penetration

data interpolated from bent reflux tube capsule tests are presented in Figure 9 as a function of the reciprocal of absolute temperature. In general, the plot for Haynes alloy No. 25 shows that penetrations observed in the 1000 hour loop tests are on the order of about threefold greater than those interpolated from bent reflux tube capsule tests. In the case of the Type 300 series stainless steels, penetrations from both bent reflux tube and loop tests tend to overlap; however, the loop test penetration results again appear to be generally more severe, especially in the lower temperature regions. Measured penetrations from bent reflux tube tests are usually on the order of at least tenfold greater than those calculated from weight loss data (assuming general corrosion).

Penetrations for the 1000 hour loop tests are seen to increase with temperature for the lower limit. However, the upper limit in the case of the Type 300 series steels is only slightly dependent upon temperature, and for the Haynes alloy No. 25 this effect is seen to at least 700°F, as it is seen similarly for the bent reflux tube test results. On the other hand, the 5000 hours Haynes alloy No. 25 loop test penetration data show no temperature dependence in the lower temperature regions. The penetrations tend to become uniform over a temperature range in a loop system before 5000 hours for Haynes alloy No. 25 and possibly over 1000 hours for the more easily corrodible Type 300 series steels. The titanium and magnesium additions used in the 5000 hour loop test may have been a contributory factor by removing surface oxide films and thereby promoting wetting, although the Type 300 series results imply differently.

The extrapolated 5000 hour bent reflux tube maximum penetration curve for Haynes alloy No. 25 coincides with the upper limit of the 1000 hour Haynes alloy No. 25 loop data. No apparent correlation exists between the 5000 hour bent reflux tube and loop data, except that the penetrations roughly coincide at approximately the loop (G 11) boiling temperature of 1000°F. These data suggest that the corrosion penetration rate in a loop decelerates after an initial stabilizing period, and that bent reflux tube extrapolated penetration data in excess of 5000 hours may possibly be used with caution to predict loop and possibly other system penetrations based on the highest liquid mercury temperature in the system.

The differences in loop and bent reflux tube penetrations may be attributable to the circulation of corrosion products, higher flow rate, and temperature differentials. The fact that corrosion products may be influential was demonstrated in bent reflux tube tests. Both Haynes alloy No. 25 and Type 410 steel specimens suffered a threefold increase in weight losses at 600°F when the mercury contained corrosion products (Table 8).

In light of the mechanisms of corrosion described previously under time-temperature effects for bent reflux tube specimens, corrosion in a loop system is probably initiated as described. However, in the loop system the mercury becomes laden with corrosion products. The apparent activity of the mercury is, therefore, probably increased because of solid solution, compound formation, etc., between the leachable elements in the mercury. The maximum temperature of operation apparently determines the general level of attack, and other portions of the system at lower temperatures tend to approach this level. This results in a decelerating rate of

attack on the sections of the system at higher temperatures since a protective corrosion layer has been built up, and an accelerated rate of attack on the lower temperature sections until equivalent protective corrosion layers have been developed. Accordingly, the penetration becomes only slightly temperature dependent.

5.0 CONCLUSIONS

1. Corrosion in a loop system proceeds according to a decelerating rate after an initial stabilizing period.
2. Loop tests suggest that penetrations in the lower temperature regions of the loop system become only slightly dependent upon temperature over 500°F to 1000°F with increase in exposure duration over 1000 hours for Type 300 series steels and under 5000 hours for Haynes alloy No. 25. The additives titanium and magnesium may have contributed to this effect by promoting surface wetting. The general level of corrosion or crud generation is set by the highest temperature of boiling mercury.
3. Reasonably straight lines obtained for plots of $\log k$ vs $1/T$ yield credence to bent reflux tube capsule data.
4. Bent reflux tube data suggests for mercury corrosion only slight temperature dependence to at least 700°F and possibly higher.
5. In the bent reflux tube capsule test the energy of activation of 5,400 calories up to at least 700°F suggests that diffusion in the liquid metal controls corrosion. Energy of activation of 38,000 calories over 700°F suggests that vacancy diffusion controls corrosion.
6. Loop tests concerning bimetallic combinations for PCS piping have suggested the following:
 - a. Haynes alloy No. 25-PH15-7Mo steel combination yielded excessive weld penetration at 1029°F.
 - b. The PH15-7Mo material lost grains of material by corrosion when in combination with Haynes alloy No. 25.
7. Pretreatment with 40 ppm titanium and 80 ppm magnesium, and additions of titanium to 11 ppm appeared to be ineffective in inhibiting corrosion in a Haynes alloy No. 25 loop system at a mercury boiling temperature of 1000°F run for 5000 hours.
8. Nickel, chromium and manganese additions to alloys usually increase corrosion weight losses.
9. Moderate variations of heat flux appeared to have no influence on corrosion.
10. Wetting caused by pretreatment with titanium and magnesium appeared to

aid deposition in the lower temperature regions of the loop system.

11. As an inhibitor, titanium additive appeared to be more effective than zirconium for concentrations of 2 ppm at 900°F.
12. Titanium (2 ppm) and magnesium (20 ppm) became ineffective in inhibiting corrosion prior to 120 days exposure at 900°F, effective to at least 90 days at 700°F and below, and ineffective at 1000°F for Haynes alloy No. 25.
13. Wetting by titanium (2 ppm) occurred within one day at 900°F and within four days at 600°F.
14. Wetting by titanium (2 ppm) and magnesium (20 ppm) occurred within one day at room temperature.
15. Depending upon the purity of the mercury the following effects may result:
 - a. Pure mercury requires a longer time for the initiation of corrosion.
 - b. Impure mercury may protect if deposition of certain soluble corrosion products occurs; i.e., nickel.
 - c. Impure mercury may accelerate corrosion in lower temperature regions.
16. Additional materials screened at 900°F are considered to be classified as follows:

Class II

Vicalloy
BG 41
Tool Steels M36, T15, M4, A7
AMS 5623
440 C
Ferrotic S 45, S55
Haynes Stellite 151, 31, 21

Nivco 10
Vanadium
J8400

Class III

Beryllium
Haynes Stellite 56
Carp 7Mo (329)

Tenelon
Hastelloy B, F

Class IV

Hastelloy C

17. A Haynes alloy No. 25 loop suffered less penetration at 1000°F than

expected. However, loop amalgam mass formed in low temperature area could conceivably plug the system.

6.0 RECOMMENDATIONS

1. Since deleterious corrosion and mass transfer effects are still major problems, the following recommendations are being made:
 - a. Evaluate refractory materials at 1200°F, including loop tests.
 - b. Investigate means of controlling the transport of corrosion products with filters, surface precipitators, cold (and hot) traps, magnetic separators, etc.
 - c. Investigate means of controlling the container surface so as to inhibit the development of corrosion products by:
 1. Chemical treatment to alter the surface to a less corrosion prone composition.
 2. Inhibitor treatment.
 3. Coating.
2. Continue mapping of time and temperature effects especially at higher temperatures to possibly 1400°F to determine if corrosion rate changes and to substantiate present data.
3. Operate a Haynes alloy No. 25 loop with a heavy titanium-magnesium pretreatment and with a titanium source of supply in the boiler.
4. Continue evaluation of inhibitor additions with temperature, and determine:
 - a. Stability of the inhibited surface in a flow of pure mercury, and
 - b. mass transfer rates in a mercury system having a continuous source of titanium.
5. Correlate surface treatments, coatings and inhibitor treatments with heat transfer capability and wettability for boiler and radiator-condenser materials.
6. Operate a loop and determine the effects of other possible bimetallic combinations that exist in the system, for example the Type 347 used in the heat shields around the turbine journal bearing in combination with PH15-7Mo, and other 17-4PH, Haynes alloy No. 25, Stellite 21, BG41 and Alnico combinations.
7. Since the influence of gases either retained on or near the surface of metal or of inadvertent atmospheric leaks is unknown as to effects on

corrosion rate, wetting and heat transfer, and mass transfer of oxides, it is proposed that two loops be run to (a) determine the effects of degassing on corrosion and wetting, and (b) determine the effects of atmospheric contamination on mass transfer of oxides and corrosion rate.

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APPENDIX I
FIGURES

FIG.1 PRESSURIZED FURNACE FOR TESTING
BENT REFLUX TUBE CAPSULES. (05557)

FIG. 2 WEIGHT LOSS VERSUS TIME FOR VARIOUS ALLOYS IN REFLUXING LIQUID MERCURY AT 900°F

FIG.3 VARIATION OF HAYNES ALLOY NO.25 PARABOLIC CORROSION RATE CONSTANT WITH TEMPERATURE.

FIG.4 VARIATION OF PHI5-7MO PARABOLIC CORROSION RATE CONSTANT WITH TEMPERATURE.

FIG.5 VARIATION OF TYPE 410 PARABOLIC CORROSION RATE CONSTANT WITH TEMPERATURE.

FIG.6 VARIATION OF AISI 1010 PARABOLIC CORROSION RATE CONSTANT WITH TEMPERATURE.

FIG.7 VARIATION OF TYPE 347 AND SICROMO 5S
PARABOLIC CORROSION RATE CONSTANTS
WITH TEMPERATURE.

FIG.8 VARIATION OF PARABOLIC CORROSION RATE CONSTANTS WITH TEMPERATURE FOR SELECT MATERIALS.

FIG.9 COMPARISON OF MERCURY PENETRATION DATA OBTAINED FROM LOOP AND BENT REFLUX TUBE (BRT) TESTS.

APPENDIX II

TABLES

TABLE 1
NOMINAL COMPOSITION OF ALLOYS

Material	Nominal Composition, Percent									
	C	Cr	Ni	Co	Fe	Mo	W	Mn	Si	Others
Haynes alloy No. 25	0.15 max	20	10	bal	3 max	--	15	--	--	--
Tenelon	0.10 max	18.0	--	--	bal	--	-	14.5	1.0 max	0.4N
Vicalloy I	-	--	--	52	38	--	-	--	--	10 V
Ferrotic, S-45	-	11.0	7.3	--	42.7	--	-	--	--	39 Ti C
Ferrotic, S-55	-	9.6	5.7	--	33.7	--	-	--	--	52 Ti C
440 C	1.0	17.0	--	--	bal	--	-	1.0 max	1.0 max	--
Hastelloy B	0.05 max	1.0 max	61	2.5 max	5.5	28.0	-	1.0 max	1.0 max	0.4 V
Hastelloy C	0.08 max	15.0	54	2.5 max	5.5	16.0	4.0	1.0 max	1.0 max	--
Hastelloy F	0.05 max	22.0	45.5	2.5 max	bal	6.5	1.0 max	1.5	1.0 max	2 Cb + Ta
Haynes Stellite 151	0.45	20.0	3.0 max	bal	3 max	--	12.5	1.0 max	1.0 max	0.05 B
Braze J 8400	0.4	21.0	21.0	bal	--	--	3.5	--	8.0	0.8 B
AMS 5623	0.6	--	9.5	--	bal	--	-	5.5	1.0 max	--
Lesco BG-41	1.05	14.5	--	--	bal	4.0	-	1.0 max	1.0 max	0.12V
AISI Type M10	0.87	4.0	--	--	bal	8.25	-	0.3 max	.35 max	1.9V
Cast Haynes Stellite 21	0.27	27	2.5	bal	2 max	5.5	-	--	--	--
Cast Haynes Stellite 31	0.50	25	10.5	bal	2 max	--	7.5	--	--	--
AISI Type M36	0.89	4.1	--	9.0	bal	5.25	5.75	--	--	1.9V
AISI Type T15	1.50	4.5	--	5.0	bal	0.50	13.5	--	--	4.75V
Haynes alloy No. 56	0.30	21	13	11.5	bal	4.5	1.5	1.5	1.0 max	0.75 Cb+Ta; 0.1 N
Nivco 10	0.02	--	22.5	bal	0.03	--	-	0.35	--	1.1 Zr; 1.8 Ti
Carp 7 Mo (329)	0.02 max	25.5	3.5	--	bal	2.0	-	--	--	--
AISI Type M4 (Neatro)	1.27	4.5	--	--	bal	4.5	5.5	0.25	0.3	4V
AISI Type A7 (Chromewear)	2.3	5.3	--	--	bal	1.1	1.1	0.7	0.4	4.8V

TABLE 2

HEAT TREATMENTS

<u>Material</u>	<u>Designation</u>	<u>Heat Treatment</u>
18-8 Type Stainless Steels	Ann	Annealed at 2000°F and water quenched.
PH15-7Mo	A	Annealed 1/2 hour at 1950°F and water quenched.
	TH1050	Subsequent to Cond. A, 1-1/2 hours at 1400°F, air-cooled and held 1/2 hour at 60°F. Aged 1-1/2 hours at 1050°F and air-cooled.
410	QT	Soaked at 1800°F and water quenched. Tempered at 1350°F and air cooled.
(Neatro) AISI Type M4	HT	Preheated at 1400-1500°F, soaked at 2200°F and oil quenched. Double tempered at 1040°F.
(Chromewear) AISI Type A7	HT	Preheated at 1400-1500°F, soaked 30 minutes at 1725°F and oil quenched. Tempered at 1000°F.
440C	QT	Soaked 1 hour at 1850°F and oil quenched. Tempered 2 hours at 1050°F.
AISI Type M10	QT	Preheated 1300-1400°F, soaked 30 minutes at 2190-2225°F and oil quenched. Double tempered at 1040°F for 2 hours.
Lesco BG41	QT	Soaked 20 minutes at 2050°F and oil quenched. Tempered 1 hour at 300°F. Cold treated 15 minutes at -100°F. Double tempered 2 hours at 1000°F.
AISI Type T15	QT	Preheated at 1450-1550°F, soaked at 2250-2300°F and oil quenched. Double tempered at 1040°F for 2 + 2 hours.
AISI Type M36	QT	Preheated 1450-1550°F, soaked at 2220-2250°F and oil quenched. Double tempered for 2 hours at 1040°F.
Carp 7Mo (329)	Ann	Soaked at 1750-1800°F and water quenched.
	HT	Soaked at 1350°F for 12 hours and furnace cooled.

TABLE 3
Rent Reflux Tube Test Data at 900°F

Test No.	Material & Condition	Test Time Days	Weight Change Mg	Penetration Inches	Wetted	Remarks
308	347 (Ann)* (O ₂ treatment)**	60	- 0.6	0.0004	No	Crevice and intergranular-few areas.
309	347 (Ann) (O ₂ treatment)	30	- 0.5	0.0005	No	Crevice and intergranular-few areas. met; deposit.
309A	347 (Ann) (O ₂ treatment)	30	- 0.2	---	No	
314	347 (Ann) (O ₂ treatment)	13	0	---	No	
314R	Rerun 314	60	0	0	No	Roughened surface; layer deposit.
286	347 (Ann) + 2 ppm Zr	30	-12.8	---	Yes	
286R	Rerun 286	30	+ 5.7	0.0014	No	Oxidized.
286A	347 (Ann) + 2ppm Zr	30	-13.0	---	Yes	
287	347 (Ann) + 2ppm Zr	12	- 3.1	---	Yes	
287R	Rerun 287 in clean Hg	30	- 0.1	0.0028	No	One area of attack.
287A	347 (Ann) + 2ppm Zr	12	- 2.6	---	Yes	
287AR	Rerun 287A in clean Hg	30	- 0.2	---	No	
288	347 (Ann) + 2ppm Zr	30	-13.9	---	Yes	
288R	Rerun 288 in clean Hg	30	- 1.1	0.0025	Yes	
288A	347 (Ann) + 2ppm Zr	30	-12.4	---	Yes	
288AR	Rerun 288A in clean Hg	30	- 1.0	---	No	Oxidized.
360	347 (Ann) + 2ppm Ti	12	- 0.6	---	Yes	
360A	347 (Ann) + 2ppm Ti	12	- 0.3	---	Yes	
361	347 (Ann) + 2ppm Ti	30	- 6.7	0.0025	Yes	Intergranular cusps; deposit.
361A	347 (Ann) + 2ppm Ti	30	- 2.1	---	Yes	
369A	347 (Ann)	14	- 0.1	0.00014	Yes	Metasalts high purity Hg. Crevice attack.
362	347 (Ann) + 2ppm Ti	60	+ 0.3	0.00013	Yes	Crevice attack; deposit.
362A	347 (Ann) + 2ppm Ti	60	-11.05	0.002	Yes	
390	AlSi 1010	90	- 2.2	0.00028	Yes	Crevice attack.
390A	AlSi 1010	90	- 1.5	---	Yes	
391	Sicromo 5S	90	- 0.5	0.0004	Yes	Crevice attack. Heavy deposit.
391A	Sicromo 5S	90	--	---	---	Capsule cracked.
392	Type 440	90	- 0.9	0.00014	No	Crevice attack.
392A	Type 440	90	- 1.2	---	No	
375	PH15-7Mo (TH 1050)	90	- 1.2	0.00014	Yes	Crevice and half-moon attack.
375A	PH15-7Mo (TH 1050)	90	- 1.2	---	Yes	
347	PH15-7Mo (TH 1050) +2ppm Ti	112	- 2.1	0.0006	Yes	Wetted within 1 day. Crevice attack.
323	17-7 PH (A)	30	- 0.6	---	Slight	
323A	17-7 PH (A)	30	- 0.9	0	Slight	
324	17-7 PH (A)	65	- 0.7	0	Yes	
324A	17-7 PH (A)	65	- 1.0	---	Yes	
350	AMS 5623	19	- 0.3	0	Yes	
351	AMS 5623	19	- 0.3	0	Yes	
352	AMS 5623	32	- 0.5	0.00012	Yes	
353	AMS 5623	32	- 0.4	---	Yes	
354	AMS 5623	60	- 0.6	0.00005	Yes	
355	AMS 5623	60	- 2.6	0.0012	Yes	Crevice, intergranular.
370	BGL1 (Qt)	30	- 0.2	0	Yes	
370A	BGL1 (Qt)	30	- 0.2	---	Yes	
371	BGL1 (Qt)	60	- 0.6	---	Slight	
371A	BGL1 (Qt)	60	- 0.6	---	Slight	
372	BGL1 (Qt)	90	- 0.4	0.00028	Partial	Crevice attack.
372A	BGL1 (Qt)	90	- 0.5	---	Partial	
272	Neatro (AISI Type M4)	57	- 1.4	0	Yes	
272A	Neatro	57	- 1.4	---	Yes	
296	Neatro (Ht)	30	- 0.1	0.00028	No	
296A	Neatro (Ht)	30	0	---	No	
297	Neatro (Ht)	60	0	0	Slightly	
297A	Neatro (Ht)	60	0	---	Slightly	
274	Chromewear (AISI Type A7)	57	- 0.8	0.00028	Yes	
274A	Chromewear	57	- 1.3	---	Yes	
279	Chromewear (Ht)	30	+ 0.8	0.00005	Yes	
279A	Chromewear (Ht)	30	+ 0.6	---	Yes	
280	Chromewear (Ht)	60	- 1.1	0.0023	Yes	
280A	Chromewear (Ht)	60	- 0.8	---	Yes	
346	AlSi Type M 4 (Qt) + 2ppm Ti	112	- 2.2	0.0006	Yes	Wetted within 1 day.
325	440 C (Qt)	12	- 0.2	0	No	
325A	440 C (Qt)	12	- 0.4	0	No	
326	440 C (Qt)	30	- 0.7	0	Slightly	
326A	440 C (Qt)	30	- 0.4	---	Slightly	
327	440 C (Qt)	60	- 0.9	0	Yes	
327A	440 C (Qt)	60	- 0.7	0	Yes	Crystal deposit.
330	Hastelloy B	30	- 2.9	0.0044	Yes	Crevice and intergranular-one area.
330A	Hastelloy B	30	- 2.0	---	Yes	
331	Hastelloy B	60	-102.9	---	Yes	
331A	Hastelloy B	60	-112.1	0.0014	Yes	Crevice and general attack.

* See Table 2 for heat treatment procedure.

** O₂ treatment: Three hour oxidation in wet hydrogen at 1400°F.

TABLE 3 (Contd.)
Bent Reflux Tube Test Data at 900°F

Test No.	Material & Condition	Test Time Days	Weight Change Mg	Penetration Inches	Wetted	Remarks
334	Hastelloy C	30	- 0.4	0.0011	Yes	Deposition.
334A	Hastelloy C	30	- 0.8	---	Yes	
335	Hastelloy C	60	-78.2	0.0027	Yes	Crevise, general solution.
335A	Hastelloy C	60	-81.5	---	Yes	
332	Hastelloy F	30	-26.1	0.0013	Yes	Layer and crevice attack; crystal deposit.
332A	Hastelloy F	30	-26.3	---	Yes	
333	Hastelloy F	60	- 4.9	---	Yes	Amalgam on surface.
333A	Hastelloy F	60	- 2.4	0.0011	Yes	Amalgam on surface, heavy crystal deposit.
368	Hastelloy B	30	-55.3	0.0032	Yes	
369	Hastelloy C	30	-124.8	---	Yes	
367	Hastelloy F	30	-41.6	---	Yes	
317	Tenelon	12	-14.1	0.0177	Yes	
317A	Tenelon	12	-18.8	---	Yes	
318	Tenelon	30	-56.6	0.0085H	Yes	
318A	Tenelon	30	-54.2	---	Yes	
319	Tenelon	60	+27.7	0.0172	Yes	Amalgam on surface.
319A	Tenelon	60	+135.0	0.0125	Yes	Amalgam on surface
395	AlSi M10 (Qt)	31	- 0.9	0.00011	No	Crevise attack
395A	AlSi M10 (Qt)	31	- 0.3	---	No	
394	AlSi M10 (Qt)	60	- 1.0	---	Slight	
394A	AlSi M10 (Qt)	60	- 1.3	0.0004	Slight	Intergranular and crevice attack.
393	AlSi Type M 10	90	- 1.6	0.00012	Yes	Crevise attack.
393A	AlSi Type M 10	90	- 1.4	---	Yes	
417	Type T 15 (Qt)	30	- 0.1	0.00005	No	Crevise attack.
417A	Type T 15 (Qt)	30	- 0.3	---	No	
418	Type T 15 (Qt)	60	- 1.0	0.00008	No	
418A	Type T 15 (Qt)	60	- 1.0	---	Partial	
437	Type M 36 (Qt)	30	- 0.3	0.00002	No	Pitting and deposition.
437A	Type M 36 (Qt)	30	- 0.2	---	Partial	
438A	Type M 36 (Qt)	36	+ 0.4	---	Yes	Capsule cracked. Spec. Oxidized.
438	Type M 36 (Qt)	60	- 0.6	0.000025	Partial	
438A	Type M 36 (Qt)	62	- 1.0	0.00005	Yes	
320	Vicalloy I	12	- 0.1	---	No	
320A	Vicalloy I	12	- 0.1	---	No	
321	Vicalloy I	30	- 0.3	0	No	
321A	Vicalloy I	30	- 0.4	---	No	
322	Vicalloy I	60	- 0.7	0	Yes	
322A	Vicalloy I	60	- 0.4	---	Yes	
429	Haynes Stellite 31	30	- 2.2	0.00028	Yes	Crevise attack along second phase.
429A	Haynes Stellite 31	30	- 3.0	---	Yes	
430	Haynes Stellite 31	60	- 4.5	0.0005	Yes	
428A	Haynes Stellite 21	12	- 2.3	0.00012	Slight	Crevise attack.
425A	Haynes Stellite 21	30	- 4.3	---	Yes	
425	Haynes Stellite 21	30	- 4.1	0.0005	Yes	Crevise attack.
425A	Haynes Stellite 21	30	- 4.3	---	Yes	
426	Haynes Stellite 21	60	- 7.9	0.00028	Yes	
426A	Haynes Stellite 21	60	- 5.2	---	Yes	
421	Haynes Alloy 56	30	- 24.1	0.003	Yes	Intergranular cusps
421A	Haynes Alloy 56	30	- 13.3	---	Yes	
422	Haynes Alloy 56	60	- 28.5	0.0045	Yes	
422A	Haynes Alloy 56	60	- 31.3	---	Yes	
291	Haynes Alloy 25 + 2 ppm Zr	30	0	---	Yes	
291R	Rerun 291 in clean Hg	30	- 0.4	0	No	Metallic layer.
291A	Haynes Alloy 25 + 2 ppm Zr	30	0	---	Yes	
291AR	Rerun 291A in clean Hg	30	- 0.4	---	No	
292	Haynes Alloy 25 + 2 ppm Zr	30	0	---	Yes	
292R	Rerun 292 in clean Hg	60	- 1.5	0.00013	No	Oxidized black. Crevise attack.
292A	Haynes Alloy 25 + 2 ppm Zr	30	0	0.00014	Yes	light crevice attack
293	Haynes Alloy 25 + 2 ppm Zr	12	- 0.3	---	Yes	
293R	Rerun 293 in clean Hg	30	0	0	No	Layer of oxide
293A	Haynes Alloy 25 + 2 ppm Zr	12	- 0.3	---	Yes	
293AR	Rerun 293A in clean Hg	30	0	---	No	
369	Haynes Alloy 25	30	- 0.5	0.00013	Slight	Metallic Crp. High purity Hg. Slight intergranular.
376	Haynes Alloy 25	90	- 1.2	---	Yes	
376A	Haynes Alloy 25	90	- 2.9	0.000	Yes	Crevise attack.
336	Haynes Alloy 25 + 20 ppm Mg + 2 ppm Ti	12	0	0	Yes	
336A	Haynes Alloy 25 + 20 ppm Mg + 2 ppm Ti	12	0	---	Yes	
336AR	Rerun 336A in clean Hg	30	0	0	No	
337	Haynes Alloy 25 + 20 ppm Mg + 2 ppm Ti	30	0	0	Yes	
337A	Haynes Alloy 25 + 20 ppm Mg + 2 ppm Ti	30	0	---	Yes	

TABLE 3 (Contd.)

Bent Reflux Tube Test Data at 900°F

Test No.	Material & Condition	Test Time Days	Weight Change Mg	Penetration Inches	Wetted	Remarks
349	Haynes Alloy 25 + 20 ppm Mg + 2 ppm Ti	3	---	---	Yes	
349R	Rerun 349 in clean Hg	60	-0.6	0.00028	Yes	Crevice attack. Layer deposit.
380	Haynes Alloy 25 + 2 ppm Ti + 20 ppm Mg	120	-1.0	0.00028	Yes	Semi-circular areas of attack.
380A	Haynes Alloy 25 + 2 ppm Ti + 20 ppm Mg	120	-5.7	0.0005	Yes	Certain atomic planes attacked.
381	Haynes Alloy 25 + 2 ppm Ti	120	-2.7	0.00028	Yes	Crevice attack.
381A	Haynes Alloy 25 + 2 ppm Ti	120	-3.1		Yes	
348	Haynes Alloy 25 + 20 ppm Mg + 2 ppm Ti	3	--	--	Yes	
348R	Rerun 348 in clean Hg	30	--	0	Yes	
345	Haynes Alloy No. 25 + 2 ppm Ti	112	+0.9	0.00028	Yes	Wetted within 1 day; deposit.
455	Nivco 10	12	-2.8	0.0003	Yes	Crevice attack.
455A	Nivco 10	12	-3.1		Yes	
456	Nivco 10	30	-5.2	0.0005	Yes	
456A	Nivco 10	30	-4.9		Yes	
312	Haynes Stellite 151	30	-2.3	0.0005	No	General dissolution; crystal deposit.
312A	Haynes Stellite 151	30	-1.7	--	No	
263	Cb-5Ti, 5W (80% cold rolled)	29	+0.2	0.00028	Yes	Crevice attack and deposition.
264	Cb-10Ti, 10W, 12r (80% cold rolled)	29	+0.7	0.00028	Yes	Crevice attack?
265	Cb-10Ti, 10W (80% cold rolled)	29	+0.3	0.0014	Yes	Crevice attack?
373	Beryllium	30	-4.2	0.0008	Yes	Crevice attack.
373A	Beryllium	20	-8.4		Yes	
374	Beryllium	60	-11.6	0.0014	Yes	Amalgam on surface. Crevice attack.
329	Vanadium (cold rolled)	12	0	--	Yes	
329A	Vanadium (cold rolled)	30	- 0.9	0	Yes	
329B	Vanadium (cold rolled)	60	- 0.6	0	Yes	
310	Ferrotic, S-45	30	- 3.2	.00013	Yes	
310A	Ferrotic, S-45	30	- 0.9	--	Yes	
311	Ferrotic, S-55	30	- 1.1	--	Slight	
311A	Ferrotic, S-55	30	- 4.5	0.00028	Slight	
356	Ferrotic, S45	60	- 1.9	--	Yes	
357	Ferrotic, S45	60	- 2.0	0.0005	Yes	Metallic deposit - heavy.
358	Ferrotic, S55	60	- 1.5	--	Yes	
359	Ferrotic, S55	60	- 1.8	0.0004	Yes	Heavy metallic deposit.

TABLE 4

Bent Reflux Tube Test Data at 600°F for Selected Materials

Test No.	Material & Condition	Test Time Days	Weight Change Mg	Penetration Inches	Wetted	Remarks
402	Sicromo 5S	30	+ 0.5		No	Crevice attack on all specimens. Deposition on all specimens.
402A	Sicromo 5S	30	+ 0.4		No	
403	Sicromo 5S	60	- 0.1		No	
403A	Sicromo 5S	60	+ 0.2		No	
404	Sicromo 5S	90	+ 0.5	0.00028	No	Deposition.
404A	Sicromo 5S	90	+ 0.8		No	
405	Type 410 (Qt)	30	0		No	
405A	Type 410 (Qt)	30	- 0.1		No	
406	Type 410 (Qt)	60	0		No	
406A	Type 410 (Qt)	60	0		No	
407	Type 410 (Qt)	90	- 0.1	0.00005	No	Crevice.
407A	Type 410 (Qt)	90	- 0.2		No	
399	PH15-7Mo (TH 1050)	30	+ 0.3		No	
399A	PH15-7Mo (TH 1050)	30	+ 0.2		No	
400	PH15-7Mo (TH 1050)	60	+ 0.1		No	
400A	PH15-7Mo (TH 1050)	60	0		No	
401	PH15-7Mo (TH 1050)	90	0		No	
401A	PH15-7Mo (TH 1050)	90	- 0.1	0.00028	No	
396	AlSi 1010	30	+ 0.3	0.0001	No	Deposition.
396A	AlSi 1010	30	+ 0.2		No	
397	AlSi 1010	60	+ 0.2		No	Crevice attack and deposition on all specimens.
397A	AlSi 1010	60	0		No	
398	AlSi 1010	90	- 0.2	0.00014	No	
398A	AlSi 1010	90	- 0.2		No	
408	Haynes Alloy No. 25	30	- 0.1		No	
408A	Haynes Alloy No. 25	30	- 0.1		No	
409	Haynes Alloy No. 25	60	0	0.00028	No	
409A	Haynes Alloy No. 25	60	0		No	
410	Haynes Alloy No. 25	90	+ 0.2		No	

TABLE 4 (Contd.)

Bent Reflux Tube Test Data at 600°F for Selected Materials

Test No.	Material & Condition	Test Time Days	Weight Change Mg	Penetration Inches	Wetted	Remarks
410A	Haynes Alloy No. 25	90	-0.1	0.00005	No	
411	Haynes Alloy No. 25					
	+ 2ppm Ti	30	+0.4	0	Yes	Deposit.
411A	Haynes Alloy No. 25					
	+ 2ppm Ti	30	+0.4		Yes	
412	Haynes Alloy No. 25					
	+ 2 ppm Ti	60	+1.3		Yes	
412A	Haynes Alloy No. 25					
	+ 2ppm Ti	60	-0.6		Yes	
413	Haynes Alloy No. 25					
	+ 2ppm Ti	90	+1.0	0.00014	Yes	0.00005 in. crevice attack in carbide segregated area.
413A	Haynes Alloy No. 25					
	+ 2ppm Ti	90	0		Yes	
414	Haynes Alloy No. 25					
	+ 2ppm Ti + 20ppm Mg	30	+0.1	0.00028	Yes	Deposit, crevice attack
414A	Haynes Alloy No. 25					
	+ 2ppm Ti + 20ppm Mg		0		Yes	
415	Haynes Alloy No. 25					
	+ 2ppm Ti + 20ppm Mg	60	+0.2	0.0004	Yes	
415A	Haynes Alloy No. 25					
	+ 2ppm Ti + 20ppm Mg	60	+0.3		Yes	
416	Haynes Alloy No. 25					
	+ 2ppm Ti + 20ppm Mg	90		0.00008		
416A	Haynes Alloy No. 25					
	+ 2ppm Ti + 20ppm Mg	90	+0.7		Yes	

TABLE 5

Bent Reflux Tube Test Data at 700°F for Selected Materials

Test No.	Material & Condition	Test Time Days	Weight Change Mg	Penetration Inches	Wetted	Remarks
364	Sicromo 5S	30	-0.2	0	No	Crystal deposit.
364A	Sicromo 5S	30	-0.2	0.00022	No	Crevice attack; Crystal deposit.
363	Sicromo 5S	90	0	0.0003	No	Crevice and intergranular attack.
363A	Sicromo 5S	90	-1.2	---	No	
365	410 (Qt)	30	-0.2	0.00017	No	Crevice attack; deposit.
365A	410 (Qt)	30	-0.2	0.00013	No	Crevice attack; deposit.
366	410 (Qt)	90	-0.5	0.00014	No	Crevice attack; deposit.
366A	410 (Qt)	90	-0.5	---	No	
367	AlSi 1010	30	-0.5	0.00013	No	Crevice attack; deposit.
367A	AlSi 1010	30	-0.2	0.0008	No	Crevice attack; deposit.
368	AlSi 1010	90	-0.4	0.00014	No	Crevice attack; deposit.
368A	AlSi 1010	90	-0.3	0.00014	No	
379	Haynes Alloy 25	31	-0.2	0.00028	No	Deposition.
379A	Haynes Alloy 25	31	-0.2	0.00028	No	Crevice attack; deposit.
377	Haynes Alloy 25	90	0	---	No	Crevice attack; deposit.
377A	Haynes Alloy 25	90	-0.2	0.0004	No	Crevice attack; deposit.
378	PH15-7Mo (TH 1050)	31	0	0.00028	No	Crevice attack. Deposition.
378A	PH15-7Mo (TH 1050)	31	-0.2	0.0005	No	Crevice attack; deposit.
385	Haynes Alloy 25+Ti+Mg	30	0		Yes	
385A	Haynes Alloy 25+Ti+Mg	30	+0.4	0.00028	Yes	Crevice attack; deposit
386	Haynes Alloy 25+Ti+Mg	63	0	0	Yes	Deposit.
386A	Haynes Alloy 25+Ti+Mg	63	+0.3	---	Yes	
382	PH15-7Mo (TH 1050)	63	+0.4	0	No	
382A	PH15-7Mo (TH 1050)	63	+0.5	---	No	
383	PH15-7Mo (TH 1050)	90	+0.3	0.00014	No	Oxidized? Crevice attack; deposit.
383A	PH15-7Mo (TH 1050)	90	+0.2		No	Oxidized.
384	Haynes Alloy 25+2ppmTi60		0	0	Yes	
384A	Haynes Alloy 25+2ppmTi60		+0.1	0.00028	Yes	Crevice attack; deposit.

TABLE 6

Bent Reflux Tube Test Data at 1000°F for Selected Materials

Test No.	Material & Condition	Test Time Days	Weight Change Mg	Penetration Inches	Wetted	Remarks
341	1010	30	-4.1	0.0005	Yes	Crevice attack.
344	Haynes Alloy 25	30	-2.1	0	Yes	Deposits.
343	PH15-7Mo (TH1050)	30	-3.2	0.0021	Yes	Cracking along ferrite grains.
342	410 (Qt)	30	-4.5	0.001	Yes	Crevice attack. Deposition.
442	Haynes Alloy 25	10	-4.0	0.0006	Yes	Crevice attack.
443	Haynes Alloy 25	30	-3.1	0.0006	Yes	Discolored spec. Deposit.
443A	Haynes Alloy 25	30	-1.2		Yes	Discolored spec.
444	Haynes Alloy 25 + 2ppm Ti	30	-1.9	0.00028	Yes	
444A						
445	Haynes Alloy 25 + 2ppm Ti + 20 ppm Mg	30	-3.9	0.0007	Yes	
445A	Haynes Alloy 25 + 2ppm Ti + 20 ppm Mg					
450	410 (Qt)	30	-1.3	0.0004	Yes	Crevice attack. Deposit.
450A	410 (Qt)					
448	1010	30	-1.0	0.0006	Yes	Crevice attack.
448A	1010					
446	PH15-7Mo (TH 1050)	30	-1.7	0.00028	Yes	Crevice attack. Deposit.
446A	PH15-7Mo (TH 1050)		-1.5		Yes	

TABLE 7

Bent Reflux Tube Test Data at 900°F for Various Bimetallic Combinations

Test No.	Material & Condition	Test Time Days	Weight Change Mg	Penetration Inches	Wetted	Remarks
459	Haynes Alloy 25	30	-1.3	0.00028	No	Deposition.
	410 (Qt)		-0.4	0.0027	Yes	Pitted; deposition.
459A	Haynes Alloy 25	30	-1.2		Yes	
	410 (Qt)		-0.4		Yes	
463	Haynes Alloy 25	30	-1.7	0.0022	Yes	Crevice attack; deposition.
	PH15-7Mo (cond TH 1050)		-0.2	0.00014	Yes	Crevice attack; deposition
463A	Haynes Alloy 25	30	-1.1		No	
	PH15-7Mo (cond TH 1050)		-0.5		Yes	
467	Haynes Alloy 25	30	-2.1	0.00014	Yes	Crevice attack; deposition. Amalgam on contact surface.
	347 (Ann)		-7.3	0.0022	Yes	
467A	Haynes Alloy 25	30	-2.6		Yes	
	347 (Ann)		-6.5		Yes	
471	Haynes Alloy 25	30	-0.2	0.0006	No	Crevice attack; deposition.
	17-4PH (cond TH 1050)		-0.6	0.00028	No	Crevice attack; deposition.
471A	Haynes Alloy 25	30	-1.0		Yes	
	17-4PH (cond TH 1050)		-0.9		No	
338	Hyperco 27 brazed with J 8400 to Haynes 25	12	0	0	Yes	
339	Hyperco 27 brazed with J 8400 to Haynes 25	33	-0.3	0	Yes	Crystal deposit.
340	Hyperco 27 brazed with J 8400 to Haynes 25	60	-0.4	0	Yes	
313	Braze J 8400 on Haynes 25	30	-0.2	0	No	
316	Braze J 8400 on Haynes 25	12	-0.2		Yes	
316A	Braze J 8400 on Haynes 25	30	-0.1	0.0008	No	General dissolution. Crystal deposit.

TABLE 8

Bent Reflux Tube Test Data at 600°F for Various Bimetallic Combinations

Test No.	Material & Condition	Test Time Days	Weight Change Mg	Penetration Inches	Wetted	Remarks
457	Haynes Alloy 25	30	+0.1	0.0002	No	Crevice attack; deposition.
	410 (Qt)		0	0.0001	No	Crevice attack; deposition.
457A	Haynes Alloy 25	30	+0.1	0.0004	No	Crevice attack; deposition.
	410 (Qt)		-0.3	0.00028	No	Crevice attack; deposition.
461	Haynes Alloy 25	30	0	0.0008	No	Crevice attack; deposition.
	PH15-7Mo (cond TH 1050)		-0.2	0.0004	No	Crevice attack; deposition.
461A	Haynes Alloy 25	30	0		No	
	PH15-7Mo (cond TH 1050)		0		No	
465	Haynes Alloy 25	30	0	0.00028	No	Crevice attack; deposition.
	347 (Ann)		-0.2	0.0002	No	Crevice attack.
465A	Haynes Alloy 25	30	-0.3		No	
	347 (Ann)		-0.6		No	
469	Haynes Alloy 25	30	0	0.00005	No	Crevice attack; deposition.
	17-4 PH (cond TH 1050)		-0.3	0.00028	No	Crevice attack; deposition.
469A	Haynes Alloy 25	30	0		No	
	17-4 PH (cond TH 1050)		-0.2		No	
473	Haynes Alloy 25 + dirty Hg	30	-0.6	0.00014	Yes	Crevice.
473A	Haynes Alloy 25 + dirty Hg	30	-0.6		Yes	
474	410 (Qt) + dirty Hg	30	-0.2	0.0001	Yes	Crevice; deposition.
474A	410 (Qt) + dirty Hg	30	0		Yes

TABLE 9

Chemical Analysis of Mercury and Deposit From
Haynes Alloy 25-PH15-7Mo Stainless Steel Loop (5)

Deposit (1.852g)

Wet Analysis:

Cr - 3.29%	Co - 15.90%	Mg - 1.06%
W - 3.77	Fe - 12.09	Hg - bal

Spectrographic Analysis:

Major - Co, Cr
Appreciable - Fe, Mn
Minor - Ni, Mg, W
Trace - Ag, Al, Ca, Cu, Si, Ti, Mo

Mercury Residue

Spectrographic Analysis:

Major - Cr, Co, Ni, Fe, Mn, Cu
Minor - Ag, Si, Sn, Pb, Ti, Mo, W

Mercury Filtrate

Spectrographic Analysis:

Trace - Si, Ag, Ca
Faint Trace - Mg

Adherent Superheater Deposit

Spectrographic Analysis:

High - Mn, Ag, Co
Present - Si, Cr, Ni, Cu, Fe, W, Hg
Trace - Ca, Al, Ti
Faint Trace - Mg

TABLE 10

Chemical Analysis of Mercury From Haynes Alloy 25 Loop (6)

Pretreatment Mercury

Residue (0.3g)

Wet Analysis:

2.91% Mg
0.48% Ti
bal Hg

Filtrate

Spectrographic Analysis:

appreciable - Mg, Mn
minor - Al, Ca, Cu, Fe, Si, W
Trace - Ag, Mo, Sn

5000 Hour Run Mercury

Residue (0.1g)

Wet Analysis:

10.3% Mg	39.1% Co
1.32 Ti	4.84 W
9.26 Cr	0.68 Fe
Nil Ni	

Spectrographic Analysis:

major - Mg, Cr, Co, Hg
minor - Fe, Ti, Si, W
trace - Al, Ca, Cu, Mo, Sn, Ag

Filtrate

Spectrographic Analysis:

trace - Si, Ca, Mg

TABLE 11

Chemical Analysis of Deposits from Haynes Alloy 25 Loop (6)

<u>Location</u>	<u>Weight-Grams</u>		<u>Elements (Based on Dry Weight)</u>								
	<u>Total</u>	<u>Dry</u>	<u>W</u>	<u>Mg</u>	<u>Fe</u>	<u>Cr</u>	<u>Co</u>	<u>Ni</u>	<u>Ti</u>	<u>Mn</u>	<u>Hg</u>
Subcooler	13.44	3.00	0.4	1.15	0.56	11.97	16.51	nil	nil	nil	bal
Boiler through Superheater	0.946	0.600	0.7	1.18	1.33	2.08	21.9	nil	nil	nil	bal
Post Condenser	1.459	1.00	0.3	1.69	0.48	4.99	19.50	nil	nil	nil	bal

Spectrographic analysis of each deposit was the same as listed below:

major - Co, Cr, Hg

minor - Cu, Ni, W, Mg, Fe, Mn, Ti

trace - Al, Ag, Ca, Si, Sn, Mo

Spectrographic analysis of adherent superheater deposit:

high - Mn, Ni, Ag, Hg

present - Cr, Cu, Co, Ti

trace - Ca, Mg

faint trace - Si, Al, W

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Langley Research Center
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George C. Marshall Space Flight Center
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National Aeronautics and Space Administration
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Washington 25, D.C.
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Director NASA Western Operations Office
150 Pico Blvd.
Santa Monica, California
Attn: Mr. John S. Keeler

Naval Ordnance Laboratory 1

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U.S. Naval Ordnance Laboratory
White Oak
Silver Spring, Maryland

Naval Radiological Defense Laboratory 1

Commanding Officer and Director
U.S. Naval Radiological Defense Laboratory
San Francisco 20, California
Attn: Dr. Eugene P. Cooper

Naval Research Laboratory 2

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U.S. Naval Research Laboratory, Code 1572
Washington 25, D.C.
Attn: Classified Material Control Branch

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U.S. Atomic Energy Commission
New York Operations Office
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New York 14, New York
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Nuclear Development Corp. of America 2

Nuclear Development Corp. of America
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Office of the Chief of Ordnance, DOFL 1

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Diamond Ordnance Fuze Laboratories
Washington 25, D.C.
Attn: ORDTL 06.33, Mrs. Elizabeth W. Channell

Office of Naval Research 2

Office of Naval Research
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Office of Technical Information Extension,
USAEC, Oak Ridge, Tennessee 30

U.S. Atomic Energy Commission
Office of Technical Information Extension
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Power Information Center, University of Pennsylvania 1

University of Pennsylvania
The Institute for Cooperative Research
3400 Walnut Street
Philadelphia 4, Pennsylvania
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Project RAND 1

Los Angeles Air Procurement District
1700 Main Street
Santa Monica, California
Attn: Administrative Contracting Officer
For: Frank R. Collbohm

Rome Air Development Center 1

Commander, Rome Air Development Center
Griffiss Air Force Base, New York
Attn: J.L. Briggs Jr.
Directorate of Engineering

School of Aviation Medicine 1

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School of Aviation Medicine
USAF Aerospace Medical Center (ATC)
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Wright Air Development Division 3

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Brookhaven National Laboratory 1

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