UNCLASSIFIED

[redacted]

ORNL-1934
C-84 – Reactors–Special Features of Aircraft Reactors

This document consists of 40 pages.
Copy 160 of 186 copies. Series A.

Contract No. W-7405-eng-26

METALLURGY DIVISION

AN EVALUATION OF THE CORROSION AND OXIDATION RESISTANCE OF HIGH-TEMPERATURE BRAZING ALLOYS

E. E. Hoffman C. F. Leitten, Jr.
P. Patriarca G. M. Slaughter

Period Covered by Work: July 1954 – September 1955

Work Performed by

J. E. Pope C. E. Shubert
L. C. Williams

Metallographic Work by

M. D. Allen R. M. Wallace
R. J. Gray

DATE ISSUED

NOV 7 1956

Classification cancelled (or changed to UNCLASSIFIED)
by authority of Lt. Jr. Declassification Branch, dated 10/9/59
by JB T.I. date 10/21/59

OAK RIDGE NATIONAL LABORATORY
Operated by
UNION CARBIDE NUCLEAR COMPANY
A Division of Union Carbide and Carbon Corporation
Post Office Box P
Oak Ridge, Tennessee

RESTRICTED DATA

This document contains Restricted Data as defined in the Atomic Energy Act of 1954. Its transmittal or the disclosure of its contents in any manner to an unauthorized person is prohibited.

SECRET

UNCLASSIFIED

CONTENTS

AN EVALUATION OF THE CORROSION AND OXIDATION RESISTANCE OF HIGH-TEMPERATURE BRAZING ALLOYS

E. E. Hoffman
P. Patriarca
C. F. Leitten, Jr.
G. M. Slaughter

INTRODUCTION

The fabrication of heat exchangers and radiators to be used in conjunction with high-temperature nuclear reactors may present exceedingly complex problems. Rigid heat transfer requirements may necessitate the use of compact assemblies of thin-walled small-diameter tubes as integral parts of the heat transfer units. Intricate designs may also be required in which cooling fins must be securely joined to the tubes at closely spaced intervals.

In addition to the difficulties in fabrication imposed by the designs themselves, the high operating temperatures involved require the careful selection of materials and joining techniques. The choice of fabrication procedure for a given component must not only be based upon the stresses and temperatures to be encountered, but also upon special factors peculiar to nuclear service. Since many reactor applications employ highly corrosive environments, compatibility of the structural materials with the corrosive media is of paramount importance. The low nuclear cross-section requirement for brazing alloys to be used inside the reactor also places stringent limitations on the possible choices of in-pile applications. The use of boron in alloys for certain service may not be considered feasible, for example, because of its high nuclear absorption cross section.

Although welding is used extensively in the construction of radiators and heat exchangers, high-temperature brazing is also attractive for several applications.[1] In Fig. 1, a photograph of a liquid-metal-to-air radiator, it can be seen that brazing serves as the most feasible method of attaching cooling fins to thin-walled tubes. Typical of the joints obtainable is that shown in Fig. 2, in which are shown stainless-steel-clad-copper high-conductivity fins[2] brazed to an Inconel tube. High-temperature brazing is also advantageous as a means for reinforcing tube-to-header welds. In Fig. 3, a photomicrograph of a typical back-brazed tube-to-header weld, it can be seen that only partial weld penetration was obtained. The brazed joint eliminates the notch effect and assists in the prevention of serious leaks in the system if corrosion through localized areas of shallow weld penetration occurs during service.

A long-range brazing alloy development and evaluation program has therefore been in progress in the Metallurgy Division of the Oak Ridge National Laboratory for several years to obtain fundamental information regarding the feasibility of using brazing alloys in high-temperature heat exchanger and radiator applications. Numerous commercially available brazing alloys have been extensively investigated as have many more alloys developed at ORNL and other laboratories. Listings of the alloys and their brazing temperatures are presented in Tables 1 and 2. Initial tests, which are performed by the Welding and Brazing Group, permit a determination of the general overall suitabilities of the alloys for high-temperature, dry-hydrogen (flux-free) brazing. These tests include preliminary studies of such properties as flow point, flowability, and ductility. The Welding and Brazing Group also conducts high-temperature oxidation tests on brazed joints and, in general, correlates information and test results obtained from other groups in the Metallurgy Division and from certain outside sources. Corrosion studies on these alloys have been under the direction of the General Corrosion Group and limited physical property tests have been conducted by the Physical Testing Group. This paper, however, covers only the results of the high-temperature corrosion and oxidation testing programs. Comments on the other phases of investigation are added only where they are pertinent to the subject under discussion.

As a result of these investigations and evaluations, it is possible to suggest logical brazing

[1] P. Patriarca *et al.*, *Fabrication of Heat Exchangers and Radiators for High-Temperature Reactor Applications*, ORNL-1955 (June 14, 1956).

[2] H. Inouye, *A High-Conductivity Fin Material for Radiators*, ORNL-2065 (to be published).

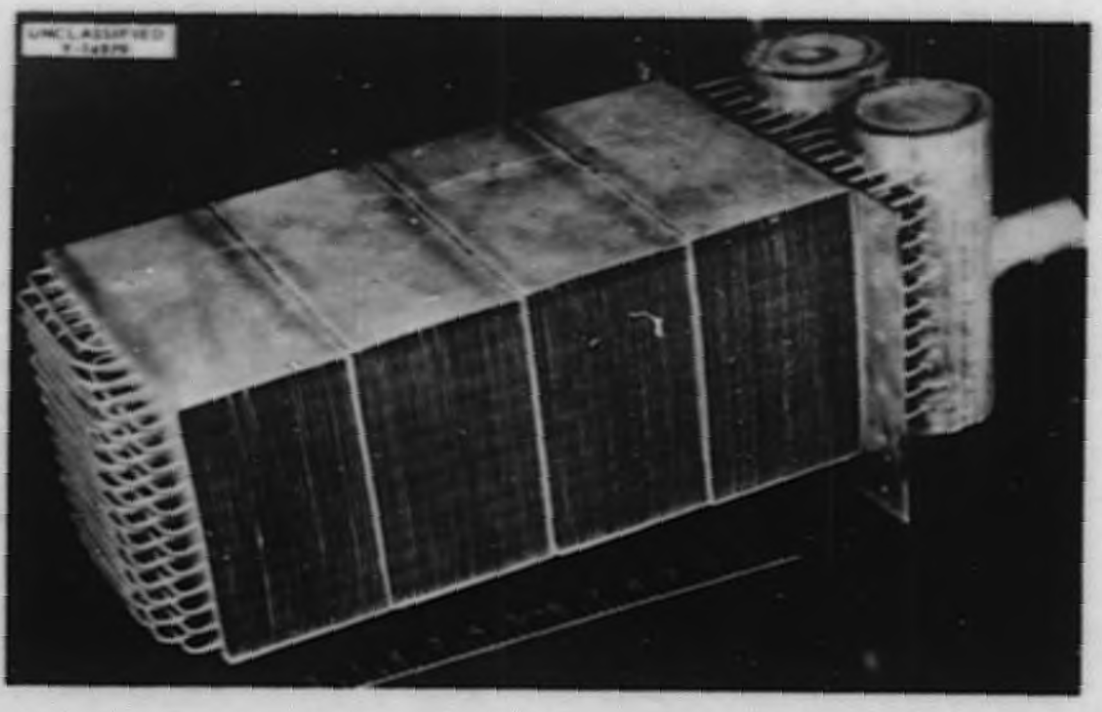

Fig. 1. Sodium-to-Air Radiator in Which Stainless-Steel-Clad-Copper High-Conductivity Fins Are Brazed to Inconel Tubes.

Fig. 2. Photomicrograph of a Section of a Sodium-to-Air Radiator Showing a Brazed Tube-to-Fin Joint. As polished. 50X. Reduced 12.5%.

TABLE I. COMMERCIAL BRAZING ALLOYS

Composition (wt %)	Trade Name	Brazing Temperature (°F)
73.2 Ni–13.5 Cr–4.5 Si–3.5 B–4.5 Fe–0.8 C	Wall Colmonoy Nicrobraz	2050
83.4 Ni–6.0 Cr–5.0 Si–3.0 B–2.5 Fe–0.1 C	Wall Colmonoy LM Nicrobraz	2000
93.2 Ni–3.5 Si–1.9 B–1.4 Fe	Coast Metals No. 50	2050
91.8 Ni–4.5 Si–2.6 B–1.1 Fe	Coast Metals No. 51	1950
91.2 Ni–4.5 Si–2.9 B–3.5 Fe	Coast Metals No. 52	1900
82.1 Ni–7.0 Cr–4.5 Si–2.9 B–3.5 Fe	Coast Metals No. 53	1880
50.0 Ni–11.8 Si–29.3 Fe–3.5 P–5.4 Mo	Coast Metals NP	2050
100 Cu		2050

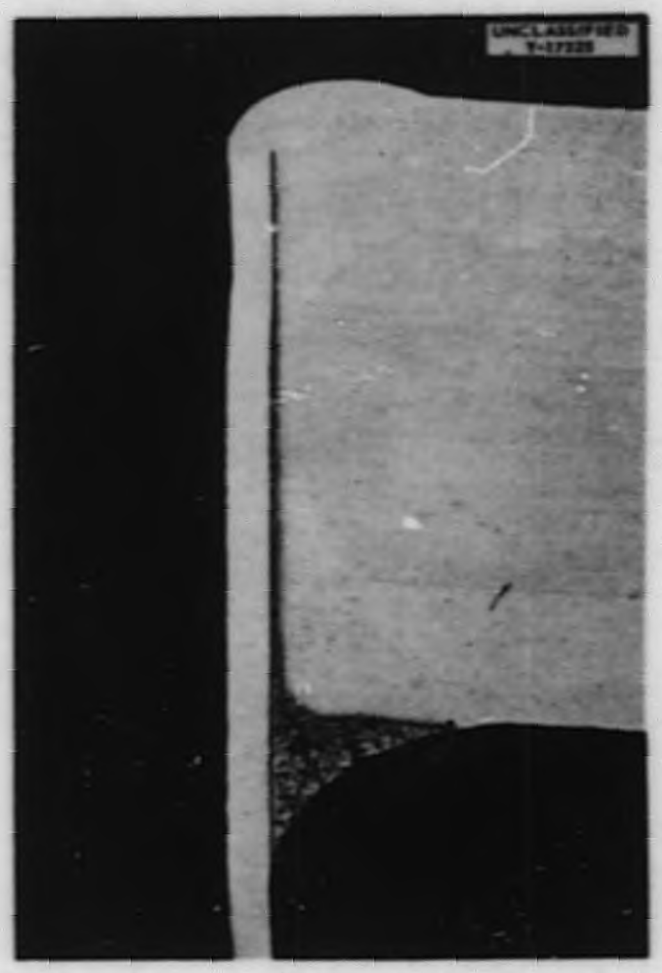

Fig. 3. Photomicrograph of a Typical Back-Brazed Tube-to-Header Weld. Etchant: oxalic acid. 12X. Reduced 14.5%.

alloys for specific applications. The most important of these applications are the following:

Sodium-to-Air Radiators[1] *(Fig. 1).* – Brazing is applicable to this fabrication problem for the production of tube-to-fin and back-brazed tube-to-header joints. Excellent resistance of the brazing alloy to high-temperature oxidation is a requisite and good compatibility with the liquid sodium is desirable. This second requirement results from the fact that the alloy may be in direct contact with the liquid metal if corrosion through an area of shallow penetration is present in the tube-to-header welds. This stipulation may also be important if dilution or solid state diffusion, through the tube wall during brazing or service, permits a relatively high concentration of brazing alloy constituents near the liquid-metal–tube-wall interface.

Fused-Fluoride-to-Sodium Heat Exchanger. – The use of liquid fluoride fuels in certain reactor applications creates a need for the fused-fluoride-to-sodium heat exchangers (Fig. 4). The liquid sodium passes through the small tubes while a flow of the fuel is maintained on the exteriors. Back-brazing of the tube-to-header joints is extremely desirable to minimize the formation and propagation of weld cracks during service. Although the brazing alloy is applied to the fuel side of these assemblies, its compatibility with liquid sodium is considered essential, since corrosion, dilution, or diffusion may bring the alloy or alloy constituents into contact with the fluid inside the tubes.

TABLE 2. EXPERIMENTAL BRAZING ALLOYS

Composition (wt %)	Brazing Temperature (°F)	Composition (wt %)	Brazing Temperature (°F)
87 Ni–13 Si (E-11)[a]	2150	88 Ni–10 P–2 Cr (C-27)[a]	1800
70 Ni–10 Si–20 Cr[b]	2150	77 Ni–10 P–13 Cr (C-29)[a]	1850
73 Ni–9 Si–18 Cr (F-11)[a]	2150	81 Ni–11 P–8 Mn (I-10)[a]	1950
54 Ni–10 Si–14 Cr–19 Fe–3 Mo (S-10)[a]	2175	79 Ni–10 P–11 Fe (D-11)[a]	1850
78 Ni–16 Si–6 Mn (P-10)[a]	2175	86 Ni–10 P–4 Mo (H-10)[a]	1850
82 Ni–10 Si–8 Mn (P-11)[a]	2000	80 Ni–11 P–9 Si (B-11)[a]	2050
64 Ni–6 Si–30 Mn (P-14)[a]	1950	89 Ni–5 P–6 Si (B-15)[a]	2000
75 Ni–25 Ge	2150	89 Ni–8 P–3 Si (B-17)[a]	1900
65 Ni–25 Ge–10 Cr	2100	88 Ni–3 P–9 Si (B-13)[a]	2050
70 Ni–13 Ge–11 Cr–6 Si	2080	80 Ni–9 P–11 W (G-20)[a]	2000
50 Ni–25 Mo–25 Ge	2150	71 Ni–9 P–15 Fe–5 Cr (J-10)[a]	2100
68 Ni–32 Sn	2150	64 Ag–33 Pd–3 Mn[e]	2150
40 Ni–60 Mn	1950	60 Pd–40 Ni	2300
35 Ni–55 Mn–10 Cr	2050	60 Pd–37 Ni–3 Si	2150
38 Ni–57 Mn–5 Cr (L-20)[a]	2000	92 Pd–8 Al	2020
90 Ni–10 P[c]	1800	90 Pd–10 Ge	2000
88 Ni–12 P (A-10)[a]	1800	82 Au–18 Ni	1830
77 Ni–23 P (A-16)[a]	2100	90 Au–10 Cu	1830
80 Ni–10 P–10 Cr[d]	1850	80 Au–20 Cu	1740

[a]Developed by Wall Colmonoy Corporation under Wright Air Development Center Materials Laboratory Contract No. AF 33(616)2287.

[b]General Electric No. 81 alloy.

[c]Electroless nickel.

[d]Electroless nickel with electrodeposited chromium.

[e]Developed by Mond Nickel Company.

Sodium Hydroxide Service.[3] – The desirability of sodium hydroxide as a circulating moderator is well known. However, its extremely corrosive reaction on most structural materials has prevented its use in reactor applications. Several brazing alloy systems were corrosion tested in this environment to obtain information with regard to their use in proposed systems containing this material.

The extent of corrosion and oxidation upon many potential high-temperature brazing alloys is presented in tabular form in this report and the most promising alloys for each environment combination are listed. Photomicrographs showing the resistance of many of these alloys to attack from sodium hydroxide are included to permit a visual analysis by the reader.

This report presents the results of tests conducted up to the present time. A continuing program is under way to determine the corrosion and oxidation resistance of other brazing materials as they are developed. Reports describing these later phases will be prepared as results of significance are obtained.

[3]*Proceedings of the First Information Meeting on Hydroxide and Metal Interaction*, ORNL CF-51-11-204 (Aug. 31, 1953).

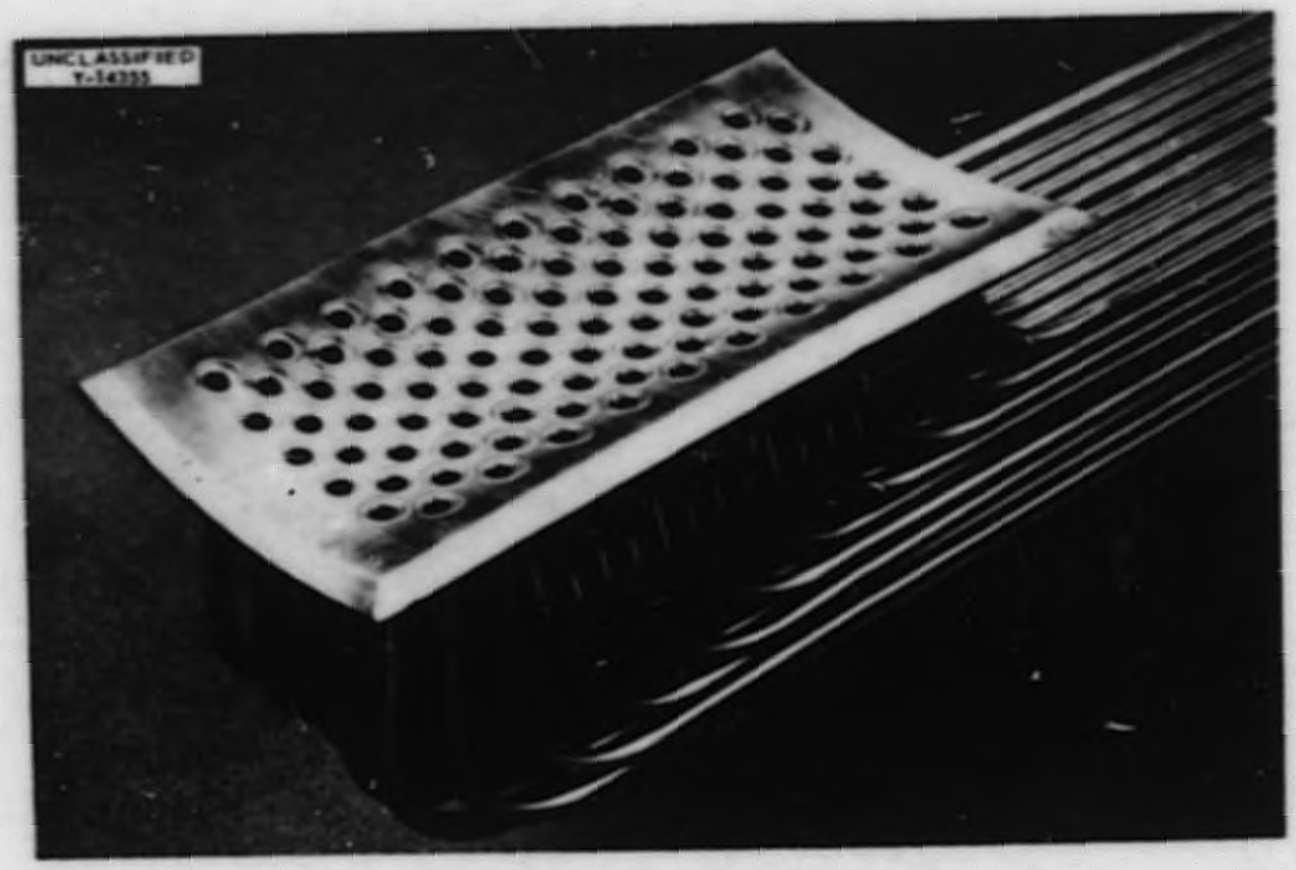

Fig. 4. Fused-Fluoride-to-Sodium Heat Exchanger.

ASPECTS OF BRAZING ALLOY DEVELOPMENT

Brazing alloys containing nickel as the base metal are of primary interest for use in heat exchanger and radiator applications for high-temperature, high-corrosion service. Nickel is compatible with static sodium at temperatures in the range of 1500–1700°F; however, it does suffer to a slight extent from mass transfer in dynamic nonisothermal sodium systems at 1500°F and above. Its resistance to oxidation at these temperatures is also promising and can be made exceptional with slight additions of some alloying elements. Nickel is exceptionally malleable in its pure form, thereby presenting a good starting point for the production of alloys containing an inherent degree of ductility. Its nuclear absorption cross section is also relatively low.

The melting point of nickel is 2650°F, but brazing alloys for use in ordinary high-temperature applications utilizing Inconel or the stainless steels should melt below 2200°F to minimize distortion and grain growth in the structural materials. Fortunately, however, certain elements, when alloyed with nickel in small quantities, cause rapid reductions in melting point. Some elements, such as boron and phosphorus, form binary eutectics with nickel and the phase diagram of these systems is shown in Figs. 5 and 6, respectively. Other elements of interest which form alloys of a similar type are silicon, germanium, and tin. Complex brazing alloy compositions containing various percentages of each component can be prepared, and

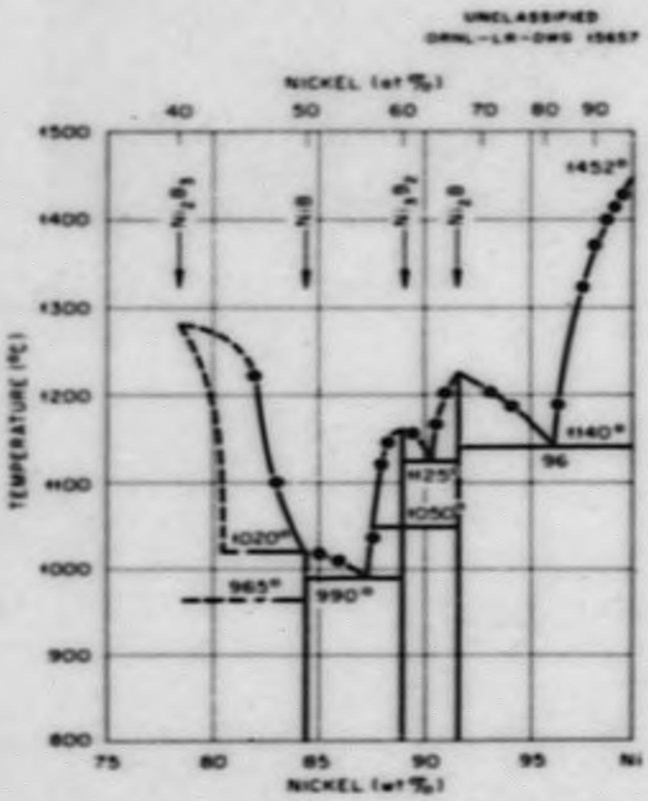

Fig. 5. The Nickel-Boron Equilibrium Phase Diagram. (From *Der AufBau der Zweistofflegierungen* by M. Hansen)

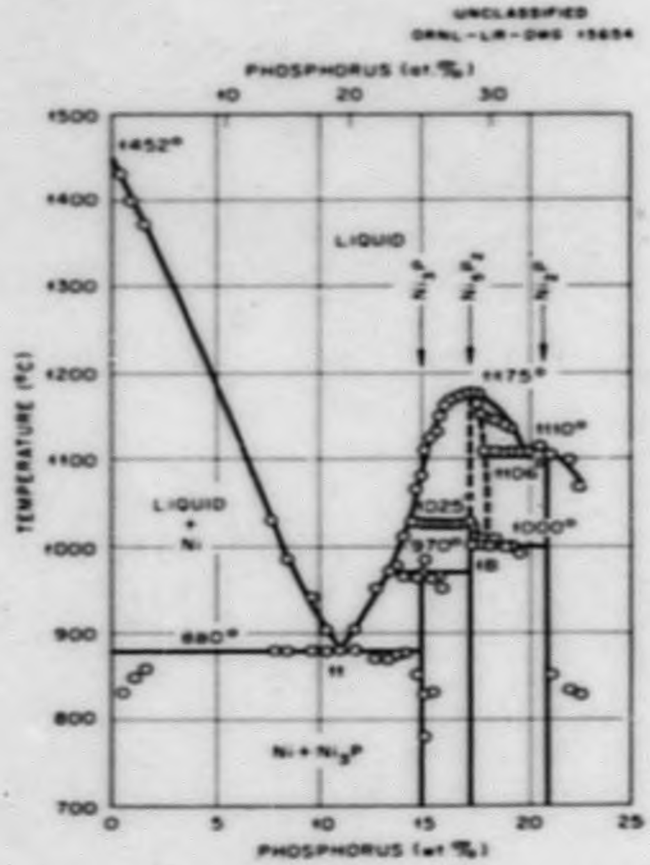

Fig. 6. The Nickel-Phosphorus Equilibrium Phase Diagram. (From *Der AufBau der Zweistofflegierungen* by M. Hansen)

the melting points vary accordingly. However, it can be assumed for most cases that ternary or quaternary eutectics possess lower melting points than any of the binary eutectics. Each alloy composition also possesses unique physical and chemical properties, although certain trends may be followed. For example, the presence of phosphorus in nickel-base brazing alloys has been found to reduce the ductility in all cases which have been tested.

Other alloy systems which are of interest contain a minimum in the liquidus-solidus lines of their phase diagrams. Typical of these systems are nickel-manganese and nickel-gold; their respective diagrams are shown in Figs. 7 and 8. The nickel-palladium system also possesses complete solid solubility in all proportions.

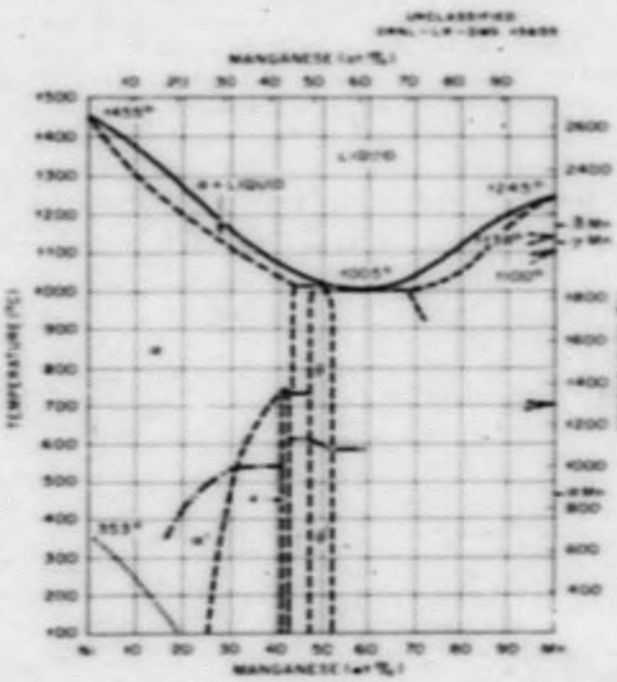

Fig. 7. The Nickel-Manganese Phase Diagram. (From *Metals Handbook*)

The development of brazing alloys for high-temperature, high-corrosion service must necessarily be based upon phase diagram analyses. With the aid of a systematic study of the melting point and flowability of alloy systems over wide variations of chemical composition, it is frequently possible to determine the presence of particular compositions having desirable characteristics for brazing. Although such investigations are time-consuming, the number of sample melts required to determine the composition of lowest melting point can be reduced by a judicious choice of samples.

This report presents a summary of the resistance to corrosion and oxidation of many alloy systems which have been investigated and developed, both commercially and by various research organizations. Systems which were promising from these standpoints were studied extensively, while alloy systems exhibiting less use for high-temperature applications were studied only slightly. However, continuing research on nickel-base alloys is being conducted; this research includes development programs on alloys for applications involving other corrosive environments.

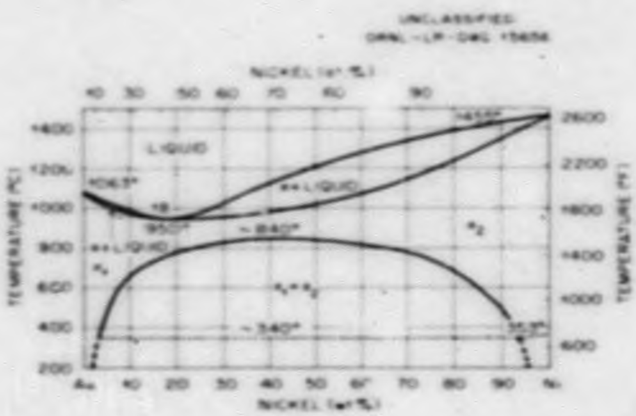

Fig. 8. The Nickel-Gold Equilibrium Phase Diagram. (From *Metals Handbook*)

BRAZING EQUIPMENT AND PREPARATION OF SPECIMEN

The process of dry-hydrogen brazing has become of recognized importance in recent years as a means of component fabrication for high-temperature, corrosion-resistant service. Flux entrapment, with its consequent deleterious effects in certain applications, is eliminated, and exceedingly high quality brazed joints can be produced. The hydrogen chemically reduces the metallic oxides to the pure metals and promotes the formation of a scale-free surface. As a result, common high-temperature structural materials such as Inconel and the stainless steels are easily wet by most brazing alloys.

A hydrogen dew point lower than −70°F is recommended for the brazing of these materials to permit satisfactory flowability. To remove impurities which may be present in the as-received bottled gas, an elaborate drying and purification train is required. Since very high flow rates may be needed for many operations, purifiers possessing a high effective capacity should be used throughout.

In this investigation, the removal of residual oxygen from the hydrogen was performed by a commercially available palladium catalyst.[4] This oxygen combines with the hydrogen to form water vapor. An activated alumina drying unit[5] absorbed this water along with the water vapor originally present in the tank hydrogen and was adequate to reduce the hydrogen dew point to −120°F or lower. Additional purification equipment in use in the Welding and Brazing Laboratory consisted of a hot titanium sponge scavenger. The Linde molecular sieve[6] also is reported to be useful for the removal of water vapor from the tank.

A Burrell Globar-heated tube furnace containing a 2-in.-dia Inconel muffle was used for brazing the specimens to be used in the corrosion and oxidation tests. A water-cooled chamber facilitated cooling to room temperature. Accurate temperature measurement and control were made possible by a platinum–platinum-rhodium thermocouple enclosed in an impervious ceramic tube.

T-joints, similar to the one shown in Fig. 9, were brazed by placing controlled quantities of brazing alloy on one end of the specimens. The alloy, upon melting, flowed evenly along the joint. All specimens were held at the brazing temperature for approximately 10 min. As described in the next section, several small corrosion samples could then be taken from this one specimen.

---

[4] Baker & Company, Inc., Newark, New Jersey.

[5] Pittsburgh Lectrodryer Corp., Pittsburgh, Pa.

[6] Linde Air Products Co., New York, N. Y.

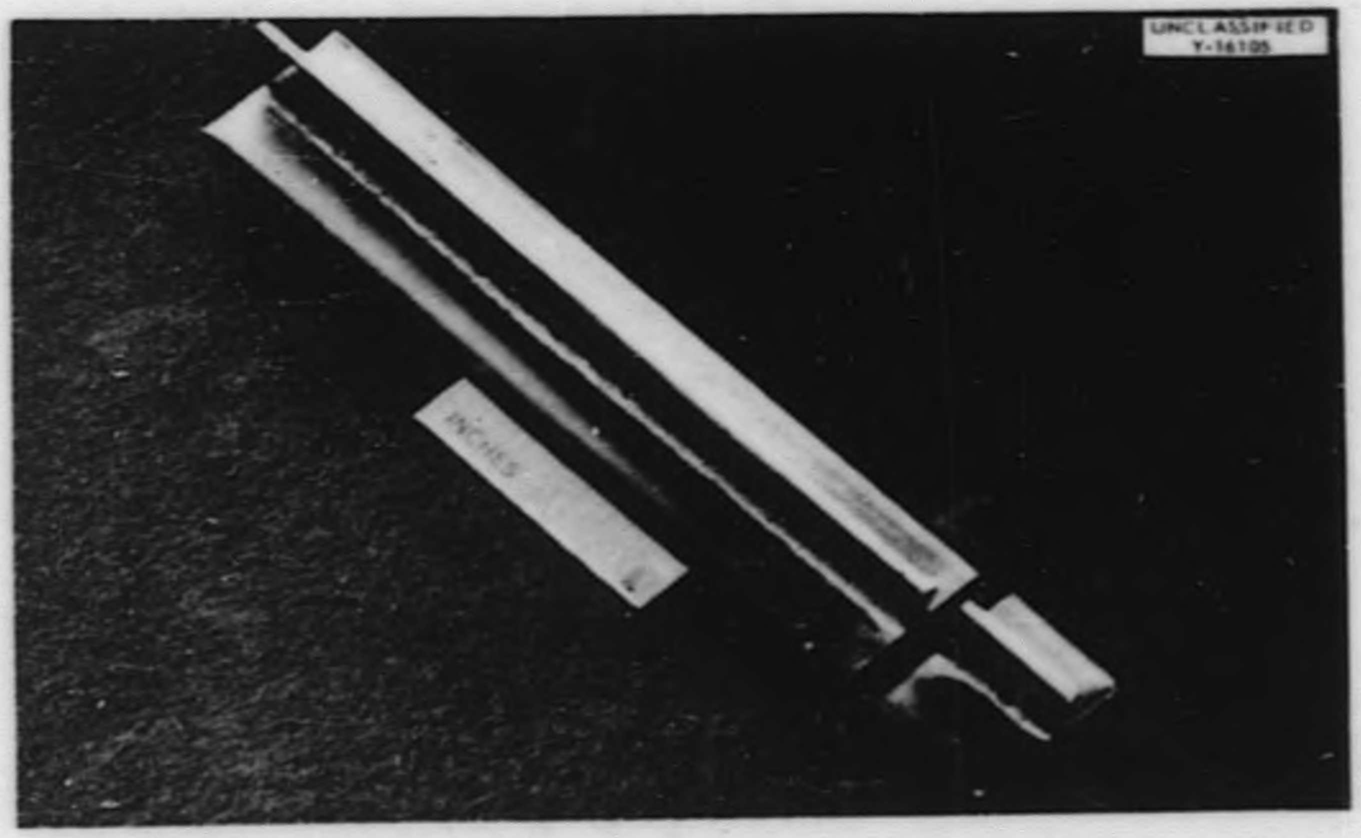

Fig. 9. Brazed T-Joint Which Had Been Prepared by Placing a Controlled Quantity of Brazing Alloy at One End and Heating to the Flow Point in a Dry-Hydrogen Atmosphere.

TESTING PROCEDURE

CORROSION

In corrosion testing of brazing alloys in various heat exchange media two testing techniques – the static and the "seesaw" – are employed. The static method is by far the simplest and serves as a rapid means for screening large numbers of brazing alloys in various heat transfer media. The seesaw method, on the other hand, is a dynamic corrosion test in which the testing medium is not stagnant with respect to the sample being tested, as it is in the static test. In the seesaw technique, the movement of the corrosive liquid is obtained by the oscillation of the furnace. Figure 10 is a photograph of the seesaw furnace which was used in the dynamic testing of the brazed samples. The rocking speed used in the brazing alloy seesaw tests was chosen as 4.25 cpm. With this equipment, the effect of a thermal gradient in the circulating bath on the corrosion resistance of the test sample can also be observed. Since the test capsule is positioned in such a manner that only a portion of it is in the hot zone of the furnace, a desired temperature differential can be obtained by regulating the distance that the capsule extends out from the hot zone. In general, it has been found that brazing alloys which were attacked during the static test were more severely attacked during the seesaw test.

The corrosion tests were performed on dry-hydrogen-brazed T-joints submitted by the Welding and Brazing Group and the Wall Colmonoy Corporation. The over-all length of each T-joint was approximately 3 in., and ½-in. sections were cut from these for corrosion testing. Each section

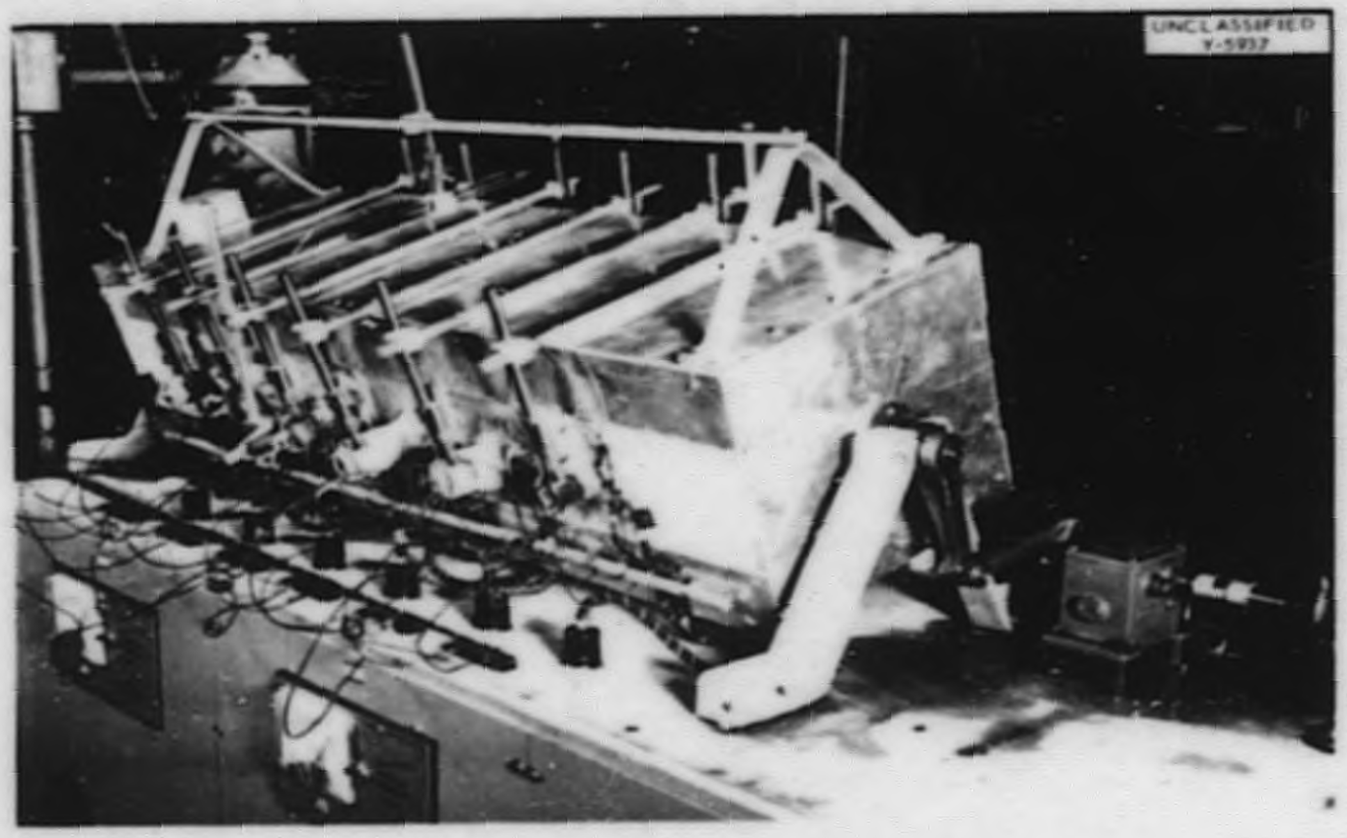

Fig. 10. Photograph of the "Seesaw" Furnace Used in the Dynamic Testing of Brazing Alloys.

was thoroughly cleaned in acetone and weighed in a Gram-atic balance before being placed in the container tube.

To minimize the existence of composition gradients, which can cause variations in corrosive attack through a mechanism of dissimilar-metal mass transfer, it is desirable to select a container material of the same composition as the base material of the brazed T-joint. In all these brazing alloy tests, this precaution was utilized.

The loading procedure used in the static and seesaw corrosion tests is schematically shown in Fig. 11. The brazed T-joint, represented in this figure by the small square specimen, is placed in a tube which has been crimped and welded at one end. A partial crimp is then applied to the tube wall in order to retain the specimen in the crimped section. In such a procedure, the bath can be removed from the test sample upon completion of the test by merely inverting the partially filled test container. This crimping practice also serves to hold the test sample in the hot zone during seesaw testing. The testing medium is loaded into the container tube in an inert-atmosphere dry box. This apparatus facilitates the handling of liquid metals and fused salts without serious contamination from the atmosphere. The tubes are then evacuated and sealed by crimping and welding.

Upon completion of the test, the capsules are sectioned for visual examination of bath, container, and test specimen. A sample of the bath is usually removed and sent for chemical analysis. The tested brazed T-joints are then thoroughly cleaned and again weighed on a Gram-atic balance in order to determine the weight change during testing. Although this weight change is not limited to the brazing alloy but also includes that of the T-joint base metal, the data is very useful in cases where a uniform solution attack has occurred on the brazing alloy. This type of attack is not readily discernible in a metallographic examination and can easily be overlooked. The final and most important stage in the examination of the tested T-joints is the metallographic examination. Before each T-joint is examined metallographically, an electrodeposited nickel plate is applied to prevent the rounding-over of the brazed fillet edges during the polishing procedure. An as-brazed T-joint is likewise plated and examined to determine the fillet contour and the degree of porosity present before corrosion testing. This procedure acts as a guide in evaluating the corrosion results.

The results of these tests can then be compiled in tabular form and general observations can be made. From an inspection of these tables, it is possible to suggest brazing alloys for use in various heat exchanger applications. It should, however, be emphasized that these results serve only as a guide, and more comprehensive tests must be conducted under conditions similar to those expected in actual service.

OXIDATION

The oxidation resistance of high-temperature brazing alloys was determined from tests conducted on small samples taken from brazed T-joints similar to those used in corrosion testing. A Nichrome-wound box-type furnace possessing a hot zone approximately 5 × 8 × 14 in. was utilized in this study. No circulation of air was maintained in the furnace other than that arising from natural convection.

Samples were tested both statically and with intermittent cycling to room temperature from the testing temperature. The cyclic testing was performed to observe the effects which might be encountered from the spalling of a protective oxide film during thermal fluctuations in service.

In these oxidation studies, the influence of several variables upon the extent of attack on several alloys was evaluated. Samples were held statically for different times at the testing temperature to permit a relative measure of the rate of oxidation. Two different testing temperatures, 1500 and 1700°F, were also investigated to determine the influence of temperature upon the extent of oxidation over the intended service temperature range. Cyclic testing was performed for 500 hr on many alloys at both temperatures.

The extent and type of oxidation was determined from a metallographic evaluation of the brazed T-joints after testing. The influence of the different testing variables was studied and the results are summarized in tabular form. As alloys of widely differing chemical compositions were investigated, a general knowledge of the influence of certain specific alloying additions upon the oxidation resistance can also be obtained.

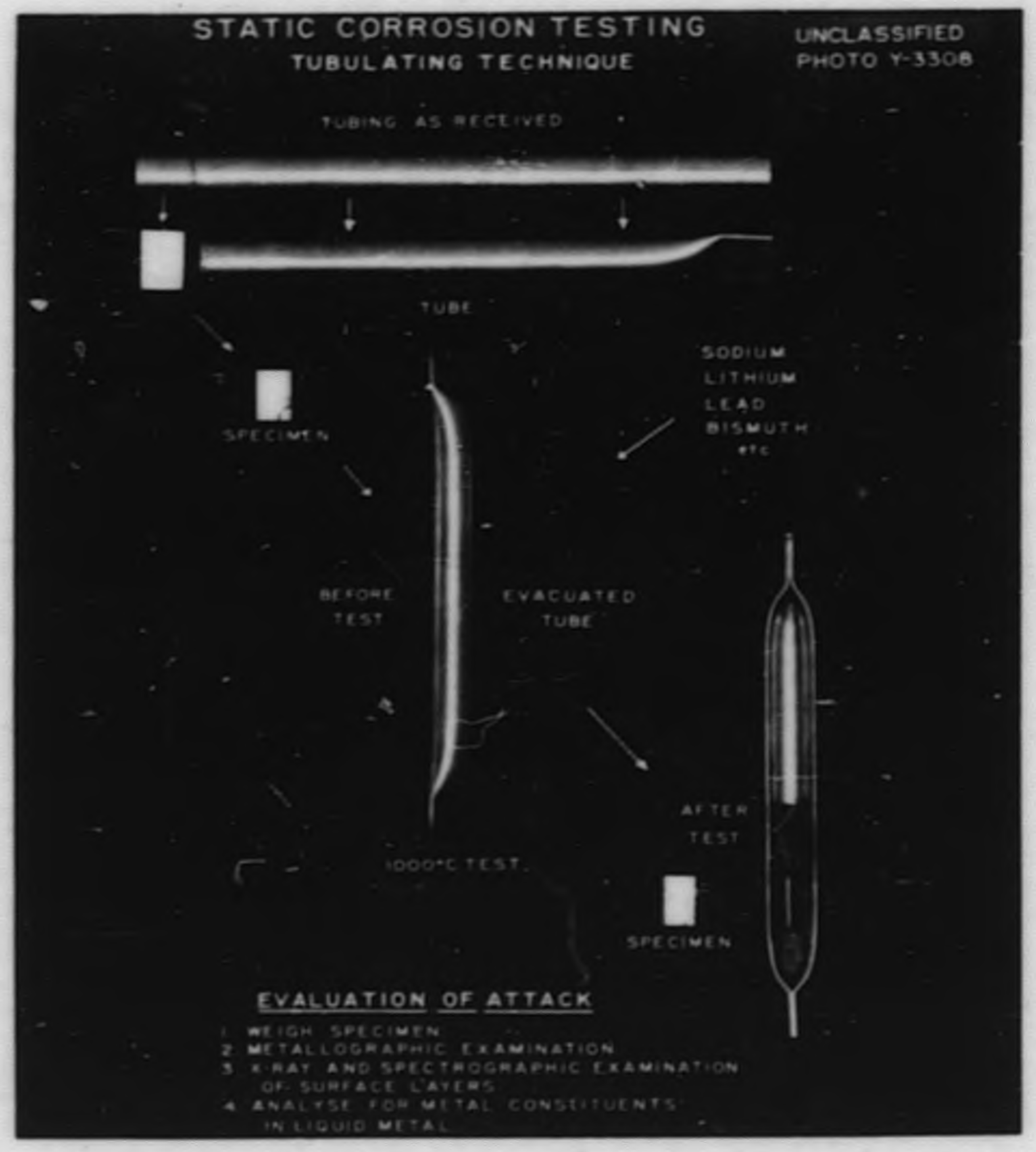

Fig. 11. Photograph Which Schematically Represents the Loading Procedure for the Seesaw and Static Corrosion Test.

RESULTS

Table 3 indicates the results of the static corrosion tests in sodium on several brazing alloys under study at ORNL. These tests were conducted for 100 hr at a temperature of 1500°F. Since previous corrosion studies on the precious metals in sodium indicated their poor corrosion resistance, no brazing alloy containing a precious metal as a constituent was tested.

The results of the static tests in sodium on some of the best brazing alloys submitted for corrosion studies by the Wall Colmonoy Corporation as part of Wright Air Development Center Materials Laboratory Contract No. AF 33(616)2287 are listed in Table 4. Several alloys are not listed in this table because of the similarity of their compositions and corrosion test results.

Table 5 shows the results obtained in seesaw tests in which sodium was circulated for 100 hr at a hot-zone temperature of 1500°F. The temperature differential, approximately 400°F, was fairly constant for all the sodium seesaw tests. Since the seesaw tests provide a more rigorous means of evaluating corrosion data, no brazing alloy which had poor corrosion resistance to sodium in the static test was seesaw tested. However, a few alloys were investigated in this test which were similar in composition to ones having adequate resistance in the static test.

The results of the fluoride-salt static tests on joints brazed with several alloys are listed in Table 6. Table 7 shows the results of Wall Colmonoy experimental alloys, tested in the fluoride mixture No. 44 – $NaF\text{-}ZrF_4\text{-}UF_4$ (53.5-40-6.5 mole %).

The results of the seesaw tests in the fluoride mixture $NaF\text{-}ZrF_4\text{-}UF_4$ No. 44 are shown in Table 8. These tests were conducted in the same manner as the sodium seesaw tests.

Table 9 indicates the results of the sodium hydroxide corrosion tests. These tests were conducted on "A" nickel T-joints for a period of 100 hr at 1100 and 1500°F.

Tables 10, 11, 12, and 13 present the results of the high-temperature oxidation tests on several brazing alloys. Table 10 presents a summary of the static oxidation resistance of several alloys at 1500 and 1700°F for times up to 1300 hr, while Tables 11 and 12 compare the resistance to static and cyclic attack at 1500 and 1700°F, respectively. Table 13 contains data on the oxidation resistance of some of the Wall Colmonoy Corporation development alloys at 1500°F.

TABLE 3. RESULTS OF STATIC TESTS OF BRAZING ALLOYS ON "A" NICKEL T-JOINTS IN SODIUM AT 1500°F FOR 100 hr

Brazing Alloy* Composition	Weight Change** (g)	Weight Change** (%)	Metallographic Notes
General Electric No. 81	+0.0001	+0.005	No attack on braze fillet
Coast Metals No. 52	–0.0019	–0.068	0.5-mil surface attack along fillet edge
80 Ni–10 P–10 Cr	–0.0017	–0.061	1-mil nonuniform attack along fillet
Nicrobraz	–0.0022	–0.082	1.5-mil layer of small sub-surface voids along fillet edge
75 Ni–25 Ge	0.0	0.0	2-mil nonuniform attack along surface of braze fillet
50 Ni–25 Mo–25 Ge	–0.0009	–0.036	2.5-mil attack along surface of fillet
65 Ni–25 Ge–10 Cr	–0.0024	–0.085	3-mil uniform surface attack along fillet
40 Ni–60 Mn	–0.0020	–0.079	9-mil uniform attack along entire fillet
35 Ni–55 Mn–10 Cr	–0.0005	–0.020	13 mils of small voids in from surface of fillet
68 Ni–32 Sn	–0.0171	–0.540	Complete attack of whole fillet

*Brazing alloys listed in order of decreasing corrosion resistance to sodium.

**Weight change data for brazing alloys and base material of joint.

TABLE 4. RESULTS OF STATIC TESTS OF BRAZING ALLOYS ON TYPES 304 AND 310 STAINLESS STEELS AND INCONEL IN SODIUM AT 1500°F FOR 100 hr

Brazing Alloy* Composition (wt %)	Base Material	Weight Change** (g)	(%)	Metallographic Notes
Alloy F-11 73 Ni–9 Si–18 Cr	304 SS	0.0	0.0	No attack along surface of braze fillet
Alloy B-13 88 Ni–3 P–9 Si	310 SS	0.0	0.0	No attack along surface of fillet; several cracks were observed in fillet
Alloy P-11 82 Ni–10 Si–8 Mn	310 SS	−0.0002	−0.018	No attack along fillet; again several cracks occurred
Alloy P-10 78 Ni–16 Si–6 Mn	310 SS	+0.0004	+0.043	No evidence of attack; however, several large cracks appeared throughout fillet
Alloy E-11 87 Ni–13 Si	304 SS	−0.0007	−0.068	Surface of braze fillet unattacked
Alloy C-29 77 Ni–10 P–13 Cr	304 SS	+0.0004	+0.054	Less than 0.5 mil of small subsurface voids
Alloy P-14 64 Ni–6 Si–30 Mn	310 SS	−0.0002	−0.022	1-mil erratic surface attack with large cracks throughout fillet
Alloy G-20 80 Ni–9 P–11 W	310 SS	−0.0002	−0.019	2.5-mil uniform attack along the surface of the braze fillet
Alloy S-10 54 Ni–10 Si–14 Cr–19 Fe–3 Mn	310 SS	0.0	0.0	Subsurface voids to a depth of 3 mils along fillet
Alloy B-15 89 Ni–5 P–6 Si	310 SS	0.0	0.0	Maximum attack of 4 mils along surface of fillet
Alloy B-11 80 Ni–11 P–9 Si	304 SS	0.0	0.0	Subsurface voids to a depth of 4 mils along fillet
Alloy B-17 89 Ni–8 P–3 Si	310 SS	−0.0012	−0.14	Maximum attack of 4 mils along surface of braze fillet
Alloy L-20 38 Ni–57 Mn–5 Cr	310 SS	−0.0004	−0.043	Attack in the form of stringers to a maximum depth of 5 mils, not uniform
Alloy A-16 77 Ni–23 P	304 SS	−0.0009	−0.135	Subsurface voids in braze fillet to a depth of 5 mils; attack confined to Ni_3P phase
Alloy C-27 88 Mn–10 P–2 Cr	304 SS	−0.0006	−0.086	Subsurface voids to depth of 5 mils; Ni_3P phase attacked
Alloy A-10 88 Ni–12 P	304 SS	−0.0015	−0.141	6-mil attack along entire fillet surface; attack in Ni_3P phase
Alloy I-10 81 Ni–11 P–8 Mn	Inconel	−0.0014	−0.135	6-mil attack nonuniform along fillet surface
Alloy J-10 71 Ni–9 P–15 Fe–5 Cr	304 SS	−0.0004	−0.067	Subsurface voids to a depth of 7 mils; Ni_3P phase removed from fillet zone

*Brazing alloys listed in order of decreasing corrosion resistance to sodium.
**Weight change data for brazing alloy and base material of joint.

TABLE 4 (continued)

Brazing Alloy* Composition (wt %)	Base Material	Weight Change**		Metallographic Notes
		(g)	(%)	
Alloy B-11 80 Ni–11 P–9 Si	Inconel	–0.0010	–0.098	4-mil erratic surface attack; subsurface voids to a depth of 9 mils
Alloy H-10 86 Ni–10 P–4 Mo	Inconel	–0.0011	–0.107	9 mils of subsurface voids along fillet surface
Alloy A-10 88 Ni–12 P	Inconel	–0.0005	–0.110	11-mil attack along surface of braze fillet
Alloy I-10 81 Ni–11 P–8 Mn	304 SS	–0.0018	–0.346	11 mils of subsurface voids in braze fillet
Alloy H-10 86 Ni–10 P–4 Mo	304 SS	–0.0006	–0.108	19 mils of subsurface voids in braze fillet
Alloy D-11 79 Ni–10 P–11 Fe	304 SS	+0.0006	+0.108	25 mils of subsurface voids in braze fillet

*Brazing alloys listed in order of decreasing corrosion resistance to sodium.

**Weight change data for brazing alloy and base material of joint.

TABLE 5. BRAZING ALLOYS ON INCONEL T-JOINTS SEESAW TESTED IN SODIUM FOR 100 hr AT A HOT-ZONE TEMPERATURE OF 1500°F

Brazing Alloy* Composition	Weight Change**		Metallographic Notes
	(g)	(%)	
Coast Metals No. 52	–0.0011	–0.073	No attack along surface of braze fillet
Coast Metals No. 53	–0.0009	–0.071	1-mil erratic attack along surface of braze fillet
Low-melting Nicrobraz	–0.0007	–0.051	Sub-surface voids to a maximum depth of 1.5 mils along surface of braze fillet
Coast Metals No. 50	–0.0012	–0.077	1.5-mil very erratic surface attack along fillet
70 Ni–13 Ge–11 Cr–6 Si	–0.0023	–0.139	Nonuniform attack along surface of braze fillet to a depth of 2.5 mils
Coast Metals NP	–0.0069	–0.622	2.5-mil uniform attack along surface of braze fillet
General Electric No. 81	–0.0018	–0.163	3-mil uniform surface attack along braze fillet
Nicrobraz	0.0	0.0	Very erratic stringer attack to a maximum depth of 4 mils along surface of braze fillet
65 Ni–25 Ge–10 Cr	–0.0019	–0.113	Intermittent surface attack to a maximum depth of 4 mils along braze fillet

*Brazing alloys listed in order of decreasing corrosion resistance to sodium.

**Weight change data for brazing alloys and base material of joint.

TABLE 6. RESULTS OF STATIC TESTS OF BRAZING ALLOYS ON "A" NICKEL T-JOINTS IN FLUORIDE MIXTURE $NaF-ZrF_4-UF_4$ (53.5-40-6.5 mole %) AT 1500°F FOR 100 hr

Brazing Alloy* Composition	Weight Change** (g)	Weight Change** (%)	Metallographic Notes
82 Au–18 Ni	–0.0010	–0.036	Braze fillet unattacked
60 Pd–40 Ni	–0.0016	–0.06	No surface attack along braze fillet
60 Pd–37 Ni–3 Si	+0.0008	+0.027	No attack along surface of braze fillet
80 Ni–10 P–10 Cr	0.0	0.0	No attack on braze fillet
50 Ni–25 Mo–25 Ge	0.0	0.0	No attack along surface of braze fillet
Nicrobraz	–0.0004	–0.016	No attack along fillet
80 Au–20 Cu	–0.0007	–0.026	No attack on braze fillet
75 Ni–25 Ge	–0.0001	–0.01	Maximum attack of 0.5 mil along surface of fillet
100 Cu	–0.0006	–0.019	0.5-mil surface attack along braze fillet
65 Ni–25 Ge–10 Cr	0.0	0.0	Small subsurface voids to a depth of 0.5 mil along braze fillet
Coast Metals No. 52	–0.0004	–0.05	Nonuniform attack of 6 mils along surface of fillet
General Electric No. 81	–0.0003	–0.012	Nonuniform attack of 12 mils along fillet
35 Ni–55 Mn–10 Cr	–0.0111	–0.48	Complete attack of braze fillet
40 Ni–60 Mn	–0.0159	–0.59	Complete attack of braze fillet
68 Ni–32 Sn	–0.0998	–3.49	Joint partially dissolved at fillet surface

*Brazing alloys listed in order of decreasing corrosion resistance to fluoride mixture.

**Weight change data for brazing alloys and base material of joint.

TABLE 7. BRAZING ALLOYS ON TYPES 304 AND 310 STAINLESS STEELS AND INCONEL STATIC TESTED IN FLUORIDE MIXTURE NO. 44 FOR 100 hr AT 1500°F

Brazing Alloy* Composition (wt %)	Base Material	Weight Change**		Metallographic Notes
		(g)	(%)	
Alloy C-27 89 Ni–10 P–2 Cr	304 SS	0.0	0.0	No attack on surface of braze fillet
Alloy A-16 77 Ni–23 P	304 SS	−0.000[illegible]	−0.042	No attack on surface of braze fillet
Alloy I-10 81 Ni–11 P–8 Mn	304 SS	+0.0008	+0.112	No attack on surface of braze fillet
Alloy A-10 88 Ni–12 P	Inconel	−0.0004	−0.068	No attack on surface of braze fillet
Alloy C-29 77 Ni–10 P–13 Cr	304 SS	+0.0011	+0.180	No attack on surface of braze fillet
Alloy D-11 79 Ni–10 P–1[illegible] Fe	304 SS	+0.001[illegible]	+0.304	No attack on surface of braze fillet
Alloy A-10 88 Ni–12 P	304 SS	−0.0031	−0.30	No attack on surface of braze fillet
Alloy G-20 80 Ni–9 P–11 W	310 SS	−0.0017	−0.152	No attack on surface of fillet, several cracks were present in fillet
Alloy J-10 71 Ni–9 P–15 Fe–5 Cr	304 SS	+0.0007	+0.153	0.5-mil small subsurface voids in braze joint
Alloy H-10 86 Ni–10 P–4 Mo	304 SS	+0.036	+0.730	Maximum attack of 0.5 mil in the form of small subsurface voids
Alloy H-10 86 Ni–10 P–4 Mo	Inconel	−0.0016	−0.154	0.5-mil attack along surface of fillet
Alloy I-10 81 Ni–11 P–8 Mn	Inconel	−0.0016	−0.157	Surface of fillet attacked to a depth of 0.5 mil
Alloy B-15 89 Ni–5 P–6 Si	310 SS	−0.046	−0.510	0.5-mil uniform surface attack along fillet
Alloy B-17 89 Ni–8 P–3 Si	310 SS	−0.0053	−0.516	0.5-mil surface attack along fillet, several cracks were present in the fillet
Alloy B-11 80 Ni–11 P–9 Si	304 SS	−0.0006	−0.082	Braze fillet attacked to a depth of 1 mil in several areas
Alloy B-11 80 Ni–11 P–9 Si	Inconel	−0.0018	−0.166	Fillet surface attacked to a depth of 1 mil
Alloy B-13 88 Ni–3 P–9 Si	310 SS	−0.0027	−0.279	1-mil surface attack along entire fillet
Alloy P-11 82 Ni–10 Si–8 Mn	310 SS	−0.0042	−0.401	1.5-mil surface attack with several cracks in fillet
Alloy P-10 78 Ni–16 Si–6 Mn	310 SS	−0.0026	−0.290	3-mil uniform surface attack along fillet

*Brazing alloys listed in order of decreasing corrosion resistance to fluoride mixture.
**Weight change data for brazing alloys and base material of joint.

TABLE 7 (continued)

Brazing Alloy* Composition (wt %)	Base Material	Weight Change**		Metallographic Notes
		(g)	(%)	
Alloy F-11 73 Ni–9 Si–18 Cr	Inconel	–0.0052	–0.52	6-mil attack on surface of braze fillet
Alloy S-10 54 Ni–10 Si–14 Cr– 19 Fe–3 Mo	310 SS	–0.0030	–0.344	Surface attack to a maximum depth of 7.5 mils along entire fillet
Alloy E-11 87 Ni–13 Si	304 SS	–0.0036	–0.358	Braze fillet completely attacked
Alloy L-20 38 Ni–57 Mn–5 Cr	310 SS	–0.0078	–0.74	Complete attack of entire fillet
Alloy P-14 64 Ni–6 Si–30 Mn	310 SS	–0.0099	–1.06	Complete attack of entire fillet

*Brazing alloys listed in order of decreasing corrosion resistance to fluoride mixture.

**Weight change data for brazing alloys and base material of joint.

TABLE 8. BRAZING ALLOYS ON INCONEL T-JOINTS SEESAW TESTED IN FLUORIDE SALT NO. 44 FOR 100 hr AT A HOT-ZONE TEMPERATURE OF 1500°F

Brazing Alloy* Composition	Weight Change**		Metallographic Notes
	(g)	(%)	
100 Cu	–0.0002	–0.026	0.5-mil surface attack along fillet
Coast Metals No. 52	–0.0008	–0.052	0.5-mil nonuniform surface attack along fillet
Low-melting Nicrobraz	–0.0008	–0.063	0.5-mil nonuniform surface attack along fillet
Coast Metals No. 50	–0.0014	–0.085	0.5-mil uniform surface attack along fillet
70 Ni–13 Ge–11 Cr– 6 Si	–0.0011	–0.067	Nonuniform attack of 1.5 mils along surface of braze fillet
Coast Metals NP	–0.0009	–0.092	1.5-mil uniform surface attack along braze fillet
Nicrobraz	–0.0005	–0.030	1.5-mil erratic surface attack along braze fillet
Coast Metals No. 53	–0.0011	–0.092	1.5-mil nonuniform attack along surface of braze fillet
General Electric No. 81	–0.0008	–0.067	3.5-mil attack along surface of braze fillet
65 Ni–25 Ge–10 Cr	–0.0019	–0.056	Stringer-type attack to a maximum depth of 4 mils in a few localized areas

*Brazing alloys listed in order of decreasing corrosion resistance to fluoride salt No. 44.

**Weight change data for brazing alloy and base material.

TABLE 9. RESULTS OF STATIC TESTS OF BRAZING ALLOYS IN "A" NICKEL T-JOINTS IN SODIUM HYDROXIDE AT 1100 AND 1500°F FOR 100 hr

Brazing Alloy* Composition (wt %)	Test Temperature (°F)	Weight Change**		Metallographic Notes
		(g)	(%)	
82 Au–18 Ni	1500	–0.0040	–0.144	Nonuniform surface attack on braze to depth of 1 mil
82 Au–18 Ni	1100	–0.0007	–0.027	No attack on surface of braze
80 Au–20 Cu	1500	–0.0106	–0.38	Uniform surface attack on entire braze to a depth of 3 mils
80 Au–20 Cu	1100	–0.0050	–0.164	Surface attack on braze to a depth of 1 mil
60 Pd–40 Ni	1500	–0.0015	–0.049	Surface of braze fairly clean with attack in the form of small stringers running to a depth of 4 mils
60 Pd–40 Ni	1100	–0.0007	–0.028	Surface attack to a depth of 0.5 mil
60 Pd–37 Ni–3 Si	1500	+0.0023	+0.083	Surface attack on braze fillet to a depth of 6 mils
60 Pd–37 Ni–3 Si	1100	+0.0008	+0.028	No attack present on braze surface
100 Cu	1500	–0.0118	–0.408	Braze attacked completely, large voids appear throughout
100 Cu	1100	–0.0011	–0.038	Uniform surface attack on braze to a depth of 3 mils
90 Ni–10 P	1500	–0.0054	–0.15	Braze completely attacked; attack centered in brittle Ni_3P phase
90 Ni–10 P	1100	–0.0012	–0.047	Braze attacked completely; attack centered in Ni_3P phase
70 Ni–20 Cr–10 Si	1500			Braze failed completely
70 Ni–20 Cr–10 Si	1100	+0.0024	+0.093	Braze attacked completely

*Brazing alloys listed in order of decreasing corrosion resistance to sodium hydroxide.

**Weight change data for brazing alloys and base material of joint.

TABLE 10. OXIDATION RESISTANCE OF DRY-HYDROGEN-BRAZED INCONEL T-JOINTS

Brazing Alloy*	Oxidation in Static Air**				
	At 1500°F			At 1700°F	
	200 hr	500 hr	1300 hr	200 hr	500 hr
92 Pd–8 Al	Very slight	Very slight	Very slight	Very slight	Slight
Wall Colmonoy Nicrobraz	Slight	Slight	Slight	Slight	Slight
Wall Colmonoy low-melting Nicrobraz	Slight	Slight	Slight	Slight	Slight
Coast Metals No. 50	Slight	Slight	Slight	Slight	Slight
Coast Metals No. 51	Slight	Slight	Slight	Slight	Slight
Coast Metals No. 52	Slight	Slight	Slight	Slight	Slight
Coast Metals No. 53	Slight	Slight	Slight	Slight	Slight
Coast Metals NP	Slight	Slight	Slight	Slight	Moderate
General Electric No. 81	Slight	Slight	Slight	Slight	Moderate
65 Ni–25 Ge–10 Cr	Slight	Slight	Slight	Slight	Moderate
70 Ni–13 Ge–11 Cr–6 Si	Slight	Slight	Slight	Slight	Moderate
60 Pd–40 Ni	Very slight	Slight	Moderate	Very slight	Slight
90 Ni–10 P	Slight	Slight	Slight	Above melting point of alloy	
80 Ni–10 P–10 Cr	Slight	Slight	Slight	Above solidus of alloy	
60 Pd–37 Ni–3 Si	Very slight	Slight	Moderate	Slight	Moderate
82 Au–18 Ni	Very slight	Very slight	Slight	Moderate	Moderate
75 Ni–25 Ge	Slight	Slight	Slight	Moderate	Severe
50 Ni–25 Mo–25 Ge	Slight	Slight	Slight	Moderate	Moderate
90 Au–10 Co	Very slight	Very slight	Moderate	Slight	Severe
90 Pd–10 Ge	Very slight	Slight	Severe	Complete	
68 Ni–32 Sn	Slight	Moderate	Severe	Severe	Complete
64 Ag–33 Pd–3 Mn	Severe	Severe	Severe	Complete	
35 Ni–55 Mn–10 Cr	Severe	Severe	Complete	Severe	Complete
80 Au–20 Cu	Moderate	Complete		Complete	
40 Ni–60 Mn	Complete			Complete	
Copper	Complete			Complete	

*Alloys are listed in order of decreasing oxidation resistance.

**Very slight, less than 1 mil penetration; slight, 1 to 2 mils of penetration; moderate, 2 to 5 mils of penetration; severe, greater than 5 mils of penetration; complete, fillet completely destroyed.

TABLE 11. OXIDATION RESISTANCE OF DRY-HYDROGEN-BRAZED INCONEL T-JOINTS AT 1500°F

Brazing Alloy*	Oxidation in 500 hr**	
	In Static Air	With 190 Air Cools to Room Temperature
82 Au–18 Ni	Very slight	Slight
90 Au–10 Co	Very slight	Slight
Wall Colmonoy Nicrobraz	Slight	Slight
Wall Colmonoy low-melting Nicrobraz	Slight	Slight
Coast Metals No. 50	Slight	Slight
Coast Metals No. 53	Slight	Slight
Coast Metals NP	Slight	Slight
General Electric No. 81	Slight	Slight
75 Ni–25 Ge	Slight	Slight
65 Ni–25 Ge–10 Cr	Slight	Slight
70 Ni–13 Ge–11 Cr–6 Si	Slight	Slight
50 Ni–25 Mo–25 Ge	Slight	Slight
80 Ni–10 P–10 Cr	Slight	Slight
60 Pd–37 Ni–3 Si	Slight	Slight
92 Pd–8 Al	Very slight	Moderate
Coast Metals No. 51	Slight	Moderate
Coast Metals No. 52	Slight	Moderate
90 Ni–10 P	Slight	Moderate
90 Pd–10 Ge	Slight	Severe
68 Ni–32 Sn	Moderate	Severe
35 Ni–55 Mn–10 Cr	Severe	Severe
64 Ag–33 Pd–3 Mn	Severe	Severe
Copper	Complete	Complete
40 Ni–60 Mn	Complete	Complete
80 Au–20 Cu	Complete	Complete

*Alloys are listed in order of decreasing oxidation resistance.

**Very slight, less than 1 mil penetration; slight, 1 to 2 mils of penetration; moderate, 2 to 5 mils of penetration; severe, greater than 5 mils of penetration; complete, fillet completely destroyed.

TABLE 12. OXIDATION RESISTANCE OF DRY-HYDROGEN-BRAZED INCONEL T-JOINTS AT 1700°F

Brazing Alloy*	Oxidation in 500 hr**	
	In Static Air	With 220 Air Cools to Room Temperature
Wall Colmonoy Nicrobraz	Slight	Slight
Coast Metals No. 53	Slight	Slight
Wall Colmonoy low-melting Nicrobraz	Slight	Moderate
Coast Metals No. 50	Slight	Moderate
60 Pd–40 Ni	Slight	Moderate
92 Pd–8 Al	Slight	Moderate
Coast Metals No. 51	Slight	Severe
Coast Metals No. 52	Slight	Severe
Coast Metals NP	Moderate	Moderate
General Electric No. 81	Moderate	Moderate
75 Ni–25 Ge	Moderate	Moderate
65 Ni–25 Ge–10 Cr	Moderate	Moderate
50 Ni–25 Mo–25 Ge	Moderate	Moderate
82 Au–18 Ni	Moderate	Severe
90 Au–10 Cu	Severe	Severe
90 Pd–10 Ge	Complete	Complete
68 Ni–32 Sn	Complete	Complete
64 Ag–33 Pd–3 Mn	Complete	Complete
40 Ni–60 Mn	Complete	Complete
35 Ni–55 Mn–10 Cr	Complete	Complete
80 Au–20 Cu	Complete	Complete
40 Ni–60 Mn	Complete	Complete
Copper	Complete	Complete

*Alloys are listed in order of decreasing oxidation resistance.

**Very slight, less than 1 mil penetration; slight, 1 to 2 mils of penetration; moderate, 2 to 5 mils of penetration; severe, greater than 5 mils of penetration; complete, fillet completely destroyed.

TABLE 13. OXIDATION RESISTANCE OF INCONEL T-JOINTS DRY-HYDROGEN-BRAZED WITH SOME OF THE ALLOYS DEVELOPED BY WALL COLMONOY CORPORATION UNDER WRIGHT AIR DEVELOPMENT CENTER MATERIALS LABORATORY CONTRACT NO. AF 33(616)2287

Alloy (wt %)	Oxidation*		
	Static Air (500 hr)	Cyclic Testing with 190 Air Cools to Room Temperature (500 hr)	Static Air (1300 hr)
		Inconel Base Material	
88 Ni–12 P	Slight	Moderate	Slight
80 Ni–11 P–9 Si	Slight	Slight	Moderate
86 Ni–10 P–4 Mn	Slight	Slight	Moderate
81 Ni–11 P–8 Mn	Moderate	Moderate	Moderate
		Type 304 SS Base Material	
77 Ni–10 P–13 Cr	Slight	Slight	Slight
77 Ni–23 P	Slight	Slight	Moderate
88 Ni–10 P–2 Cr	Slight	Slight	Moderate
71 Ni–9 P–15 Fe–5 Cr	Slight	Slight	Severe
79 Ni–10 P–11 Fe	Slight	Moderate	Severe

*Very slight, less than 1 mil penetration; slight, 1 to 2 mils of penetration; moderate, 2 to 5 mils of penetration; severe, greater than 5 mils of penetration; complete, fillet completely destroyed.

SODIUM-TO-AIR SERVICE

It is highly desirable that brazing alloys for use in high-temperature sodium-to-air applications be compatible with liquid sodium as well as with high-temperature air. This is important since extensive tube wall dilution and diffusion, during brazing and service, or corrosion through an area of shallow weld penetration during service may result in a high concentration of brazing alloy constituents in immediate contact with the liquid metal. An example of the attack of sodium on precious metal alloys can be seen in Fig. 12, a photomicrograph of a T-joint brazed with 60 Pd–37 Ni–3 Si and tested for 100 hr at 1500°F. The 60 Mn–40 Ni alloy is severely attacked by high-temperature air, and a brazed T-joint after 500 hr at 1500°F is shown in Fig. 13.

An analysis of the previous tables indicates that the following alloys may be seriously considered for use in radiator fabrication.

Coast Metals No. 52,
Coast Metals No. 53,
Low-melting Nicrobraz,
General Electric No. 81,
80 Ni–10 Cr–10 P,
Coast Metal's No. 50, and
Nicrobraz.

It is recognized that other alloy systems may also be entirely satisfactory, but, since testing has not been completed, they are not presented at this time.

The Coast Metals No. 52 alloy is of intense interest because its flow temperature of 1020°C

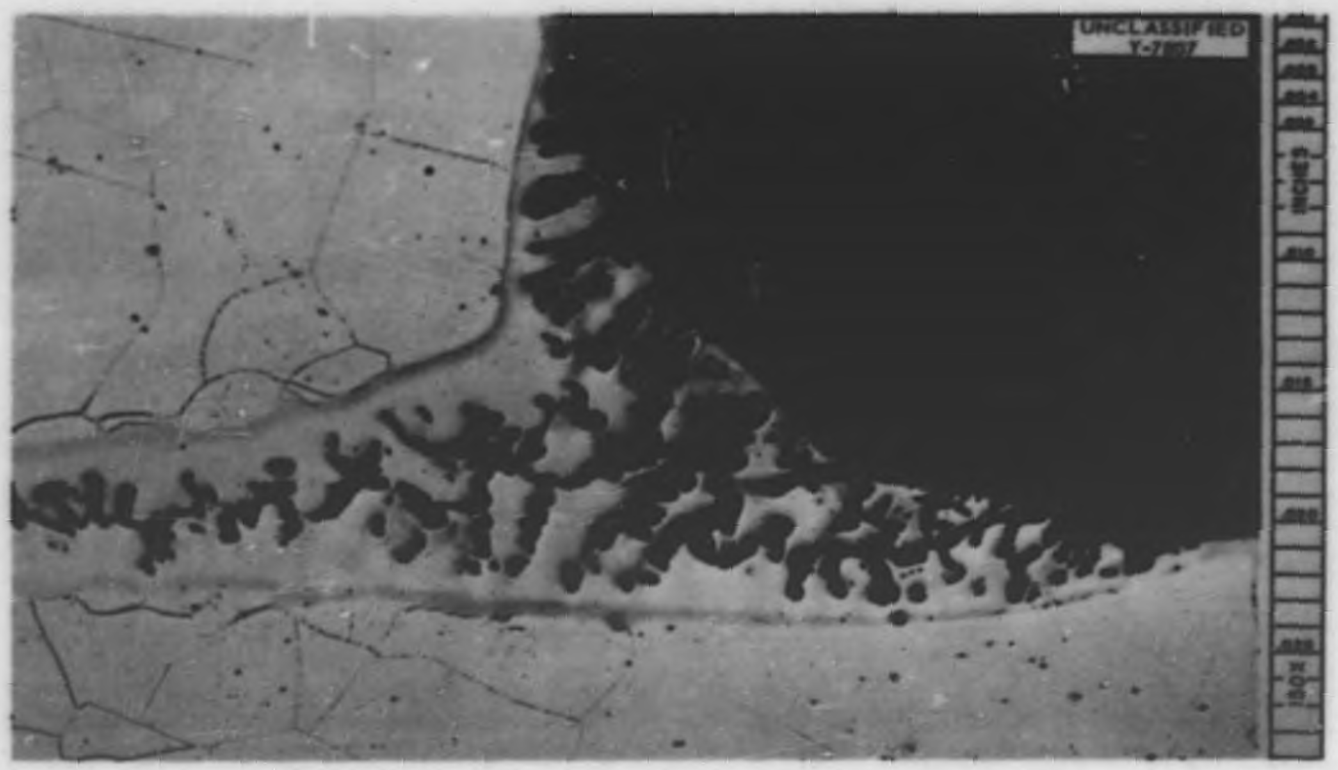

Fig. 12. Photomicrograph of a T-Joint Brazed with the 60 Pd–37 Ni–3 Si Alloy After Static Testing for 100 hr at 1500°F in Sodium. Note the extensive attack in the braze fillet. Etchant: glyceria regia. 150X.

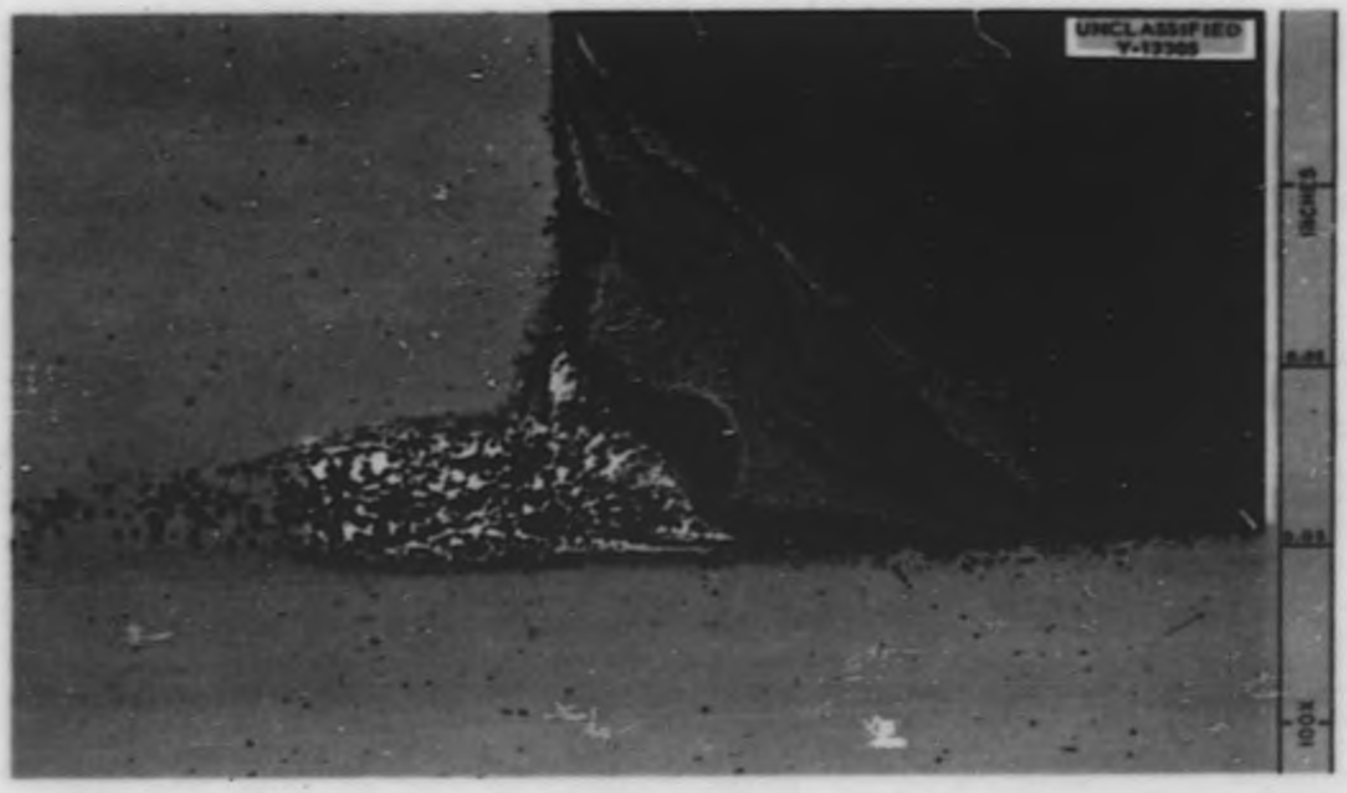

Fig. 13. Photomicrograph of a T-Joint Brazed with 60 Mn–40 Ni After Testing in Static Air for 500 hr at 1500°F. Note the poor oxidation resistance of this alloy. Unetched. 100X.

is sufficiently low to permit its use on radiators utilizing stainless-steel-clad-copper high-conductivity fins. A brazing temperature higher than the melting point of copper is required for many of the other alloys; therefore, their application is limited to radiators incorporating fins of more conventional composition. The excellent resistance of this alloy to attack in sodium and oxidation is shown in Fig. 14, which is a photomicrograph of brazed T-joints after testing in these media at 1500°F. Coast Metals No. 53, Coast Metals No. 50, low-melting Nicrobraz, and Nicrobraz are other boron-containing alloys possessing good compatibility in both environments.

Alloys of the Ni-Cr-Si type, such as General Electric No. 81 alloy, also have sufficient corrosion and oxidation resistance at 1500°F to permit their use in these applications. Photomicrographs of a No. 81 braze which was tested in sodium and air are presented in Fig. 15.

The 80 Ni–10 Cr–10 P alloy also possessed fair resistance to attack, as is shown in Tables 3 and 10. However, experiments to date have shown that phosphorus-containing alloys may be subject to undesirable brittleness caused by the formation of complex intermediate phases. This condition, which is shown in Fig. 16, is evident in the alloy 88 Ni–12 P. The propagation of cracks through the brittle Ni_3P phase is further shown in Fig. 17, a photomicrograph of the alloy at higher magnification.

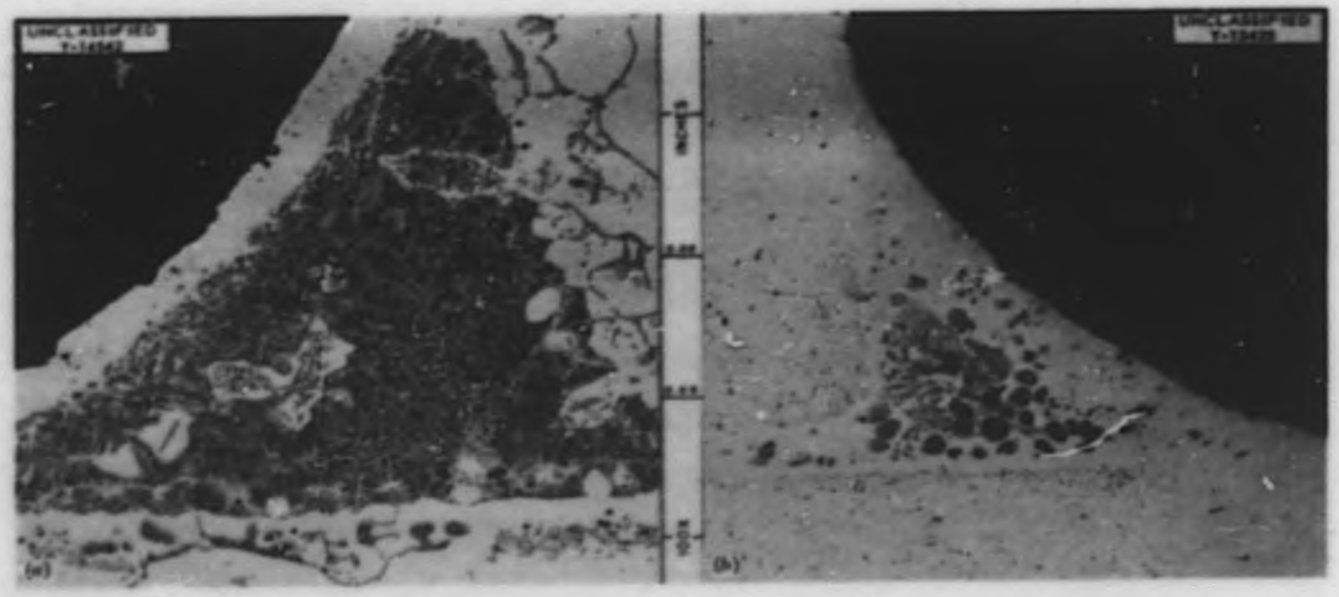

Fig. 14. Photomicrographs of T-Joints Brazed with Coast Metals No. 52 After Exposure at 1500°F to (*a*) Sodium for 100 hr and (*b*) Air for 500 hr. Note good resistance in both testing media. Etchant: (*a*) oxalic acid, (*b*) as polished. 100 X. Reduced 19%.

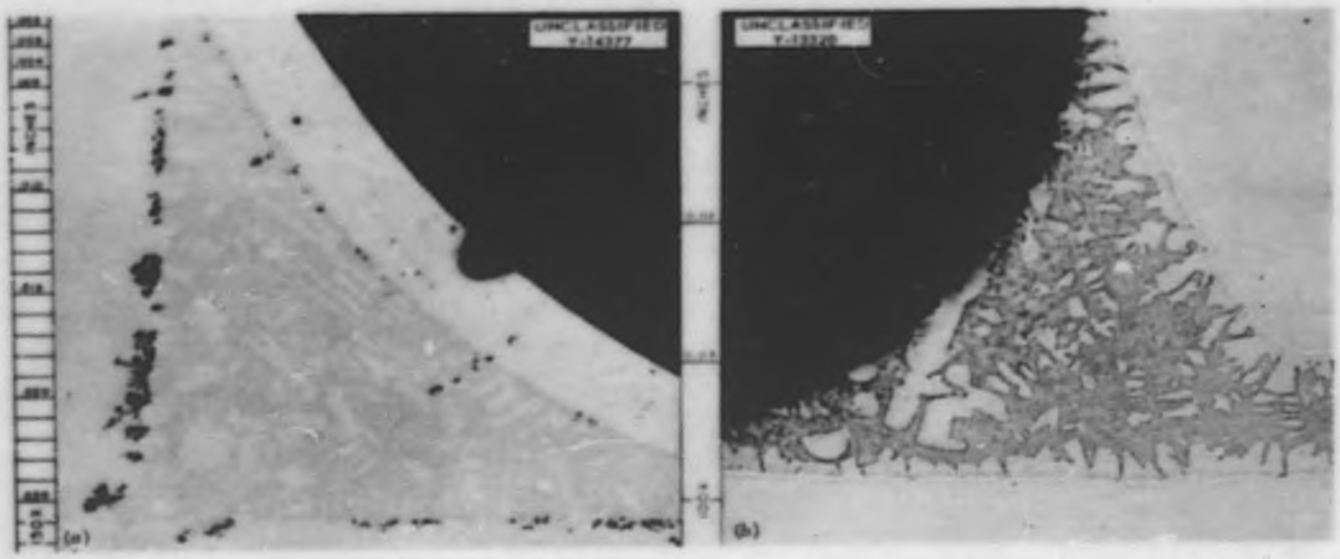

Fig. 15. Photomicrographs of T-Joints Brazed with General Electric No. 81 After Being Exposed at 1500°F to (*a*) Sodium for 100 hr and (*b*) Air for 500 hr. Note the slight attack along the surface of (*a*). Both as polished. 150X and 100X, respectively. Reduced 20%.

Fig. 16. Photomicrograph of an Inconel T-Joint Brazed with 88 Ni–12 P in the As-Brazed Condition. Note the cracks which are present in the braze fillet. Etchant: oxalic acid. 150X. Reduced 10%.

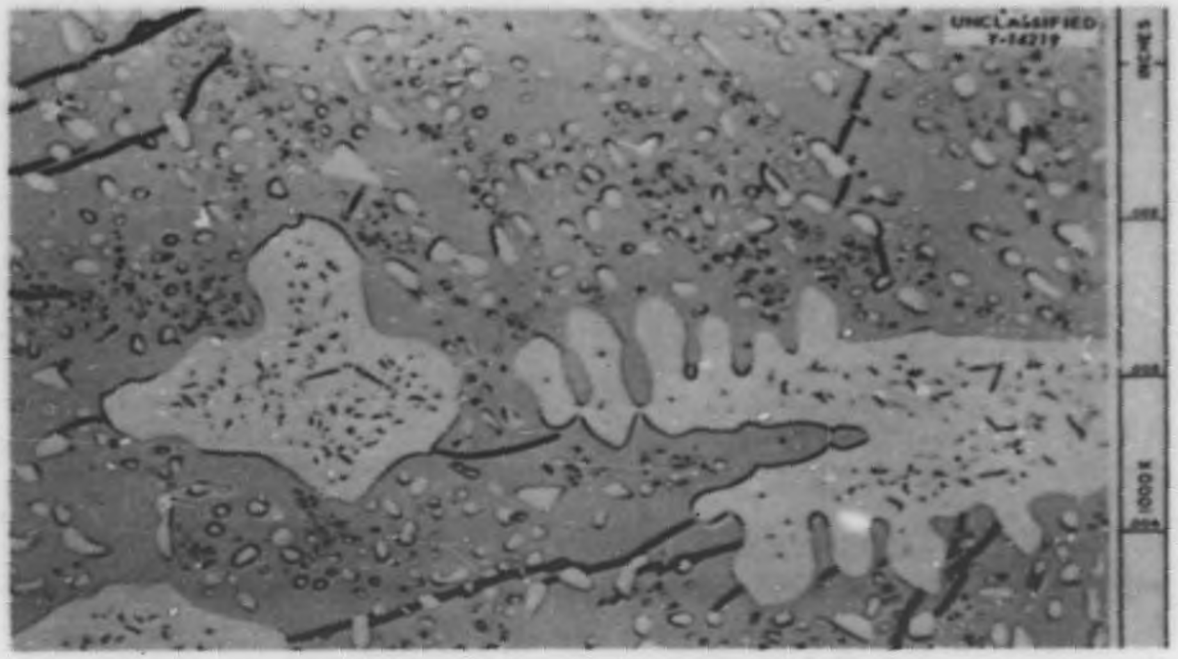

Fig. 17. Photomicrograph of the Brazing Alloy 88 Ni–12 P at High Magnification. Note the cracks which occurred in the brittle Ni_3P phase. Etchant: oxalic acid. 1000X. Reduced 10%.

FUSED-FLUORIDE-TO-SODIUM HEAT EXCHANGERS

The desirability of back-brazing tube-to-header joints in fused-fluoride-to-sodium heat exchangers is evident. Not only is the "notch effect" eliminated, but the chances for leaks resulting from corrosion through areas of shallow weld penetration are minimized. The alloy must therefore possess good compatibility with the fluoride bath and moderate compatibility with the sodium circulating inside the small-diameter tubes.

An analysis of the previous tables indicates that the following alloys may be considered for use in this heat exchanger application:

80 Ni–10 P–10 Cr,
Low-melting Nicrobraz,
Coast Metals No. 52,
Coast Metals No. 53,
Coast Metals No. 50,
Nicrobraz,
70 Ni–13 Ge–11 Cr–6 Si,
Coast Metals NP, and
50 Ni–25 Ge–25 Mo.

The 80 Ni–10 P–10 Cr alloy showed good corrosion resistance to both corrosive liquids. However, the characteristics of this alloy, as discussed in the section titled "Sodium-to-Air Radiator," may make this alloy undesirable for this application.

Low-melting Nicrobraz and Coast Metals No. 52, both boron-containing, appeared satisfactory in both the sodium and fluoride bath. Photomicrographs of the low-melting Nicrobraz alloy after corrosion testing are shown in Fig. 18. Similar photomicrographs for Coast Metals No. 52 are shown in Fig. 19. Coast Metals No. 53, Coast Metals No. 50, and Nicrobraz, which are also boron-bearing, exhibited a slightly greater degree of attack.

Since low nuclear cross-section materials are of prime interest in the construction of these units, the 70 Ni–13 Ge–11 Cr–6 Si brazing alloy should be seriously considered. The fair corrosion resistance of this alloy to both test media is illustrated by Fig. 20.

Precious-metal brazing alloys should not be considered for this application since their incompatibility with sodium has been demonstrated. However, the fluoride corrosion tests on these materials were justified, since there are several instances where fluoride-to-helium and fluoride-to-air test rigs have been built and operated.

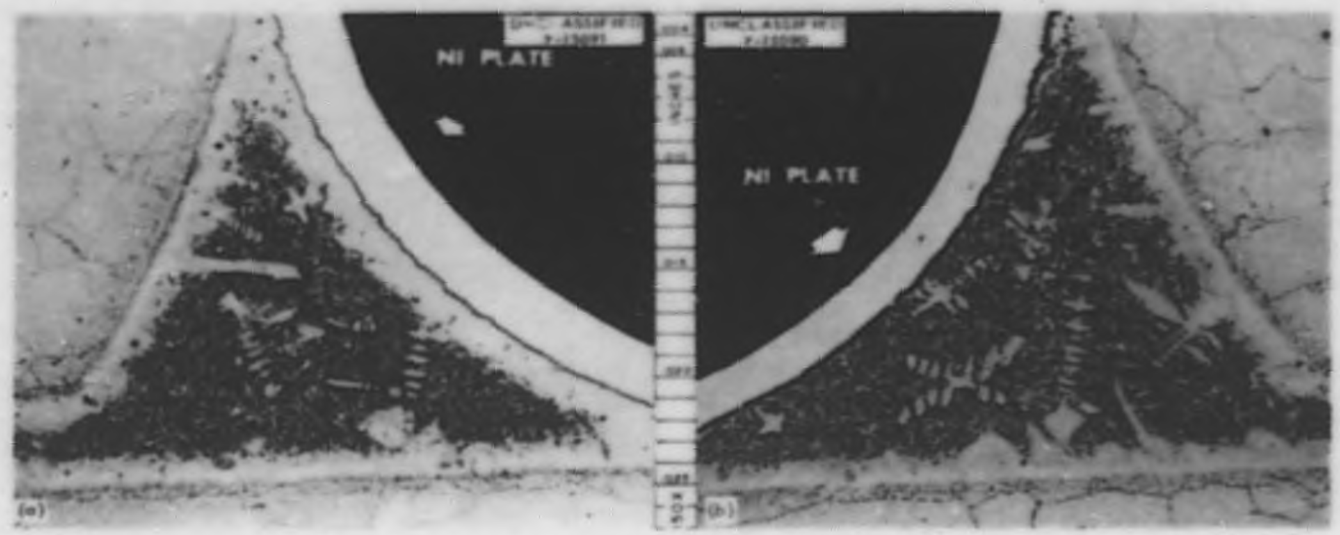

Fig. 18. Photomicrographs of T-Joints Brazed with Low-Melting Nicrobraz After Exposure at 1500°F to (*a*) Sodium and (*b*) Fused Salt for 100 hr. Note the slight attack in (*a*). Etchant: oxalic acid. 150X. Reduced 18%.

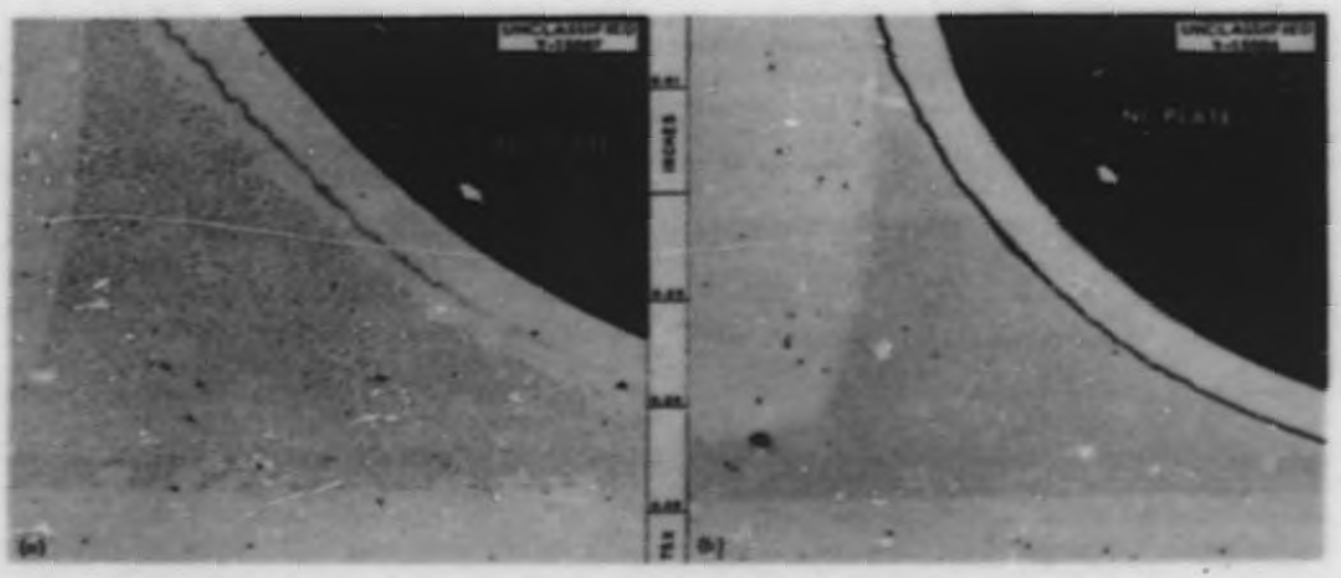

Fig. 19. Photomicrographs of T-Joints Brazed with Coast Metals No. 52 After Exposure at 1500°F to (*a*) Sodium and (*b*) Fused Salt for 100 hr. Only slight attack can be seen. Unetched. 75X. Reduced 19%.

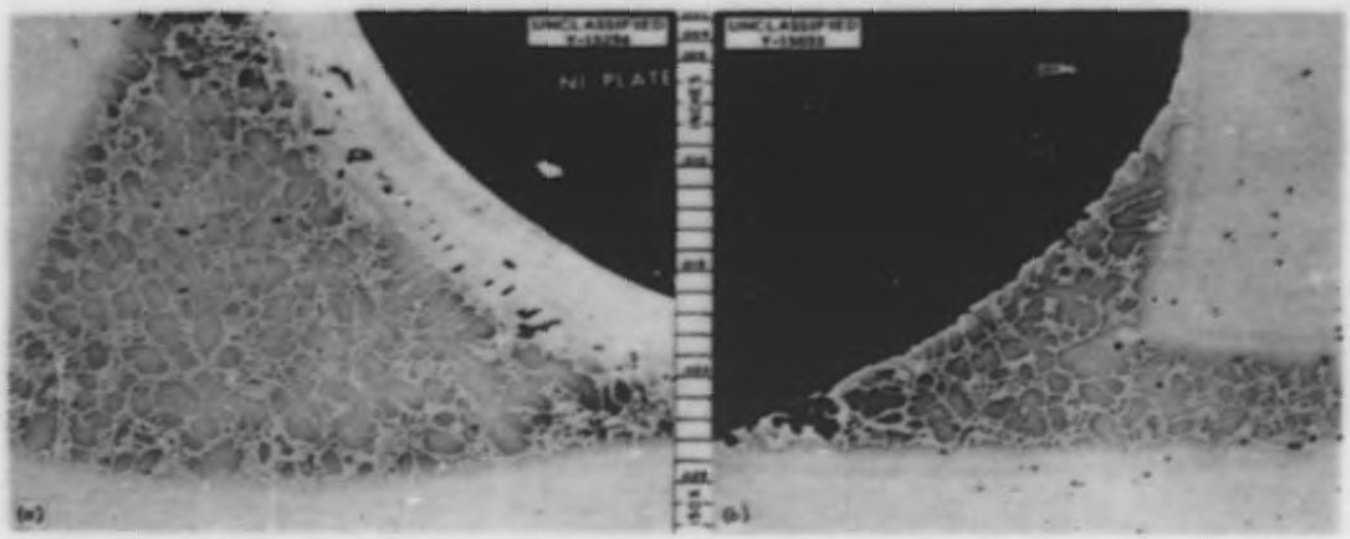

Fig. 20. Photomicrographs of T-Joints Brazed with 70 Ni–13 Ge–11 Cr–6 Si After Exposure at 1500°F to (*a*) Sodium and (*b*) Fused Salt for 100 hr. Note the slight attack along the surfaces of both photomicrographs. Etchant: oxalic acid. 150X. Reduced 19.5%.

SODIUM HYDROXIDE SERVICE

As fused sodium hydroxide is being extensively studied for future reactor technology applications, a limited investigation was conducted to obtain data concerning the corrosion resistance of brazing alloys in intimate contact with molten NaOH. These tests seem to indicate that, of the alloys investigated at 1500°F, only the gold-rich brazing alloys have adequate corrosion resistance. However, at 1100°F three other brazes, 60 Pd–40 Ni, 60 Pd–37 Ni–3 Si, and copper, exhibited moderate compatibility. Photomicrographs of a nickel T-joint brazed with 82 Au–18 Ni and tested at 1100 and 1500°F are shown in Fig. 21.

All nonprecious-metal-base alloys showed severe attack in 100 hr tests at both temperatures. Although only two such alloys are listed in Table 9, previous investigations have indicated that this conclusion may be drawn.

DIFFUSION VOID FORMATION

Several of the brazed T-joints, especially those which included copper, gold, palladium, or silicon as an alloying element in the braze material, showed numerous voids along the interface between the base material and the braze fillet. This phenomenon was observed especially in the fused-salt and sodium-hydroxide corrosion tests when "A" nickel was used as the base material. These voids were not considered to be caused by the attack of the testing media, but rather by the interdiffusion between the brazing alloy and the base material. A nickel T-joint brazed with 60 Pd–37 Ni–3 Si and then exposed to the fluoride mixture NaF-ZrF_4-UF_4 (53.5-40-6.5 mole %) for 100 hr at 1500°F is shown in Fig. 22. Many voids can be seen along the interface, and the surface of the fillet appears to be free of attack.

In order to verify the possibility of interdiffusion between the base material and the brazing alloy, several T-joints were constructed in the same manner as were the tested T-joints, placed in an evacuated capsule, and heated at 1500°F for 100 hr. Figure 23 shows the results of this heat treatment on the same brazing material (60 Pd–37 Ni–3 Si) as that used for the experiment described in the preceding paragraph. As in the previous figure, voids are apparent at the interface between the base material and the braze fillet. Thus the formation of the voids appears to be virtually independent of the environment and therefore not a result of attack by the testing medium.

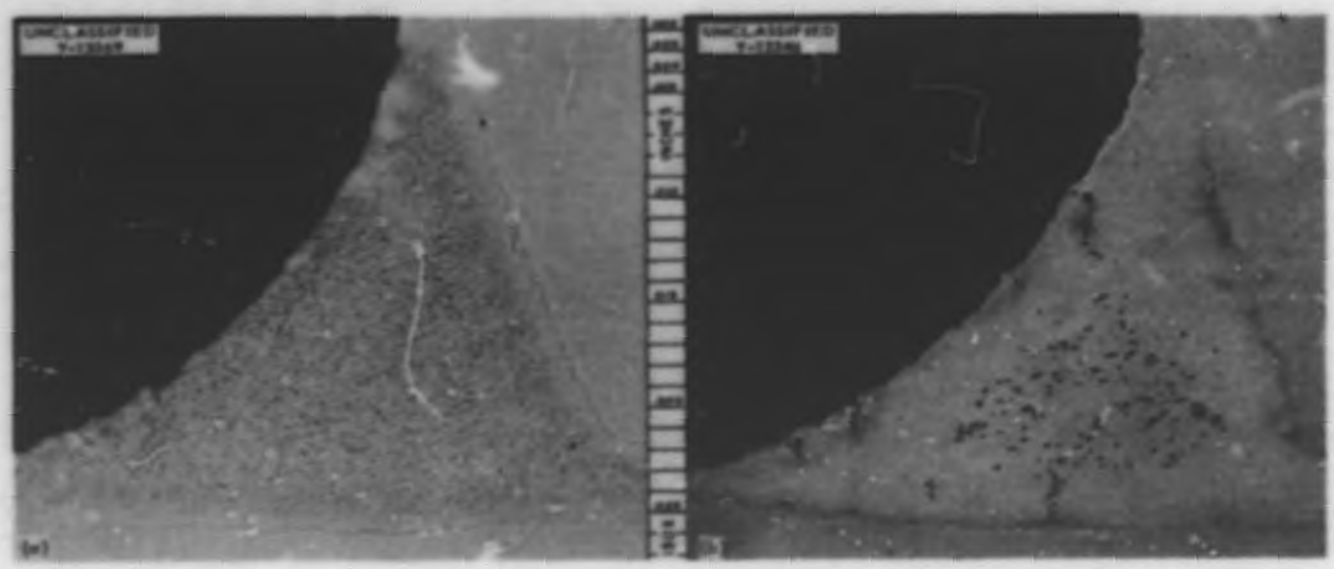

Fig. 21. Photomicrographs of Nickel T-Joints Brazed with 82 Au–18 Ni After Exposure to NaOH for 100 hr at (*a*) 1100°F and (*b*) 1500°F. Note the slight surface attack along the fillet in (*b*). Etchant: $KCN + (NH_4)_2S_2O_8$. 150X. Reduced 9.5%.

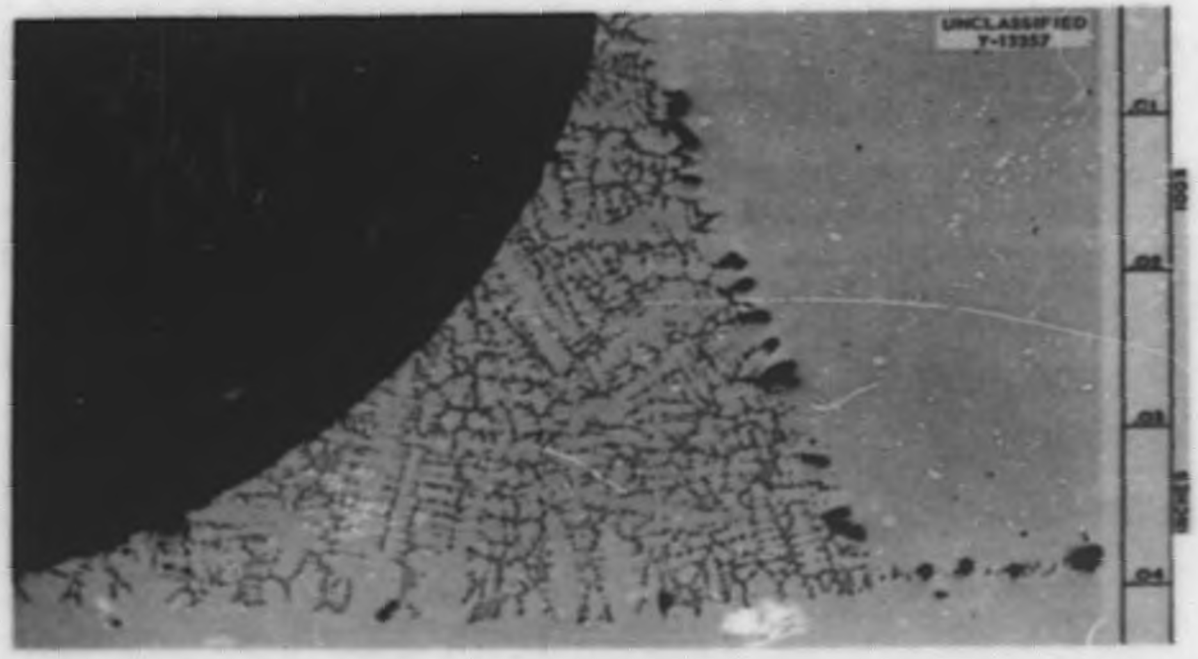

Fig. 22. Photomicrograph of a Nickel T-Joint Brazed with 60 Pd–37 Ni–3 Si After Exposure to the Fue Mixture NaF-ZrF_4-UF_4 (53.5-40-6.5 mole %) for 100 hr at 1500°F. Note the numerous voids at the interfac between the base material and the braze metal. As polished. 100X. Reduced 9%.

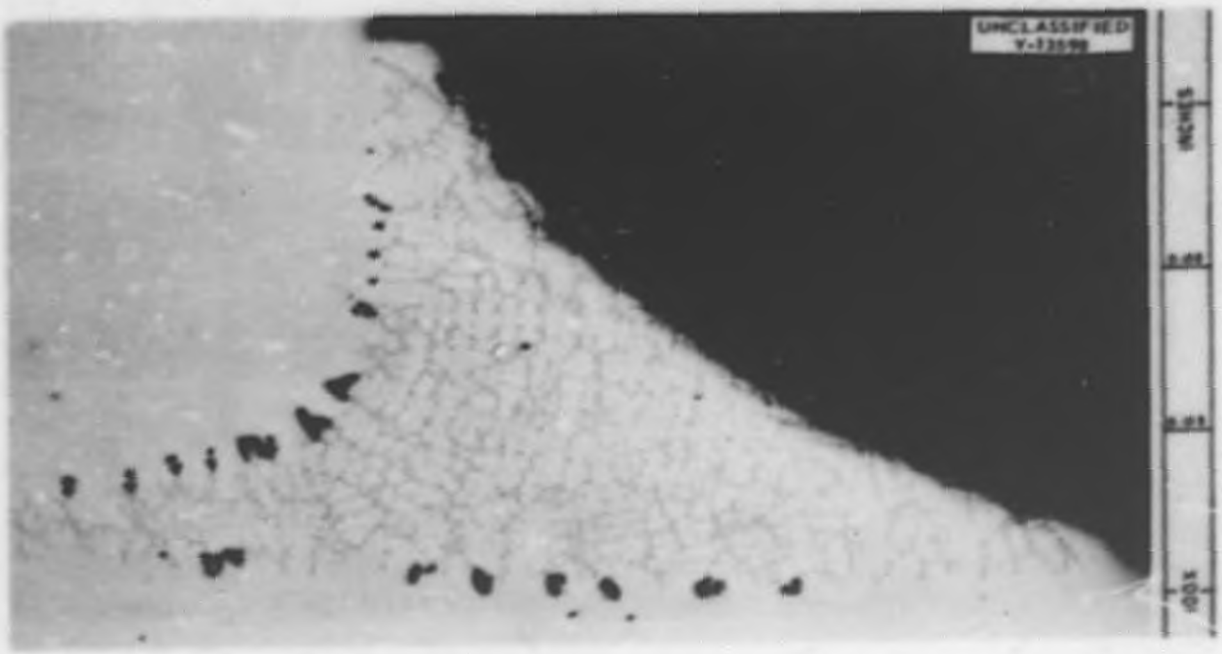

Fig. 23. Photomicrograph of the Same Specimen as in Fig. 22 After Being Annealed for 100 hr at 150 in an Evacuated Capsule. Note the similarity between the interfacial voids in this figure and in Fig. As polished. 100X. Reduced 6.5%.

As would be expected, temperature has a pronounced effect upon void formation. Figure 24 shows the brazing alloy 60 Pd–37 Ni–3 Si after being exposed to sodium hydroxide for 100 hr at 1100 and 1500°F. The 1100°F photomicrograph shows the absence of the interfacial voids, while the 1500°F photomicrograph indicates their presence. This situation is thought to be caused by the large difference in diffusion rates at these two temperatures.

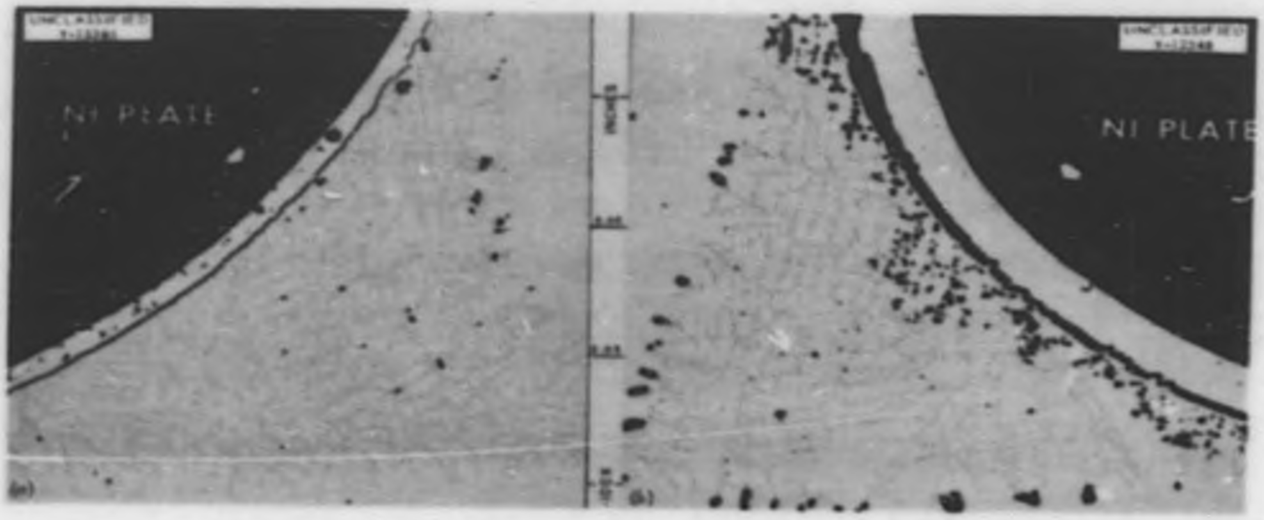

Fig. 24. Photomicrographs of Nickel T-Joints Brazed with the Alloy 60 Pd–37 Ni–3 Si After Exposure to NaOH for 100 hr at (*a*) 1100°F and (*b*) 1500°F. Note the attack and presence of interfacial voids in (*b*). As polished. 100X. Reduced 20.5%.

EN

CONCLUSIONS

As a result of this investigation the following conclusions can be obtained:

1. Many of the brazing alloys which were investigated were highly promising for sodium-to-air radiator service. Alloy systems of Ni-Si-B, Ni-Cr-Si-B, and Ni-Cr-Si were especially favorable. Precious-metal alloys were, in general, severely attacked by sodium, as were many of the silicon-free, chromium-free, phosphorus-bearing alloys. Alloys containing manganese, tin, or copper exhibited poor resistance to oxidation at 1500°F. In most cases, oxidation was more pronounced at 1700°F.

2. For fused-fluoride-to-sodium heat exchanger service, the alloy systems Ni-Cr-P, Ni-Cr-Si-B, Ni-Si-B, and Ni-Ge-Cr-Si show promising corrosion resistance. Although the Ni-Cr-Si alloy (General Electric No. 81) was compatible with sodium, it was severely attacked by the fluoride bath. The binary alloy 88 Ni–12 P (alloy A-10) was incompatible with sodium, but possessed good resistance to fluoride attack. Tests seem to indicate that complex alloy systems containing varying percentages of silicon and phosphorus as minor constituents may be compatible with both sodium and the fused salts, whereas the binary alloys exhibited compatibility with only one of these testing media.

3. The only brazing alloys found to be compatible with fused sodium hydroxide were precious-metal alloys such as 82 Au–18 Ni.

4. In evaluating the corrosion and the oxidation resistances of a brazing alloy for a specific application, emphasis was placed on the seesaw-corrosion and cyclic-oxidation studies, since these tests more nearly simulate the expected operating conditions than do the static tests. It must be remembered, however, that before a brazing alloy is selected for a given operation it should be tested further under the conditions which would closely simulate service conditions.

FUTURE STUDIES

A continuation of testing on many of the alloys listed in this report is now under way to further evaluate their suitability for reactor component fabrication. The alloys which have appeared to be the most promising for sodium and fluoride service are now being tested in Inconel thermal-convection loops. These Inconel loops are constructed with brazed sleeve-joints in their hot sections and operate with an approximate ΔT of 400°F.

New brazing alloys are continually being developed and their corrosion and oxidation resistance must be evaluated in much the same manner as were the alloys listed in this report. The use of lithium as a coolant has been proposed in some reactor designs, and the compatibility of brazing alloys with this medium must also be studied. Since preliminary studies indicate that nickel-base and precious-metal-base alloys are heavily attacked by this material, new brazing alloy systems must be investigated.

ND