

Book 104

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Research Laboratory of Electronics

Technical Report No. 104

April 5, 1949

METAL TO NONMETALLIC BRAZING

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ABSTRACT

A series of experiments has been carried out on the direct brazing of metals and nonmetallic materials by a new, simple technique using brazing alloys of active metals, such as zirconium, titanium, tantalum, and columbium. Such materials as diamond, sapphire, carbides, various ceramics, refractory oxides, glass, quartz, stainless steel, etc. have been successfully brazed to like materials or to metals.

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METAL TO NONMETALLIC BRAZING

Introduction

This report has been prepared to summarize the results of a series of experiments on the brazing of both metals and nonmetallic materials with active metals such as titanium, zirconium, columbium, and tantalum. This brazing technique has been carried out in controlled atmospheres and vacuum without the use of fluxes. The experiments described are of an exploratory nature, with little emphasis on the development of techniques for special applications. The method has been used in brazing a wide variety of materials, i.e., diamonds, sapphires, carbides, various ceramics, refractory oxides, glass, quartz, stainless steel and chrome-iron-type alloys. The active metals used in this brazing technique have the interesting property of wetting both metals and nonmetallic materials equally well, producing exceptionally strong bonds which in many cases exceed the strength of the nonmetallic materials.

Good vacuum seals with glass and ceramic have been prepared by this method. Through the use of brazed ceramics in place of glass, higher bake-out temperatures can be achieved, allowing more rapid outgassing of vacuum apparatus. The applications are not, however, limited to vacuum techniques, but should be useful in the preparation of tools or other devices for which nonmetallic materials are bonded to metal.

R. J. Bondley (1) of General Electric described a technique of brazing ceramics to metals, using titanium hydride in vacuum or in an atmosphere of highly purified hydrogen. We prepared a number of seals with titanium hydride, of the type described in the General Electric report, and extended the work into the brazing of other types of ceramics and various nonmetallic materials - using not only titanium hydride but also the hydrides of zirconium, tantalum, and columbium. We believe that zirconium hydride shows somewhat superior wetting and bonding qualities to those of titanium hydride. Good results have also been obtained with the hydrides of tantalum and columbium. It has been found possible to braze with alloys of these active metals as well as with their hydrides. Brazing operations have been carried out in vacuum or in atmospheres of highly purified hydrogen, argon, helium and nitrogen, as well as in commercial tank argon, helium, and nitrogen. In the case of zirconium, the brazing operation may be successfully carried out in ordinary commercial dry tank nitrogen.

Several experiments have indicated that it would be possible to prepare ceramics and metal-ceramic bodies by use of various metal hydrides. This general technique seems to lend itself to: the preparation of highly refractory bodies such as those used in gas turbines, jet engines, and

rockets; cemented carbide-type tools, heating elements and crucibles; also various low-temperature ceramic bodies. Furthermore, metal-ceramic bodies could be prepared with a wide range of thermal expansions to match metals and glasses by adjusting the percentages of metal and ceramic materials.

In general, our work may be divided into three groups, as follows:

1. The use of hydrides;
2. The use of special brazing alloys;
3. The investigation of controlled atmospheres.

The Use of Hydrides

Our work with the hydrides, namely titanium, zirconium, tantalum and columbium, was limited to those easily obtainable. Other hydrides, no doubt, have desirable properties and would be adaptable to this type of brazing. The chemistry and the physical properties of many hydrides are not well-known and the data in the literature are often of a contradictory nature. For this reason, no attempt will be made in this report to discuss the chemistry of the hydrides. The general properties of the hydrides are covered in a recent paper by Gibb (2). In his paper he divides hydrides into four general groups: (a) Saline, (b) Metallic, (c) Volatile, and (d) Interstitial (see Figure 1). (The interstitial group includes hydrides of doubtful nature.) Gibb also divides the hydrides into primary and secondary types. ZrH_2 is a common primary hydride, while $LiAlH_4$ represents the secondary type. The secondary type of hydrides is also represented by such organometallic compounds as trimethyl tin hydride $(CH_3)_3SnH$ and triphenyl germanium hydride $(C_6H_5)_3GeH$, as well as a number of organo-silicon and boron hydrides. A list of the known hydrides with chemical and physical properties is given in a report by Eisenstine, *et al.* (3). The property which seems to be of principal interest here is that of thermal dissociation. In a recent book (4), the subject of hydrogen in metals is covered very completely and many dissociation curves are given. The hydrides of titanium, zirconium, columbium and tantalum tend to dissociate slowly as the temperature is increased. If heated to a sufficiently high temperature in vacuum, the hydrogen may be entirely removed. The nature of these dissociation curves is shown in Figure 2.

We have observed, during the formation of alloys produced by heating metals and metallic hydrides, that most of the hydrogen may be evolved at or near the melting point of the alloy, which may be considerably below the values given for the dissociation of the hydride alone — in aluminum-zirconium alloys, for example, in our vacuum-induction furnace, the evolution of hydrogen was indicated by a bright discharge.

The general procedure, for use of the hydrides mentioned, involves

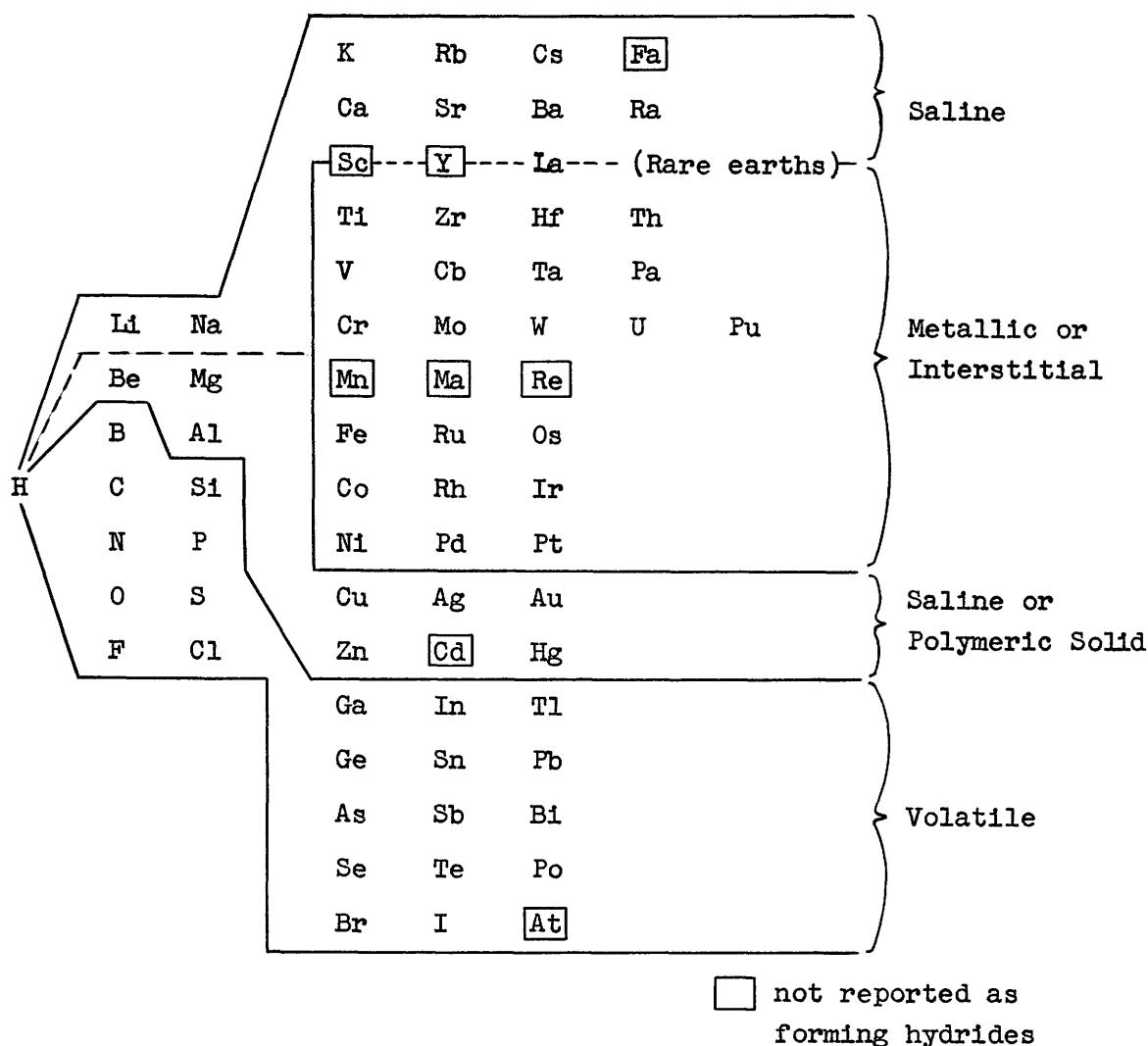


Fig. 1 Periodic distribution of hydrides (from Gibb).

coating the surface to be brazed with thin films of the hydride. A water paste or a nitrocellulose-solution binder seems to work equally well in producing thin uniform coatings of the hydride. A piece of suitable solder is then placed in contact with the hydride-coated surface. The material is heated to approximately 1000°C or to a temperature at which the solder flows freely in a vacuum (approximately 10^{-4} mm of mercury or better) or in an atmosphere of pure hydrogen or pure inert gas. When the proper temperature is reached, the brazing alloy will melt and flow over the hydride-coated surface in a manner somewhat similar to that in the brazing of metals. At the present time, our experiments with columbium and tantalum hydrides have not proved that they have any particular advantages over zirconium hydride. In general, zirconium hydride seems superior to titanium hydride for most operations.

Copper-silver eutectic solder (melting point 779°C) and pure silver (melting point 960°C) are both very satisfactory brazing materials. We have also used pure aluminum as a solder with excellent results. Although the solubilities of zirconium and titanium are very low in aluminum, the titanium-aluminum and zirconium-aluminum combinations yield good brazing alloys. Pure aluminum gives particularly good results with columbium and tantalum hydride.

Titanium hydride, used by Bondley, exhibits considerable sensitivity to small amounts of oxygen and water vapor and somewhat less sensitivity to nitrogen during the brazing operation. We have carried out the titanium-hydride brazing operation in a vacuum furnace into which small amounts of nitrogen were introduced, without seriously hindering the brazing operation. Large amounts of nitrogen, however, may completely hinder the brazing with titanium hydride. This seems reasonable in view of the fact that titanium nitride forms so readily at elevated temperatures. Zirconium hydride, on the other hand, is not so strongly affected by the presence of nitrogen, so that the brazing operation may be carried out in an atmosphere of dry commercial tank nitrogen. This is not easily explained, however, in view of zirconium's strong affinity for nitrogen. Both titanium and zirconium hydrides are, however, very sensitive to small amounts of oxygen. While the brazing operations may be carried out in atmospheres of highly purified hydrogen, in our experiments specimens heated in commercial tank hydrogen were converted to their respective oxides, thus completely inhibiting the brazing operation.

Brazing Alloys*

Zirconium hydride can be heated in vacuum at approximately 800-1000°C to remove most of the hydrogen, leaving behind a relatively pure zirconium metal powder. This partially sintered metal powder may be exposed to air and then used in a manner similar to zirconium hydride to produce an equally good braze. In contrast to most zirconium metal powders, this sintered material does not seem to be highly pyrophoric. The fact that the hydrogen may be removed prior to the brazing, and the reduced hydride exposed to the air, indicates that hydrogen is not essential to the process. Attempts to use titanium hydride in a similar manner were not successful; this may be attributed to oxidation of the titanium metal in air. Apparently the function of the hydride is to yield a relatively pure active metal, free to alloy with a suitable solder.

On the assumption that hydrogen is not necessary to the brazing

* All alloys are expressed in weight percentages.

operation, alloys of silver and zirconium were prepared by vacuum melting of the pure metals in tantalum or quartz crucibles. The data in the literature indicate that the solubility of zirconium in solid silver is small and that intermetallic compounds are formed. Sykes (5) has studied alloys containing from 0 - 30 per cent zirconium. We have found that an alloy containing 15 per cent zirconium and 85 per cent silver will wet and bond ceramics, diamond, sapphire, carbides, etc. in much the same manner as the hydride method. Equally good results were obtained by placing pieces of zirconium metal and silver wire on the surface to be brazed and heating to the flow point. The alloy formed wet, and bonded the nonmetallic materials. Alloys of aluminum and zirconium containing 0.1, 0.28, and 0.8 per cent zirconium respectively, and of aluminum-silver-zirconium (26:64:10) have also been prepared by vacuum-melting. These show good wetting and bonding properties. As in the case of silver, the solubility of zirconium in solid aluminum is very low. The Metals Handbook (1948 Edition) gives the solubility as 0.28 per cent of zirconium in aluminum at the melting point of aluminum. An intermetallic compound is formed with 53 per cent zirconium by weight corresponding to Al_3Zr (6). A titanium-silver alloy containing 10 per cent titanium gave only a fair bond in vacuum and the flow was poor. A series of low-melting-point alloys was prepared by vacuum-melting in tantalum crucibles. Lead-silver, aluminum-silver, indium-silver, indium-gold, aluminum-tin, copper-tin, and copper-tin-zirconium were prepared and bonding properties were examined in connection with pyrex glass. Good bonds were obtained with these alloys (see Table 5).

Alloys of these active metals seem to offer considerable promise in brazing the stainless-steel-type alloys. The silver-zirconium alloy produces good bonds on stainless steels. The metal surfaces need no special treatment other than ordinary solvent degreasing to remove gross oil films. Thin oxide films do not inhibit the brazing process, since the alloy readily wets and bonds oxides. The silver-zirconium alloy yields good brazes with molybdenum. Results of experiments with these alloys may be found in Table 2.

To investigate the effect of various percentages of zirconium in the zirconium-silver alloy on steatite, a series of alloys were prepared containing by weight 1,5,10,25,50, and 75 per cent zirconium, respectively. These alloys were prepared by weighing out the correct percentage of pure silver and zirconium, and placing this material on the surface of ZI-4 steatite and heating in dry tank nitrogen to the flow point. The color of the resulting alloy grew progressively darker as the zirconium content of the alloy increased above 25 per cent. With low percentages of zirconium, the alloy exhibited a light gold-orange color, grading into a very black

surface at 75 per cent zirconium. In this series of experiments, the flow qualities of the alloy seemed to reach a maximum between 10 and 25 per cent zirconium. As a result, for experiments in bonding, an alloy was prepared with 15 per cent zirconium (by vacuum-melting the pure metals in a quartz crucible). The zirconium percentage is obviously not highly critical, since good bonding and flow have been obtained with silver-zirconium alloys containing only 1 per cent zirconium. Some of the results with this brazing alloy are listed in Table 3. The alloy may be applied to the surface to be brazed without any previous treatment. The brazing process consists merely of heating to the flow point of the solder.

Platinum-zirconium alloys (0.05 to 5 per cent Zr) are described as bonding well to porcelain by Ruthardt (7). Zirconium has been suggested as a solder for tungsten, molybdenum and tantalum (8).

Controlled Atmospheres

If the brazing operation is carried out with titanium hydride in a hydrogen atmosphere, careful purification of the gas is necessary. In our work, oxygen is removed from commercial electrolytic tank hydrogen in the conventional manner by passing the gas over hot copper turnings. The hydrogen is then dried with phosphoric anhydride, then passed over hot magnesium ribbon to remove nitrogen. The purity of the hydrogen thus treated was tested by heating polished stainless steel surfaces to 1000°C in a stream of the gas. If no oxide film could be detected, the oxygen and water-vapor content was sufficiently low for the titanium-brazing method. Titanium-silver brazing carried out in this purified hydrogen yields a bright light-gold surface. Traces of oxygen will cause bluish to dark black oxide films. Clean stainless steel can be brazed with either copper or copper-silver eutectic solder in this highly purified hydrogen. When ordinary tank hydrogen is used, the stainless steel rapidly oxidizes and completely inhibits the flow of solder on the surfaces.

The brazed joints of articles processed in pure hydrogen with titanium and silver have a bright yellowish color, and on standing in air for a short time exhibit a slight tarnish. This slight darkening apparently forms a protective coating, for no further change has been observed in articles exposed to ordinary laboratory atmosphere for several months. Both zirconium and titanium exhibit the same behavior when the brazing is carried out in vacuum. As might be expected, both zirconium and titanium hydrides and zirconium and titanium alloys yield good results in an atmosphere of highly purified argon. When lamp argon containing 0.4 per cent nitrogen is used, a slight discoloration may occur on the surface of the brazing alloy. This seems to have no detrimental effect on the brazing operation. With an

atmosphere of highly purified nitrogen, titanium alloys and titanium hydride combinations flowed very poorly and exhibited considerable discoloration. Zirconium, on the other hand, exhibited good wetting and bonding qualities, yielding clean, bright surfaces. The zirconium brazing, in addition, was carried out successfully in an atmosphere of commercial dry tank nitrogen, although a certain amount of tarnish was produced on the brazed surface. The bonds produced with zirconium in tank nitrogen, although not so clean as those produced in vacuum, seem, however, to be equally sound. Aluminum solders cannot be used in nitrogen due, in all probability, to the formation of highly refractory nitrides. The zirconium-brazing operation has also been successfully carried out in commercial tank helium as well as in commercial tank argon. These results are given in Tables 1,2,3,4 and 6.

Apparatus

Our experiments were carried out in either vacuum or controlled atmospheres. Induction heating was used in all cases. Metal and ceramic combinations were usually placed in metal cups so that they could be heated by radiation and conduction to achieve a more uniform heating rate.

Our furnace for vacuum-firing consists of a tantalum cylinder, 1 inch in diameter and 1 inch long, enclosed in a vertical pyrex tube 2 inches in diameter with a window on the top for visual observation and temperature measurements (see Figure 3). The cup was attached to a ground-glass joint at the bottom to facilitate the introduction of samples. An alundum tube was used around the tantalum cylinder as a radiation shield. With this type of furnace, temperatures of 1300-1400°C may be easily obtained. The furnace was evacuated through an all-pyrex system by means of a mechanical pump and a three-stage oil (Octoil-S) diffusion pump. Condensable vapors were removed in a liquid-nitrogen trap. Pressures were measured by means of an ion gauge. Pressures of approximately 10^{-6} mm of mercury or better were used. Later experiments, using only a mechanical pump (with no liquid-nitrogen trap), were carried out at pressures of approximately 10^{-4} mm of mercury. These are designated in the Tables of Experiments as "forepump vacuum". Pure gases were introduced into the evacuated system to produce pressures sufficient to quench the high-frequency discharge.

Experiments with pure hydrogen were carried out in a horizontal pyrex tube 3 inches in diameter and 20 inches long. A piece of alundum in the center of the tube supported a small block of steel or a piece of steel tubing which was heated by an external induction coil. By this means, the brazing samples were heated by thermal conduction and radiation from the steel. A flow of several liters of hydrogen per minute was maintained

during the brazing operation (see Figure 4).

Experiments with commercial tank gases were carried out at atmospheric pressures in a vertical pyrex tube 3 inches in diameter and 20 inches long (see Figure 5). The gases were introduced into the bottom of the pyrex tube and were exhausted through an outlet arm at the top which was attached to a flow gauge. A small flow of gas was maintained during the brazing. The sample was held in a tantalum or molybdenum cup suspended from a rubber stopper at the top of the pyrex cylinder. The metal cup was heated by an external induction coil. Thus the specimen could be heated by radiation. Gases used in this system were commercial dry nitrogen, helium or lamp argon.

For many applications such as metal-ceramic seals for vacuum and pressure work, consideration must be given to the proper matching of the coefficients of expansion of the materials being brazed together. Improper matching of these coefficients can lead to considerable stress, with subsequent failure of the joint. In general, ceramic materials, like glass, are weak in tension and have their maximum strength under compressive stress; for example, Alsimag 243 used for vacuum seals has a tensile strength of 2000 pounds per square inch while the compressive strength is 85,000 pounds per square inch. Thus it obviously is desirable to avoid subjecting the ceramics to excessive tensile stress. It is furthermore desirable that the coefficients of expansion of the materials match reasonably well over the range to which they will be heated. This is important because while some metals and ceramics will match in certain ranges, they will differ widely at other temperature ranges. It is necessary to control the rates of cooling and heating metal and ceramic combinations in the brazing process, since the thermal conductivity of most ceramic materials is much lower than that of most metals. If a metal-ceramic joint to be brazed is heated rapidly, the temperature of the metal will be higher than that of the ceramic and, as a result, the brazing alloy will tend to flow towards the metal. Some caution should be exercised in cooling to avoid excessive thermal shock in the ceramic materials. Steatites, which are particularly useful in vacuum work, are much superior to glasses in their resistance to thermal shock. Two metal-ceramic combinations which have been used successfully in preparing vacuum seals in our laboratory (9) are chrome iron 430 with Alsimag 243 and Kovar with ZI-4. The physical properties of these materials are given in Table 7. Williams (10) in his work on metal-ceramic vacuum seals mentions an Alloy #52 and an Alloy #14, supplied by the Driver-Harris Company, used with Alsimag 243. Chrome iron may be obtained copper-clad for use where subsequent brazing may be carried out, or the various chromium alloys may be nickel-plated for the same purpose, using chloride-nickel strike and building up the deposit to approximately 0.001 inch in a hot nickel bath.

Applications

Although many practical applications of this brazing technique suggest themselves, we have done very little work in this direction. Two types of RF windows for vacuum tubes have been made. The first, a 4-inch diameter ceramic window $3/16$ -inch thick, was brazed with titanium hydride and copper-silver eutectic or pure silver solder. Another window, $3/16$ inch in diameter and about 0.010-inch thick, was brazed with zirconium hydride and pure silver. Ceramic tubing has also been successfully brazed to copper-clad chrome iron for discharge tubes.

A diamond tool for cutting ceramic tubing was prepared by brazing a small diamond cube to the end of a square steel rod. This was used successfully in a lathe for turning alundum tubing. Synthetic sapphire rods have been brazed in the same manner. Small synthetic sapphire balls have been brazed to the ends of steel rods for burnishing tools. Diamond-core drills have been prepared by brazing diamond powder on the ends of steel tubing.

Since there is considerable interest in metal-ceramic materials for high-temperature applications which combine the good physical properties of both metals and ceramics, we conducted several experiments to determine the feasibility of the brazing method for preparing these materials. Thin sheets of molybdenum were brazed to thin plates of beryllium-oxide ceramic and, similarly, thin sheets of tantalum to thin plates of pure aluminum-oxide ceramic, by means of the aluminum-zirconium brazing alloy. Sandwich-type materials were prepared with thin sheets of tantalum between two plates of aluminum-oxide ceramic. The materials were all prepared in vacuum. These combinations of materials were chosen because of their matching coefficients of expansion. Higher-melting-point brazing alloys could be used if necessary - for example, zirconium-iron.

The general method is also applicable to the forming of ceramic and metal-ceramic bodies. For instance, we have pressed a mixture of zirconium oxide and zirconium hydride, then heated in vacuum the compress thus formed, to produce a zirconium-oxide zirconium-metal ceramic. One corner of this material was heated with a gas torch. The zirconium ignited, burning through the entire sample and resulting in a ceramic body composed principally of zirconium oxide. Our work indicates that exceptionally good bonding in metal-ceramic materials could be achieved by adding small amounts of active metals, such as titanium and zirconium, either in the form of hydrides or alloys.

In conclusion, we believe that brazing with zirconium and with active metals seems to offer a simple, inexpensive method of preparing tools and other devices which involve attaching nonmetallic materials in the form of

solids or powders to metals, at the same time producing strong bonds which will withstand reasonably high temperatures.

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Table I
CARBIDES

MATERIAL	HYDRIDE	SOLDER	ATMOSPHERE	BOND	REMARKS
SILICON CARBIDE	TiH	pure silver	vacuum	good	discoloration
	ZrH	pure silver	vacuum	good	
	ZrH	pure silver	dry tank N ₂	good	
	ZrH	pure silver	vacuum	good	
BORON CARBIDE	TiH	pure silver	vacuum	good	
	none	15% zirconium-silver alloy	forepump vacuum	good	
				good	

Table II
METALS

MATERIAL	HYDRIDE	SOLDER	ATMOSPHERE	BOND	REMARKS
CHROME IRON 430	ZrH	pure silver	tank helium	good	orange discoloration of bond
	ZrH	pure silver	dry tank N ₂	good	
	none	15% zirconium-silver alloy	forepump vacuum	good	
	none	15% zirconium-silver alloy	dry tank N ₂	good	
	none	15% zirconium-silver alloy	dry tank hydrogen	no bond	
STAINLESS STEEL	ZrH	pure silver	vacuum	good	bonded to steatite
MOLYBDENUM	ZrH	lead silver	vacuum	good	bonded to pyrex
	none	15% zirconium-silver alloy	dry tank nitrogen	good	discoloration
COPPER	ZrH	pure silver	dry tank nitrogen		no improvement over flow of pure silver
	none	15% zirconium-silver alloy	dry tank nitrogen		dissolves copper

Table III

CERAMICS

MATERIAL	HYDRIDE	SOLDER	ATMOSPHERE	BOND	REMARKS
ZI-4*	TiH	pure silver	purified H ₂	good	
Alsimag 243**		pure silver	vacuum	good	also bonded to stainless steel
		silver-copper eutectic	purified H ₂	good	
		silver-copper eutectic	vacuum	good	
		copper-aluminum (33:67)	vacuum	fair	poor flow
		silver-aluminum (74-26)	vacuum	good	poor flow
		pure aluminum	vacuum	good	
		pure silver	high-purity N ₂	fair	fair flow
		pure silver	dry tank N ₂	no bond	
		pure silver	purified H ₂	good	
	ZrH	pure silver	vacuum	good	
		silver-copper eutectic	purified H ₂	good	
		silver-copper eutectic	vacuum	good	
		copper-aluminum (33-67)	vacuum	fair	fair flow
		silver-aluminum (74-26)	vacuum	good	fair flow
		pure silver	high-purity argon	good	
		pure silver	high-purity nitrogen	good	
		pure gold	vacuum	fair	fair flow

Table III (cont'd)

CERAMICS

MATERIAL	HYDRIDE	SOLDER	ATMOSPHERE	BOND	REMARKS		
Alsimag 243**	ZrH	pure silver	lamp argon	good	discoloration of braze; also bonded to chrome iron hydride converted to oxide		
		pure silver	tank helium	good			
		pure silver	dry tank N ₂	good			
	TaH	pure silver	tank H ₂	no bond		no bond	
		pure silver	vacuum	no bond		no bond	
		pure aluminum	vacuum	good		good	
	CbH	pure aluminum	high-purity nitrogen	no bond		no bond	
		copper	vacuum	no bond		no bond	
		aluminum-silver (26:74)	vacuum	no bond		no bond	
	none	pure silver	vacuum	no bond		no bond	
		pure aluminum	vacuum	good		good	
		pure aluminum	high-purity nitrogen	no bond		no bond	
	none	pure aluminum	vacuum	vacuum		good	poor flow
		silicon and silver	vacuum	vacuum		poor	poor flow
		germanium and silver	vacuum	vacuum		no bond	
titanium metal powder		vacuum	vacuum	no bond	powder may be oxidized		
reduced TiH and silver		vacuum	vacuum	no bond			
reduced ZrH and silver		vacuum	vacuum	good			
Zr-silver alloy (10 ZrH)	vacuum	vacuum	good				

Table III (cont'd)

CERAMICS

MATERIAL	HYDRIDE	SOLDER	ATMOSPHERE	BOND	REMARKS
Alsimag 243**	none	zirconium-silver alloy (.28% Zr)	vacuum	good	
		reduced TaH and aluminum	vacuum	good	
		reduced CbH and aluminum	vacuum	no bond	
		zirconium-silver alloy (15% Zr)	forepump vacuum	good	
		zirconium-silver alloy (15% Zr)	dry tank N ₂	good	discoloration of braze
		silver-aluminum-zirconium alloy (64:26:10)	forepump vacuum	good	
		gold-cerium*** (5:1)	forepump vacuum	poor	extremely brittle mixture; is easily chipped off
		aluminum-columbium alloy (10% Cb)	forepump vacuum	good	fair flow
		copper-zirconium eutectic	forepump vacuum	no bond	
		titanium-silver alloy (10% Ti)	forepump vacuum	fair	poor flow

*Coors Porcelain Co., Boulder, Colo.

**American Lava Corp., Chattanooga 5, Tenn.

***Misch metal alloy (Ce-Fe) 5:1

Table IV

PURE REFRACTORY OXIDES

MATERIAL	HYDRIDE	SOLDER	ATMOSPHERE	BOND	REMARKS
ALUMINUM OXIDE* (Alundum RA1139)	ZrH	pure silver	vacuum	good	bonded to tantalum heated to about 1700°C.
	ZrH	pure aluminum	vacuum	good	
	ZrH and TiH	none	vacuum	good	
	TiH	cobalt	vacuum	good	
SYNTHETIC SAPPHIRE	TiH	pure silver	vacuum	good	
	ZrH	pure silver	vacuum	good	
	TaH	pure aluminum	vacuum	good	
	CbH	pure aluminum	forepump vacuum	good	
	ZrH	pure silver	dry tank N ₂	good	
	none	15% zirconium-silver alloy	forepump vacuum	good	
BERYLLIUM OXIDE	ZrH	pure silver	vacuum	good	bonded to molybdenum
	ZrH	pure aluminum	vacuum	good	
	CbH	pure aluminum	forepump vacuum	good	
	TaH	pure aluminum	forepump vacuum	good	
	none	15% zirconium-silver alloy	forepump vacuum	good	
THORIUM OXIDE	ZrH	pure silver	vacuum	good	
	CbH	pure aluminum	forepump vacuum	good	
	TaH	pure aluminum	forepump vacuum	good	
	none	15% zirconium-silver alloy	forepump vacuum	good	

*Worton Company, Worcester, Massachusetts

Table V

VITREOUS SUBSTANCES

MATERIAL	HYDRIDE	SOLDER	ATMOSPHERE	BOND	REMARKS
PYREX	TiH	pure aluminum	vacuum	good	also bonded to molybdenum; to stainless steel; to K-Monel (but only a fair bond); to silver-plated K-Monel (a poor bond)
	ZrH	lead-silver alloy (2.5% Ag)	vacuum	good	
	ZrH	aluminum-silver alloy (26% aluminum)	vacuum	good	
	ZrH	indium-silver alloy (50:50)	vacuum	good	
	ZrH	indium-gold alloy (20:80)	vacuum	fair	
	ZrH	aluminum-tin alloy (50:50)	forepump vacuum	good	
	ZrH	copper-tin alloy (10:90)	forepump vacuum	good	
	ZrH	aluminum-tin alloy (5:95)	forepump vacuum	poor	
	ZrH	pure silver	vacuum	good	
QUARTZ	none	aluminum-tin alloy (50:50)	vacuum	good	fair in bonding 2 pieces of pyrex pyrex tubing to pyrex sheet
	none	aluminum-tin alloy (5:95)	vacuum	good	
	none	aluminum-tin alloy (10:90)	vacuum	good	
	none	copper-tin alloy (10:90)	vacuum	good	
	none	copper-tin alloy (10:90)	vacuum	no bond	
	none	copper-tin-zir- conium alloy (10:85:5)	vacuum	good	
	none		vacuum		

Table VI

DIAMOND*

MATERIAL	HYDRIDE	- SOLDER	ATMOSPHERE	BOND	REMARKS
dust #0 (80 to 100 mesh) (dust #7 also used -- is 0 to 2 microns)	ZrH	pure silver	vacuum	good	the silver wets the surfaces and completely covers the particles. A solid, dense mass was formed.
CONGO CUBE	ZrH	pure silver	vacuum	good	
	TaH	pure aluminum	vacuum	good	
	TiH	pure silver	vacuum	fairly good	
	CbH	pure aluminum	vacuum	good	
	none	cobalt metal powder	vacuum	good	
	none	nickel metal powder	vacuum	good	
	none	cobalt and aluminum	vacuum	good	
	none	15% zirconium- silver alloy	forepump vacuum	good	
	none	15% zirconium- silver alloy	dry tank N ₂	good	
	none	gold-cerium** (5:1)	forepump vacuum	no bond	

* Arthur A. Crafts Co. Inc., 603 Newbury Street, Boston, Mass.

** Misch metal alloy (Ce-Fe) 5:1

Table VII

COEFFICIENT EXPANSIONS FOR METALS AND CERAMICS
USED IN METAL-CERAMIC SEALS

METALS	COEFFICIENT OF EXPANSION (PER °C)	
Chrome iron 430 ¹ (cr, 14-18; C, 0.12; Mn, 1.0; Si, 1.0; P; S) Kovar ² (Ni, 29; Co, 17; Mn, 0.3; bal Fe) #52 ³ (Fe, 50; Ni, 50.) #14 ³ (Ni, 42; Cr, 5.5, Bal Fe)	0 - 600°C	10.5×10^{-6}
	0 - 1000°C	12.0×10^{-6}
	30 - 500°C	$5.71-6.21 \times 10^{-6}$
	----	10.7×10^{-6}
	----	9.5×10^{-6}
CERAMICS		
Alsimag 243 ⁴ (2MgO·SiO ₂) ZI-4 ⁵ (High Al ₂ O ₃ , low SiO ₂ and ZrO ₂ SiO ₂)	25 - 100°C	9.1×10^{-6}
	25 - 700°C	10.6×10^{-6}
	25 - 600°C	4.65×10^{-6}
	25 - 800°C	5.93×10^{-6}
	25 - 1000°C	5.78×10^{-6}
	600 - 800°C	7.70×10^{-6}
1. Brown and Wales Dist., Boston, Mass. 2. Stupakoff Ceramic and Mfg. Co., Latrobe, Pa. 3. Driver-Harris Co., Harrison, N. J. 4. American Lava Corp., Chattanooga, Tenn. 5. Coors Porcelain Co., Golden, Colorado.		