

# Development of Corrosion Resistant Filler Metals for Brazing Molybdenum

*Of four iron base filler metals formulated one proved best for a specific application, but the others appear desirable for different uses*

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**ABSTRACT.** We have developed under extremely stringent criteria a series of Fe-Mo-C-B and Fe-Mo-Ge-C-B iron-base brazing filler metals for joining molybdenum. The method used to develop these alloys can be adapted for many other requirements, and the filler metals may also have applications other than the ones described. Presented here is the development of the filler metals from conception (to meet a certain need) through testing (to prove that they meet the need) to use in fabricating one of the most complex structures ever constructed of molybdenum.

The filler metals exhibited excellent flowability below 2190 F (1200 C). They brazed molybdenum to itself, to austenitic stainless steels, to nickel, and to carbon steels. Molybdenum-to-molybdenum brazes possessed excellent shear strengths at room temperature ( $> 30,000$  psi) with accompanying elongations exceeding 10%. At 1200 F (650 C) the strengths were 18,000 to 29,000 psi with elongations exceeding 42%.

These alloys showed outstanding corrosion resistance when exposed to liquid sodium and molten fluoride salts at 1110 to 1290 F (600 to 700 C). In addition, the Fe-Mo-Ge-C-B and Fe-Mo-C-B brazing filler metals had satisfactory corrosion resistance when exposed to static or flow-

ing liquid bismuth at 1110 to 1290 F (600 to 700 C). The overall performance of the Fe — 15%Mo — 5%Ge — 4%C — 1%B filler metal appeared to be the best, and this alloy was used in fabricating a large molybdenum test stand.

## Introduction

Molybdenum or one of its alloys is often considered for various uses in the space and nuclear industries. Because of its excellent high temperature properties and compatibility with certain environments, it is a prime candidate for use in isotopic power systems, certain nuclear reactor components, and chemical processing systems. An example is the molten salt breeder reactor system which was being developed at the Oak Ridge National Laboratory. It required continuous chemical processing of the fuel salt, LiF-BeF<sub>2</sub>-ThF<sub>4</sub>-UF<sub>4</sub> (72-16-11.7-0.3 mole %).

The processing method involved the selective chemical reduction of the various fission products by liquid bismuth solutions. Since molybdenum is one of the few metals that resists corrosion by bismuth, it was considered as a containment material. However, molybdenum has never before been used as the structural material for such a complex system. To determine the feasibility of building and operating a chemical processing system of this type, we constructed molybdenum components to obtain engineering performance data on packed columns (Ref. 1). The test stand consisted of large components (4 in. OD  $\times$  10 to 20 in. long) interconnected by small, thin walled tubing (minimum size  $\frac{1}{4}$  in. OD  $\times$  0.020 in. wall) through which molten bismuth

and fluoride salts would circulate, both separately and countercurrently at 1110 F (600 C) to 1290 F (700 C).

Unfortunately molybdenum has several disadvantages as a structural material. It is impact sensitive, and the ductile-to-brittle transition temperature of its welds is considerably above room temperature (Ref. 2). For reinforcement against straining at the brittle weld, we shielded the welds by back-brazing protective bosses or sleeves around them. In addition to protecting the welds from thermal or mechanical shock, brazing also provides a barrier to the circulating liquid should a crack develop in the weld zone. Mechanical joints made by roll bonding were being used where welding would be extremely difficult. Figure 1 shows a schematic of one of the larger components fabricated. The roll bonded and welded sections are magnified. Both the welds and the roll bonds were back-brazed.

Several commercial brazing filler metals will braze molybdenum, but they are rich in such metals as nickel, copper, silver, and gold, which are not corrosion resistant to both molten bismuth and fluoride salts at temperatures up to 1290 F (700 C). The method used to develop suitable alloys is not limited to this specific situation, but can be adapted to development of brazing filler metals for many other requirements.

## Material

The base metals used in this study included a variety of grades of molybdenum and TZM (Mo — 0.5%Ti — 0.1%Zr — 0.03%C). Commercial powder metallurgy and arc cast stock was used. Powder metallurgy prod-

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Paper was presented at the 2nd International Brazing Conference held in San Francisco, April 26-29, 1971.

ucts when welded contain porosity, which develops along the fusion line and in the weld metal. We also had less trouble with base metal delamination in the arc cast material, and it was more readily fabricated. As a result, most work was with high purity, arc cast molybdenum. A typical chemical analysis of impurities of this material is listed in Table 1.

In the facilities of the Oak Ridge National Laboratory the experimental brazing filler metals were prepared by arc melting (Ref. 3) in an inert atmosphere, then casting it to produce an alloy ingot. The ingot was broken into small particles and ground into 100 mesh powder.

### Brazing Alloy Formulation

Good brazing filler metals must possess the following attributes:

1. suitable brazing temperature,
2. good wettability and flowability,
3. braze integrity (meaning a minimum of cracking, porosity and dissolution of braze metal),
4. strength, and
5. environmental compatibility.

For our application the most difficult requirements to meet were the suitable brazing temperature and environmental compatibility. The brazing filler metal was required to melt and flow on molybdenum at a temperature that would not seriously jeopardize the ductility of the base metal. Large grains, such as those found in welds or in material that has been heat treated at temperatures and times that cause recrystallization and grain growth, are known to adversely affect the ductility of molybdenum (Ref. 4). Its tolerance for impurities such as oxygen and carbon that can adversely affect its properties decrease as the grain size increases (Ref. 5). By bend testing according to the standards of the Materials Advisory Board (Ref. 6), we found that high purity arc cast molybdenum sheets (0.060 in. thick) in the cold worked condition were ductile at room temperature. (The specimens that bent 90 deg without cracking were considered ductile).

### Brazing Temperature

In order to determine the maximum temperature to which the unalloyed metal could be heated without unacceptable loss of ductility, specimens were heat treated at time and temperature combinations similar to those employed in brazing cycles and were bend tested. Specimens heat treated at temperatures up to 2150 F (1175 C) for times as long as 40 min were ductile. Specimens heat treated 3 min at 2190 F (1200 C) bent 90 deg, but those heat treated at 2190 F (1200 C) for 10 min achieved only a

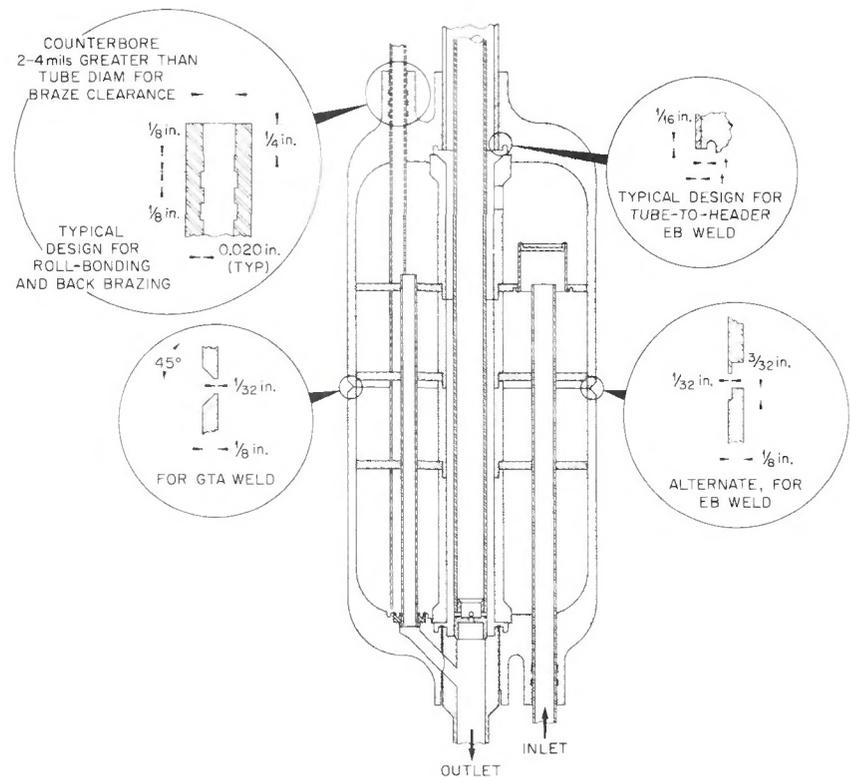


Fig. 1 — Feed pot for molybdenum chemical processing loop.

50 deg bend. Therefore, we concluded that a brazing cycle of 10 min at 2190 F (1200 C) would impair the room temperature ductility of molybdenum. Since the working history of other shapes or sizes, such as tubing and pots, can cause the recrystallization temperature to vary, we felt that we should keep the brazing temperature as far as possible below 2190 F (1200 C) when joining unalloyed molybdenum.

### Environmental Compatibility

As mentioned earlier, another important requirement in developing a brazing filler metal is its environmental compatibility. In this case, the specific requirement was compatibility with bismuth and molten fluoride salts. Unfortunately, few materials adequately resist attack by bismuth. The refractory metals, such as molybdenum, tantalum, rhenium, and tungsten, possess the best resistance. However, it is difficult to depress the melting point of a refractory metal below 2190 F (1200 C), without completely sacrificing its corrosion resistance, by the addition of large amounts of alloying elements. Yet under certain conditions, iron and some of its alloys are reasonably compatible with bismuth.

By alloying iron with small amounts of selected elements, we were able to depress the melting point of the iron base filler metals to

Table 1 — Typical Impurity Content of Arc Cast Molybdenum

| Element | Content (wt %) |
|---------|----------------|
| C       | < 0.005        |
| O       | < 0.0005       |
| H       | < 0.0001       |
| N       | < 0.0001       |
| Fe      | < 0.005        |
| Ni      | < 0.001        |
| Si      | < 0.002        |

below 2190 F (1200 C). Figure 2(a) shows portions of the binary diagrams (Refs. 7, 8), of Fe-C, Fe-B, and B-C. The diagrams show that 1 to 4% of boron or carbon added to iron depresses its melting point significantly. By adding small percentages of both boron and carbon to iron, we were able to depress the melting point to below 2100 F (1150 C). We also felt that the addition of molybdenum to the filler metal would enhance its corrosion resistance to bismuth and minimize dissolution of the molybdenum base metal by the filler metal during brazing. Even with the addition of molybdenum, we found that we could still keep the melting point of the filler metal below 2190 F (1200 C). Figure 2(b) shows the binary phase diagrams (Refs. 7, 8) of Fe-Mo, Fe-B, and Mo-B. Since the temperatures of the liquidus and

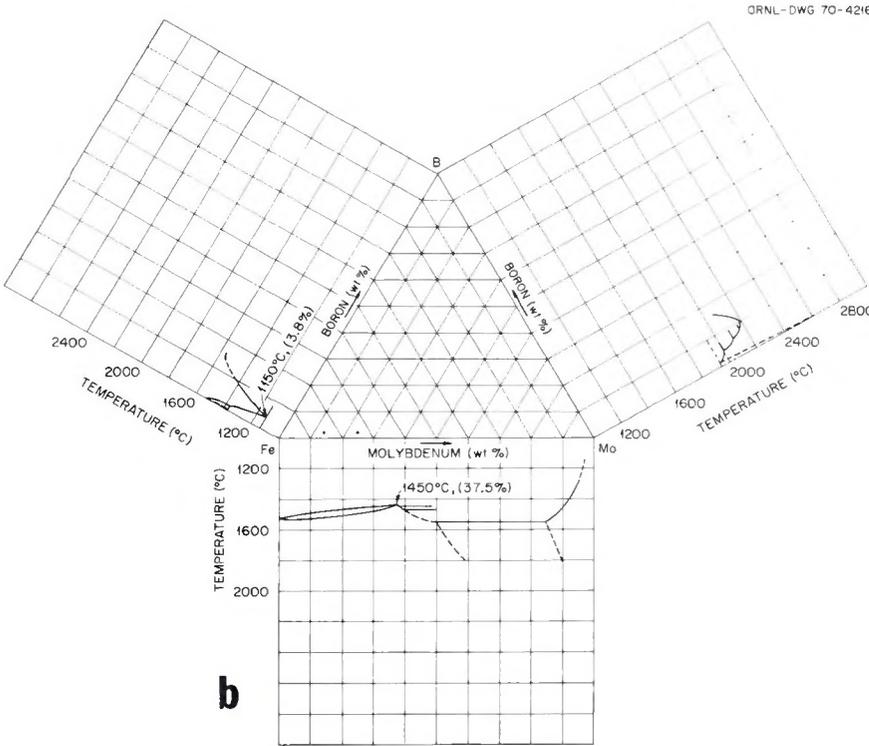
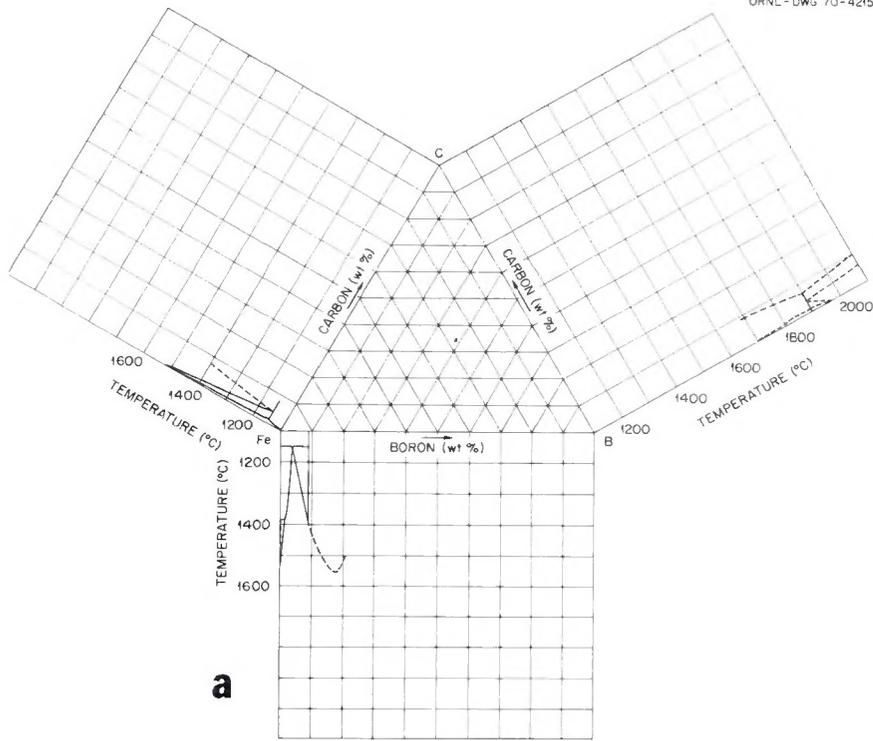


Fig. 2 — Portions of binary diagrams used to select alloy compositions for brazing studies: (a) Fe-C, Fe-B, B-C, (b) Fe-Mo, Fe-B, B-Mo

solidus of the Fe-Mo diagram decrease as the molybdenum content increases from 0 to 35%, we were able to add as much as 25% Mo to the Fe-C-B ternary alloy without raising the melting temperature above 2150 F (1175 C).

In an attempt to further depress the melting temperature, we added small amounts of germanium. Adding 5% Ge depressed the melting point of the Fe — 15%Mo — 4%C — 1%B filler metal to 1920 F (1050 C) and, as a bonus, also gave it added fluidity.

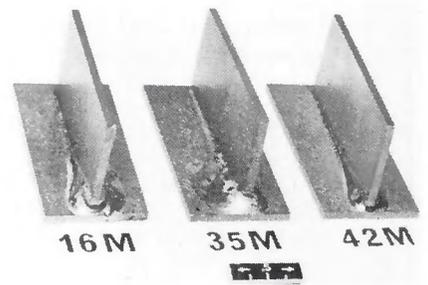


Fig. 3 — Molybdenum Inverted T-Joints Showing the Excellent Flowability of Alloys 16M (Fe — 4%C — 1%B), 35M (Fe — 15%Mo — 4%C — 1%B), and 42M (Fe — 15%Mo — 5%Ge — 4%C — 1%B)

### Brazing Procedure

Two techniques were used to add the filler metal to the joint. In some cases, the premachined feeder holes or grooves were filled with powdered filler metal. When heated, the filler metal flowed into the joint by capillary action. Alternately, the powder was mixed with an organic binder to form a paste, which was painted along the faying surfaces. Before brazing, all molybdenum parts were degreased with acetone and ethyl alcohol and etched with hot chromic acid. Molybdenum sheet, tubing, and test stand components were brazed with the experimental alloys in vacuum ( $1 \times 10^{-5}$  torr), helium, and argon in a variety of joint designs. Heating was accomplished by both resistance and induction.

### Brazing Characteristics

As the initial test, we placed each brazing filler metal on a pad of molybdenum and heated it in vacuum to determine its melting point and to assess how well it wet the molybdenum. Flowability was evaluated by fabricating inverted Tee joints. The filler metals were expected to flow along the capillary of a 3 in. long Tee joint before they were accepted for further study. For example, the three filler metals shown in Fig. 3, 16M (Fe — 4%C — 1%B), 35M (Fe — 15%Mo — 4%C — 1%B), and 42M (Fe — 15%Mo — 5%Ge — 4%C — 1%B), exhibited excellent flowability. They were examined metallographically to assure minimum dissolution of the base metal.

Mockups of components for the chemical processing test stand were brazed to test filler metal flowability and braze integrity. All the joints were checked for leak tightness and were metallographically examined to assure braze integrity (absence of cracks and porosity). Figure 4(a) shows a mockup of the end portion of one of the large components, a feed pot for bismuth containment. Figure

4(b) shows a mockup of one of the field brazes, in which a sleeve is brazed onto a small thin walled tube. Note in Fig. 4(c) that the filler metal has flowed deep into the joint. These mockups were brazed with the Fe — 15%Mo — 5%Ge — 4%C — 1%B filler metal, which has sufficient fluidity that it has been used (Ref. 9) to repair cracked welds.

The four most promising filler metals, their brazing temperatures, and brazing characteristics are listed in Table 2. All have adequate wettability and flowability, and the fluidity of the Fe-Mo-Ge-C-B alloy is excellent. The joint integrity of each is good with the exception of cracking at the filler-to-base-metal interface in the higher (25%) molybdenum brazes. Evidently 25% Mo in the filler metal causes the braze to be so brittle that the stresses from differences in thermal coefficient of expansion that occur during cooling from brazing temperature cause cracking in areas of high molybdenum concentrations.

In addition, dissimilar metal joints of molybdenum tubes to austenitic stainless steel, nickel, and carbon steel tubes have been successfully brazed with the Fe — 15%Mo — 5%Ge — 4%C — 1%B and Fe — 15%Mo — 4%C — 1%B filler metals. However, careful consideration must be given to joint design. Because of thermal expansion differences, the joints must be designed such that the material with the larger thermal expansion coefficient (nickel, stainless steel, or carbon steel) is placed on the outside so that it places the molybdenum in compression upon cooling; otherwise a leak tight braze could not be obtained.

### Joint Mechanical Properties

To determine mechanical properties of brazed joints made with the experimental filler metals, we shear tested several specimens made with two of the most promising iron base alloys. Miller-Peaslee shear test specimens (Refs. 10, 11) were brazed with alloys Fe — 15%Mo — 5%Ge — 4%C — 1%B and Fe — 15%Mo — 4%C — 1%B. They were pulled with a screw driven tensile machine at a strain rate of 0.002 in./min at both room temperature and 1200 F (650 C). Average test results are shown in Table 3.

The room temperature shear strengths of greater than 30,000 psi are considered excellent. This compares with base metal shear strengths of about 45,000 psi. At 1200 F (650 C) the average shear strength of the joint brazed with Fe-Mo-Ge-C-B was 29,000 psi, whereas that of the joint brazed with Fe-Mo-C-B was 18,000 psi. This lower strength is, however, more than ade-

Table 2 — Properties of Iron Base Filler Metals for Brazing Molybdenum

| Composition, wt % | Brazing temperature |      | Wettability and flowability | Joint Integrity  |
|-------------------|---------------------|------|-----------------------------|--|
|                   | F                   | C    |                             |  |
| Fe—4C—1B          | 2100                | 1150 | Good                        | Good   |
| Fe—15Mo—4C—1B     | 2100                | 1150 | Good                        | Good   |
| Fe—25Mo—4C—1B     | 2150                | 1175 | Good                        | Some tendency to crack along filler metal-to-molybdenum base metal interface |
| Fe—15Mo—5Ge—4C—1B | 1920                | 1050 | Excellent                   | Good   |

Table 3 — Mechanical Properties of Brazed Molybdenum Joints

| Composition, wt % | Shear strength, psi, at |                | Elongation, %, at |                |
|-------------------|-------------------------|----------------|-------------------|----------------|
|                   | room temperature        | 1200 F (650 C) | room temperature  | 1200 F (650 C) |
| Fe—15Mo—5Ge—4C—1B | 30,000                  | 29,000         | 10                | 50             |
| Fe—15Mo—4C—1B     | 31,000                  | 18,000         | 11                | 42             |

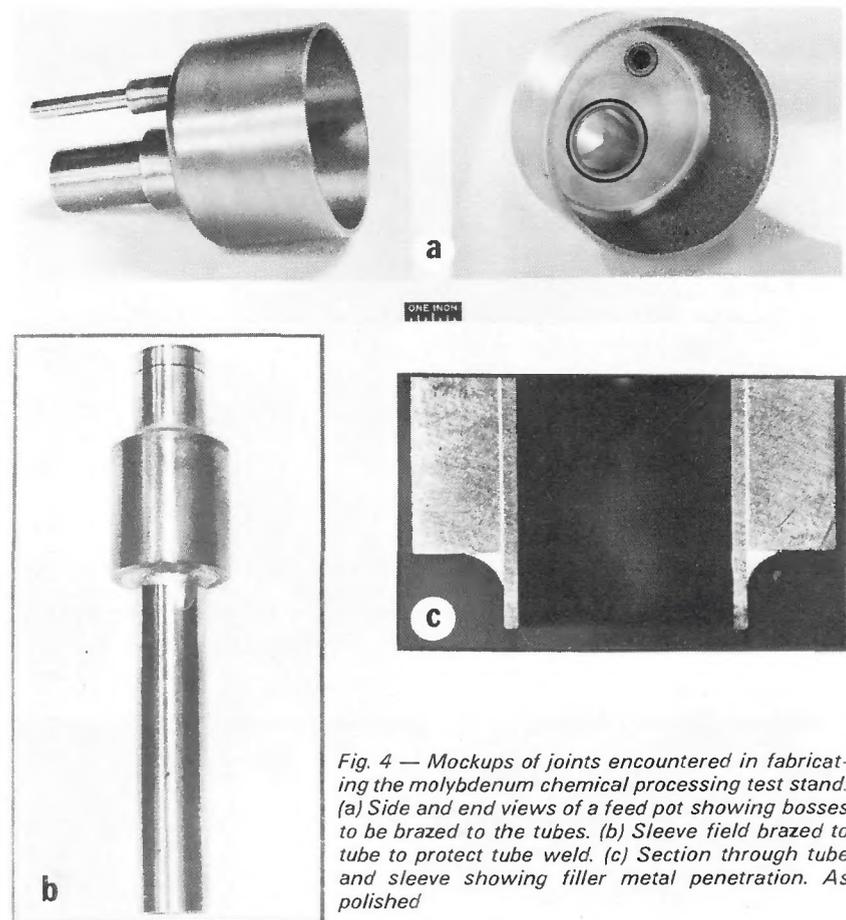


Fig. 4 — Mockups of joints encountered in fabricating the molybdenum chemical processing test stand. (a) Side and end views of a feed pot showing bosses to be brazed to the tubes. (b) Sleeve field brazed to tube to protect tube weld. (c) Section through tube and sleeve showing filler metal penetration. As polished

quate for our applications. It is interesting to note that the elongations of Miller-Peaslee specimens brazed with both filler metals at 1200 F (650 C), were over 40%. Even at room temperature, where welded molybdenum is brittle, the

elongations of the specimens were at least 10%.

### Joint Environmental Compatibility

The experimental brazing filler metals listed in Table 2 were tested in

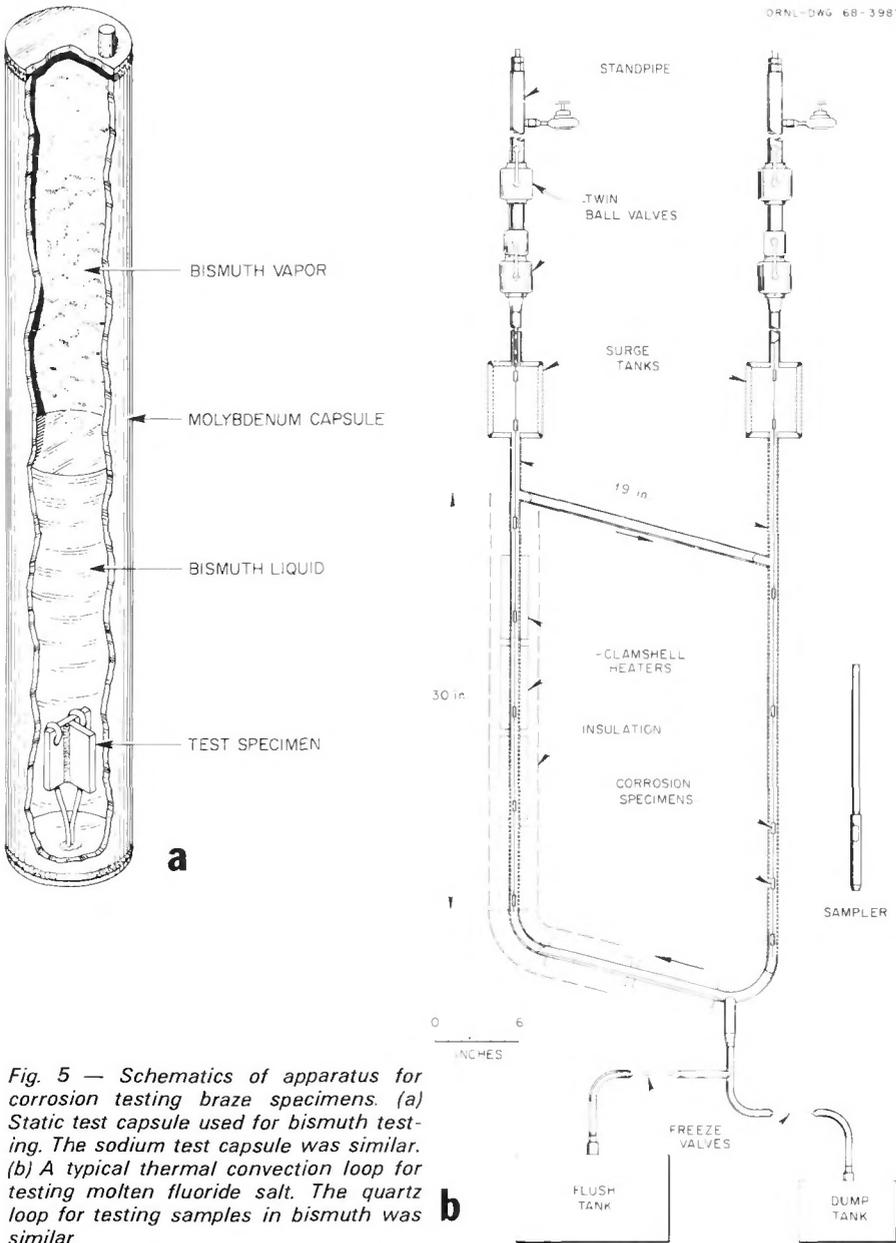


Fig. 5 — Schematics of apparatus for corrosion testing braze specimens. (a) Static test capsule used for bismuth testing. The sodium test capsule was similar. (b) A typical thermal convection loop for testing molten fluoride salt. The quartz loop for testing samples in bismuth was similar

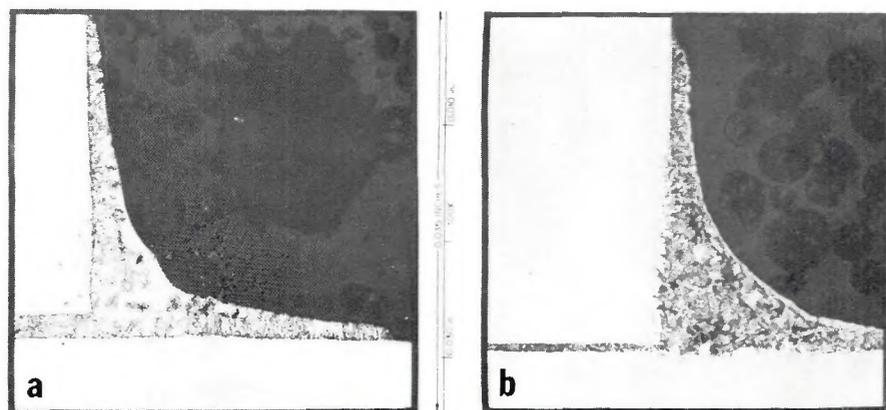


Fig. 6 — Molybdenum brazed with Fe — 15%Mo — 4%C — 1%B. (a) As brazed. (b) Exposed to flowing molten fluoride salts at 1240 F (670 C) for 1032 hr. As polished

several environments (i.e., bismuth, sodium, and fluoride salt). For chemical processing applications, the proof tests of the brazed specimens in bismuth were considered quite important, since the solubility of pure iron in bismuth is 50 ppm at 1110 F (600 C), and iron is known to undergo temperature gradient mass transfer in liquid bismuth.

Corrosion by bismuth usually involves solution of the alloy (or a constituent of an alloy) into the liquid metal. Thus, in an isothermal system, if the solubility of the material in contact with the liquid metal is high, the amount of dissolution will generally be large unless kinetic factors interfere. In a system under a temperature differential, the material being dissolved in the hotter portion of the circuit, and precipitates in the colder region of the circuit. This mass transfer is due to the variation of solubility with temperature rather than the actual solubility.

However, molten salt corrosion involves oxidation of the alloy constituent that forms the most stable fluoride. Thus, the least noble metals are more susceptible to molten salt corrosion. Again in a temperature gradient system, material is removed in the hot section and deposited in the cold section. But the mass transfer in this case is a function of temperature, and the temperature coefficient is the equilibrium constant of the oxidation-reduction reaction.

#### Test Procedure

Two types of tests were selected for determining the compatibility of the brazed joints — static capsule tests and thermal convection loops. Both were used in bismuth testing. A thermal convection loop was used to determine molten salt compatibility, and capsule tests were used to evaluate sodium compatibility. All brazed specimens consisted of molybdenum brazed to molybdenum with the experimental filler metal in an inverted Tee or lap configuration.

A schematic of the static capsule test is shown in Fig. 5(a). The capsule was made of molybdenum, TZM, or Mo — 0.5%Ti for bismuth testing and type 304 stainless steel for sodium testing. The capsule was prepared for testing by placing the brazed specimen and the bismuth or sodium in the capsule, welding the cap to the end of the capsule, and heating the capsule to the test temperature. At the end of the test the capsule was inverted to remove the specimens from the liquid metal and cooled. The tests in bismuth operated at 1110 F (600 C) for 600 to 700 hr. and the tests in sodium operated at 1290 F (700 C) for 700 hr.

A typical thermal convection loop is shown schematically in Fig. 5(b). In the molten salt test,  $\text{LiF-BiF}_2\text{-ZrF}_4\text{-UF}_4\text{-ThF}_4$  (70-23-5-1-1 mole %) circulated over the brazed specimens for 1032 hr at approximately 1240 F (690 C). The test was conducted in a type 304L stainless steel thermal convection loop, which operated at a maximum temperature of 1275 F (690 C) and a temperature difference of 180 F (82C).

The loop containing bismuth was made of quartz, and it operated 2100 hr with a maximum temperature of 1290 F (700 C) and a temperature difference of 160 F (90 C) (Ref. 12). Brazed lap joints were placed in both the hot and cold legs of the loop.

## Results

All four brazing filler metals listed in Table 2 survived the sodium and fluoride salt tests with no metallographically detectable corrosion. An example is shown in Fig. 6. This braze (Fe — 15%Mo — 4%C — 1%B) was tested in fluoride salt, and no loss of brazing alloy can be seen.

The Fe — 4%C — 1%B braze suffered extensive corrosion after 671 hr in static bismuth at 1110 F (600 C), shown in Fig. 7. However, the area between the vertical and horizontal sections of the Tee remained intact. Further analyses after test showed that in this section the filler metal now contained 15% Mo, probably as a result of alloying with the base metal during brazing. Evidently this concentration of molybdenum in the brazing filler metal resulted in modest resistance to bismuth.

The other three brazing filler metals showed adequate corrosion resistance in the bismuth capsule tests. Up to 50 ppm Fe was found in the bismuth after test, but metallographic evaluation showed good integrity as can be seen in Fig. 8. This specimen was brazed with Fe — 15%Mo — 5%Ge — 4%C — 1%B and tested 641 hr at 1110 F (600 C). Minor changes appeared in the braze microstructure after testing, but the braze fillet remained in satisfactory condition.

All four of the brazing filler metals were exposed to bismuth in a quartz thermal convection loop. The seven lap joints, representing the four experimental filler metals, remained intact after testing. Three were placed in the hot leg and four in the cold leg of the loop. (The Fe-C-B braze was placed only in the cold leg). Weight change data were unavailable, since some bismuth adhered to the specimens after test. Interestingly, we saw no evidence of cracking from expansion of bismuth upon freezing. Chemical analyses of the

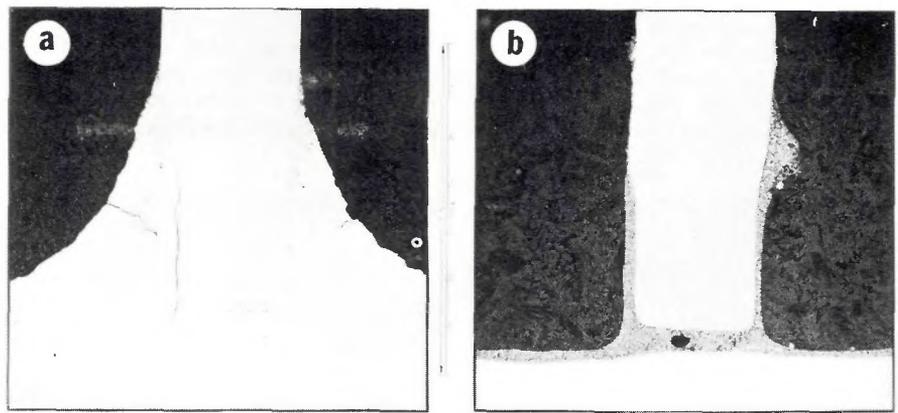


Fig. 7 — Molybdenum Tee joint brazed with Fe — 4%C — 1%B. (a) Before exposure. (b) After exposure to molten bismuth 671 hr 1110 F (600C)

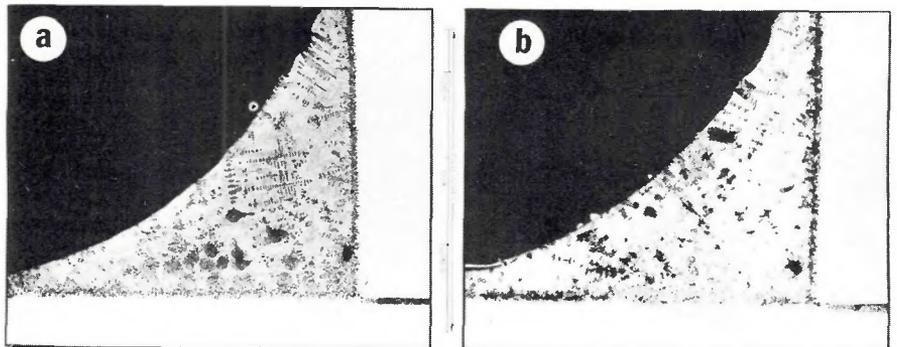


Fig. 8 — Molybdenum brazed with Fe — 15%Mo — 5%Ge — 4%C — 1%B. (a) As brazed. (b) After exposure to static molten bismuth 644 hr at 1110 F (600 C). As polished

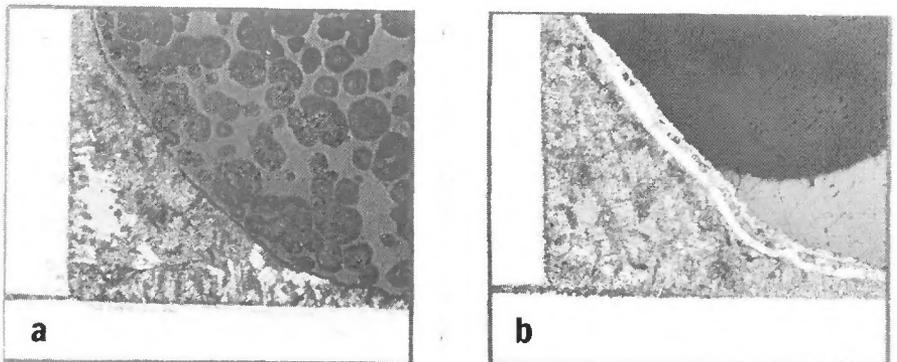


Fig. 9 — Molybdenum brazed with Fe — 15%Mo — 4%C — 1%B. (a) As brazed. (b) Exposed to circulating bismuth 2000 hr at 1200 F (650 C). As polished

bismuth drained from the loop indicated that the amounts of iron and molybdenum, if present, were below the limit of detection, 3 ppm.

Figure 9 shows microsections of a specimen brazed with Fe — 15%Mo — 4%C — 1%B before and after testing in the bismuth thermal convection loop. After testing, one or more layers appeared on the surface of the braze fillet. Microprobe analyses showed that the light layer is rich in iron and darker layer is rich in molybdenum. Figure 10 illustrates the microprobe electron beam scanning images of various elements in the corrosion tested Fe — 15%Mo —

4%C — 1%B braze. Phases within the braze and along the interface between braze and base metal are also rich in molybdenum. Also, certain areas are enriched in bismuth, and it is interesting to note that those areas are associated with the regions of high molybdenum concentration. It appears that a complex intermetallic compound has formed containing molybdenum, bismuth, and other unidentified elements (Ref. 12). (Because of limitations of the microprobe, we were unable to analyze for the presence of boron and carbon, the other elements alloyed in the brazing filler metal.)

After-test microsections of the joints brazed with the other brazing filler metals are shown in Fig. 11. The results are much the same. Each braze fillet has a surface layer, which

is more clearly seen on some than on others. However, note that little of the fillet of the Fe — 4%C — 1%B braze has been removed (contrary to the result of static bismuth corrosion

testing). Instead, bismuth has been picked up by the braze. We feel that the presence of the layers rich in iron and molybdenum may have kept the underlying material from being removed in this test.

### Conclusions

Four iron base brazing filler metals that wet and flow on molybdenum below 2190 F (1200 C) have been studied. Three of them have promising brazing capabilities under a variety of circumstances. In addition, at least two of them (Fe — 15%Mo — 5%Ge — 4%C — 1%B and Fe — 15%Mo — 4%C — 1%B) will join molybdenum to austenitic stainless steel, to nickel, and to carbon steel.

Molybdenum joints brazed with three of the filler metals (Fe — 4%C — 1%B, Fe — 15%Mo — 4%C — 1%B, and Fe — 15%Mo — 5%Ge — 4%C — 1%B) have good integrity. The fourth (Fe — 25%Mo — 4%C — 1%B) did not have enough ductility when used to braze molybdenum to avoid cracking along the braze-base metal interface. The filler metal with germanium has the lowest brazing temperature and the best flowability. All have good corrosion resistance to molten sodium and fluoride salts at 1110 F (600 C) to 1290 F (700 C). However, only two (Fe — 15%Mo — 5%Ge — 4%C — 1%B and Fe — 15%Mo — 4%C — 1%B) have satisfactory joint ductility with the molybdenum base metal and corrosion resistance to bismuth. Both of these filler metals possess excellent shear strength and ductility at 1200 F (650 C), with the Fe-Mo-Ge-C-B braze possessing greater strength and ductility. At room temperature the properties of both are more than adequate. Recognizing the special requirements for fabrication of our complex structure of molybdenum, we have selected the Fe-Mo-Ge-C-B brazing filler metal. However, for many applications, all of the filler metals appear to have considerable promise.

### Acknowledgments

The authors wish to thank O. B. Cavin for testing brazed specimens in the bismuth thermal-convection loop; D. H. Jansen for testing braze specimens in sodium; Helen Mateer Henson for the microprobe analyses; J. W. Hendricks and C. W. Houck for the brazing; W. H. Farmer for preparing the metallographic samples; K. Boling for the shear testing; and C. E. Dunn for melting and casting the brazing compositions.

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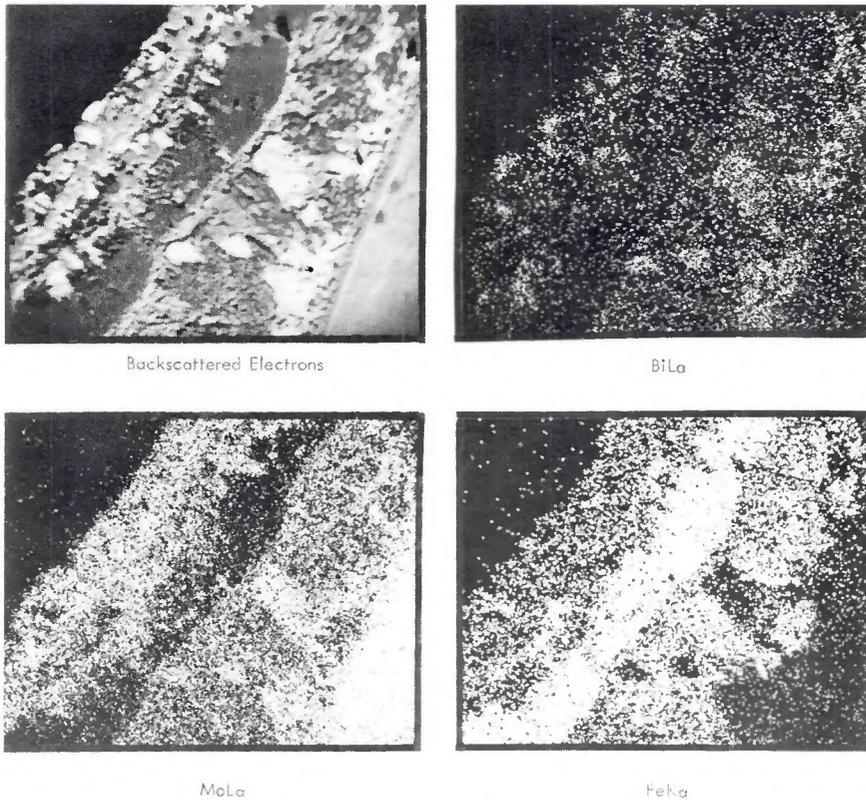


Fig. 10 — Microprobe electron beam scanning images of iron, molybdenum, and bismuth in braze after exposure to circulating bismuth

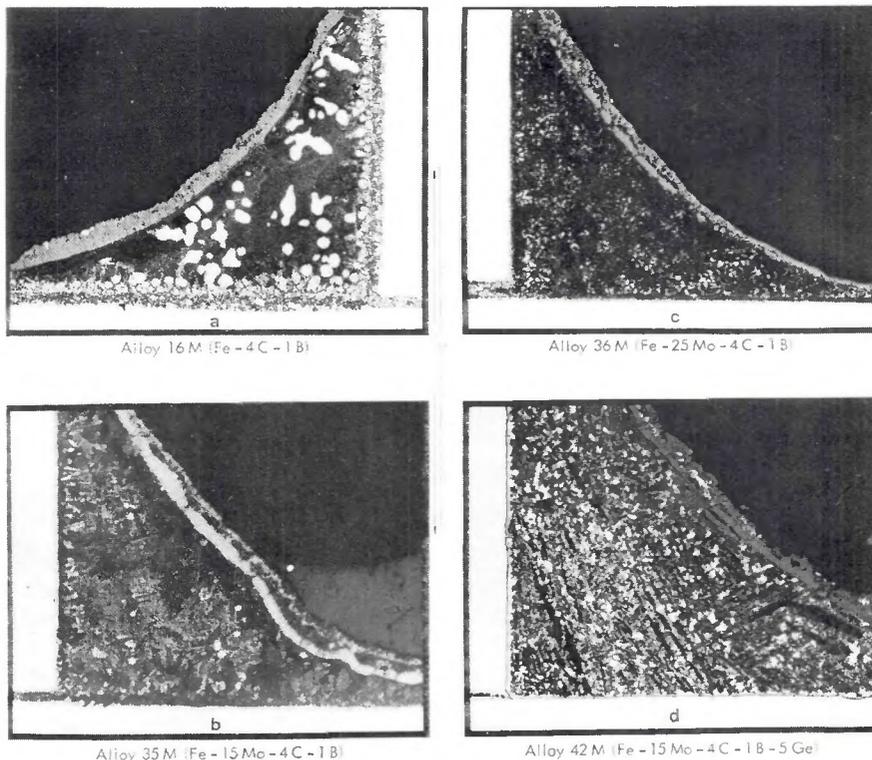


Fig. 11 — Iron base braze alloys after testing in circulating bismuth at 1130 F (610 C) to 1290 F (700 C). As polished

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WRC  
Bulletin  
No. 173  
June 1972

**"Design of Tapered Members"**  
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The use of "tapered structural elements," having tapered depths and/or widths, was first proposed by Amirikian for reasons of economy in 1952. In view of the lack of basic understanding of the behavior of these types of members, in particular the lack of information having to do with design against instability, the Naval Facilities Engineering Command, the American Institute of Steel Construction, the American Iron and Steel Institute, and the Metal Building Manufacturer's Association have jointly sponsored since 1966 a research project at the State University of New York at Buffalo to carry out such studies. As part of those studies, both analytical and experimental investigations were conducted on the behavior of such tapered members and the results were used to develop proposed design formulas. This paper, which summarizes many of the conclusions of those investigations, is concerned primarily with (a) the overall analysis of tapered member framing, and (b) the development of the design formulas regarding the proportioning of tapered members.

A general treatment for any arbitrarily tapered beam would be very ambitious and, in general, impractical due primarily to the difficulties associated with the coupling of flexural and torsional deformations. For this reason the most common tapered I section now being used was chosen for examination, and design formulas for such members were developed. It is to be recognized, however, that the formulas suggested may also be applied (with caution) to other sections which are "sufficiently braced" to prevent torsional deformation.

Also contained in this paper is a brief description of several of the frame analysis and stress analysis methods applicable to tapered framing. It also is to be noted that a later section of the report is devoted to the problem of effective length of a tapered column in rigid frames.

The basic approach used in the development of design formulas for tapered members was as follows: theoretical solutions are first obtained, then, using these solutions, the AISC prismatic member design formulas are modified to effect the same solutions by the introduction of appropriate multiplying factors which are dependent only on the tapering geometry. Since these factors (by definition) reduce to unity when there is no taper in the member, it must be recognized that this approach assumes that the current AISC allowable stress formulas for prismatic members are adequate.

The publication of this paper was sponsored by the Structural-Steel Committee of the Welding Research Council. WRC Bulletin No. 173 is \$3.00 per copy. Orders should be sent to the Welding Research Council, 345 East 47th Street, New York, N.Y. 10017.