398
UNCLASSIFIED

ANL-4417

Metallurgy and Ceramics

1
ARGONNE NATIONAL LABORATORY
P. O. Box 5207
Chicago 80, Illinois

RESISTANCE OF MATERIALS TO ATTACK
BY LIQUID METALS

by

LeRoy R. Kelman, Walter D. Wilkinson, and
Frank L. Yaggee

Metallurgy Division

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:
A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.
As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

July, 1950

CODE 11

Operated by the University of Chicago
under
Contract W-31-109-eng-38

This document is
PUBLICLY RELEASABLE

Larry E. Williams
Authorizing Official

Date: 06/13/2005

UNCLASSIFIED

51
7428-01

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

<u>Distribution</u>	<u>No. of Copies</u>
Argonne National Laboratory	252
Armed Forces Special Weapons Project	1
Atomic Energy Commission - Washington	2
Battelle Memorial Institute	1
Brush Beryllium Company	1
Brookhaven National Laboratory	4
Bureau of Medicine and Surgery	1
Bureau of Ships	1
Carbide and Carbon Chemicals Division (K-25 Plant)	4
Carbide and Carbon Chemicals Division (Y-12 Plant)	4
Chicago Operations Office	1
Columbia University (J. R. Dunning)	1
Columbia University (G. Failla)	1
Dow Chemical Company	1
H. K. Ferguson Company	1
General Electric, Richland	3
Harshaw Chemical Corporation	1
Idaho Operations Office	1
Iowa State College	2
Kansas City Operations Branch	1
Kellex Corporation	2
Knolls Atomic Power Laboratory	4
Los Alamos Scientific Laboratory	3
Mallinckrodt Chemical Works	1
Massachusetts Institute of Technology (A. Gaudin)	1
Massachusetts Institute of Technology (A. R. Kaufmann)	1
Mound Laboratory	3
National Advisory Committee for Aeronautics	1
National Bureau of Standards	3
Naval Radiological Defense Laboratory	2
New Brunswick Laboratory	1
New York Operations Office	3
North American Aviation, Inc.	1
Oak Ridge National Laboratory	8
Patent Branch (Washington)	1
RAND Corporation	1
Sandia Corporation	1
Santa Fe Operations Office	2
Sylvania Electric Products, Inc.	1
Technical Information Division (Oak Ridge)	15
USAF, Surgeon General (Col. A. P. Gagge)	1
USAF, Director of Armament (Captain C. I. Browne)	1
USAF, Director of Research and Development (Col. R. J. Mason, Fred W. Bruner)	2

<u>Distribution</u>	<u>No. of Copies</u>
USAF, Eglin Air Force Base (Major A. C. Field)	1
USAF, Kirtland Air Force Base (Col. Marcus F. Cooper)	1
USAF, Maxwell Air Force Base (Col. F. N. Moyers)	1
USAF, NEPA Office	2
USAF, Office of Atomic Energy (Col. H. C. Donelly, A. A. Fickel)	2
USAF, Offutt Air Force Base (Col. H. R. Sullivan, Jr.)	1
USAF, Wright-Patterson Air Force Base (Rodney Nudenberg)	1
U. S. Army, Atomic Energy Branch (Lt. Col. A. W. Betts)	1
U. S. Army, Army Field Forces (Captain James Kerr)	1
U. S. Army, Commanding General, Chemical Corps Technical Command (Col. John A. MacLaughlin thru Mrs. Georgia S. Benjamin)	1
U. S. Army, Chief of Ordnance (Lt. Col. A. R. Del Campo)	1
U. S. Army, Commanding Officer, Watertown Arsenal (Col. Carroll H. Deitrick)	1
U. S. Army, Director of Operations Research (Dr. Ellis Johnson)	1
U. S. Army, Office of Engineers (Allen O'Leary)	1
U. S. Army, Office of the Chief Signal Officer (Curtis T. Clayton thru Maj. George C. Hunt)	1
U. S. Army, Office of the Surgeon General (Col. W. S. Stone)	1
U. S. Geological Survey (T. B. Nolan)	2
USAF, Director of Plans and Operations (Col. R. L. Applegate)	1
U. S. Public Health Service	1
University of California at Los Angeles	1
University of California Radiation Laboratory	5
University of Rochester	2
University of Washington	1
Western Reserve University	2
Westinghouse Electric Company	4
Naval Medical Research Institute	1
Total	381

TABLE OF CONTENTS

	Page No.
Distribution	2
Foreword	5
Introduction	7
Summarizing Chart	14
Sodium and Sodium-Potassium Alloys	15
Lithium	48
Mercury	57
Lead, Bismuth, and Alloys of Lead and Bismuth	69
Lead	75
Bismuth	84
Bismuth-Lead Eutectic Alloy	88
Bismuth-Lead-Tin Eutectic Alloy	96
Magnesium	102
Cadmium	105
Thallium	107
Indium	108
Gallium	109
Aluminum	117
Tin	119
Zinc	122
Antimony	124
List of References	127

RESISTANCE OF MATERIALS TO ATTACK BY LIQUID METALS

by

LeRoy R. Kelman, Walter D. Wilkinson, and Frank L. Yaggee

FOREWORD

Existing information on the resistance of materials to attack by liquid metals is, for the most part, very meager; and much of the information that does exist is buried in progress reports and in personal files. Therefore, designers of engineering systems using liquid metal coolants often have little concrete evidence on which to base their selection of materials.

The Committee on the Basic Properties of Liquid Metals has recognized the need for assembling this information as well as information on the properties, techniques in handling, and uses of liquid metals. With the intention of publishing this material in a Liquid Metals Handbook, the Committee requested various member organizations to prepare specific chapters for the Handbook. As their contribution, the Metallurgy Division of Argonne National Laboratory was asked to assemble all available unclassified and declassifiable data on the resistance of materials to attack by liquid metals.

The resulting collation of data is contained in this report.

Since the editors of the proposed Handbook indicated a desire for a concise summary of available data, the authors have eschewed detailed descriptions of test setups and have limited theoretical considerations. However, in order to prevent misinterpretation, they have found it necessary to delimit and explain many of the results in considerable detail. Also, data obtained from classified reports and private communications are described in some detail because this information is not readily available to the general public. As a consequence, this report is longer than was first intended and will probably be condensed for use in the Liquid Metals Handbook. However, it is felt that publication of this survey in its present form is desirable in that it gives a truer evaluation of available information than would be possible in a condensed version.

Although a substantial amount of the experimental data herein presented is the result of work done at the Argonne National Laboratory, the major portion of it is the result of the efforts of investigators at other laboratories, as is indicated by the numerous references in the bibliography.

Principal sources of information which are gratefully acknowledged by the authors are reports and private communications from:

Aerojet Engineering Corporation
Aluminum Company of America
American Smelting and Refining Company
Babcock and Wilcox Company
Dow Chemical Company
General Electric Research Laboratory
Knolls Atomic Power Laboratory
Mine Safety Appliances Company
Stanford University
University of California

Special thanks are due L. F. Epstein (KAPL) who supplied most of the data on mercury as well as the KAPL data on sodium. The authors also wish to thank Miss Muriel Morris and others who helped in preparing this survey for publication.

INTRODUCTION TO RESISTANCE OF MATERIALS TO ATTACK BY LIQUID METALS

The practical value of a liquid metal as an engineering heat-transfer fluid is very much limited if ordinary materials of construction cannot be used to contain it. For example, the unusually low melting and high boiling points of gallium, together with its acceptable heat-transfer properties, have aroused interest in its use as a high-temperature coolant. However, the use of gallium as a coolant is very much restricted because of the extreme aggressiveness with which it attacks common engineering metals (see Page 110).

Until recently, the only large-scale application of a liquid metal as an engineering coolant was that of mercury in the mercury-vapor turbine process. In this connection the General Electric Company made an extensive study of the behavior of several ferrous metals in mercury (see Page 58). Recent interest in sodium, sodium-potassium alloys, lithium, lead, lead-bismuth alloys, and gallium has resulted in organized laboratory investigations of the container problem for these liquid metals so that crude but more or less quantitative information is now available. However, this information must be used with discretion in view of the limited experience in large-scale handling. For those liquid metals that have not been considered for engineering heat-transfer applications, only meager information exists to guide in the selection of containing materials.

Mechanism of Attack

The mechanism whereby solid metals are attacked by liquid metals is chiefly one of alloying where solubility and intermetallic compound formation are important. The formation of chemical compounds, such as oxides, may also be involved as well as such phenomena as intergranular penetration, and selective depletion of a constituent (i.e., decarburization of steels). The term corrosion--defined as "destruction of a metal by chemical or electrochemical reaction with its environment"⁽¹⁵⁶⁾ is not strictly applicable to all of these processes and will not be used in this survey.

Equilibrium relationships indicate the direction in which alloying reactions tend to go although they give no information about the time involved in any process. In general, the greater the difference in the melting points of two metals, the less effect they will have on each other. The ideal relationship is one of mutual insolubility between the containing metal and the liquid. Very slight solubility may be tolerated up to temperatures in excess of those under which the heat-transfer medium will be used, although experience with liquid mercury in steel containers

suggests that caution be exercised in designing and using such systems (see Page 59). The formation of intermetallic compounds is not desirable. However, such systems should not be entirely abandoned especially where there is negligible solubility of the compound in the liquid metal and in the container metal and where rates of diffusion are low. Compound layers may even inhibit attack in otherwise unsatisfactory systems by acting as diffusion barriers (see Page 112). The degree of protection in such systems depends upon the relative permeability of the compound to the reactants which in turn depends upon the relative volume of the compound to the volume of the metal consumed. Also, differences in the thermal coefficients of expansion of the compound and the underlying metal might decrease the protective value of a compound by making it sensitive to thermal shock, particularly if the compound is brittle.

The solution mechanism of attack and the influence of conditions found in dynamic systems has been examined by Epstein who used iron in sodium and in mercury as examples (see Pages 19, 59).⁽³⁵⁾ Conditions of equilibrium solubility are upset where there is a temperature coefficient of solubility and where temperature gradients occur. Even where equilibrium solubility is very low, solution of metal in hot zones and deposition in cooler zones can accelerate the rate of attack on the container walls in the hot region and can cause plugging of small openings in the lower temperature regions (see Page 58). Under these conditions the rate of transfer of container metal from one zone to another is observed to be greater for some systems (i.e., Fe in Hg) than for others (i.e., Fe in Na) even though the reverse of this would be expected from consideration of equilibrium solubilities alone. Possible explanations of this anomaly have been offered. One explanation considers a greater tendency for precipitated particles in certain systems than in others to remain in suspension in the cold zone and to be carried into the hot zone where they are redissolved (see Page 20). Another explanation that appears applicable in some cases involves a consideration of the rate of diffusion across the solid-liquid interface (solution) and the rate of diffusion from a saturated solution into the bulk phase of the liquid (see Page 59).

Mass transfer in multimetallic systems may be encountered even though there are no temperature gradients. Instead of solution of one metal stopping by virtue of saturation of the liquid, the equilibrium can be upset by the presence of a second metal that, through an affinity for the first, reacts with it to form solid solutions or compounds. The first metal will therefore dissolve and diffuse through the liquid and then alloy with the second metal. The newly formed alloy layer will act as a diffusion barrier causing mass transfer rate to decrease with time. Such a phenomena is important where copper and nickel are exposed to sodium-potassium alloy in the same system (see Page 20). Data (such as changes in weight and dimensions of specimens) obtained from such systems are often difficult to interpret.

Mass transfer in liquid metals may be influenced by electrical effects. Transfer of dissolved elements in solid and in liquid metals under the influence of applied potentials, referred to in the literature as electrolytic diffusion, has been observed and studied quantitatively. (88, 91, 142) For example, a direct potential of 5 volts with a flow of 20 amps for periods of less than a day resulted in transfer of macroscopic amounts of carbon in gamma iron. Sources of electrical potentials which might lead to such effects include the imposed voltages of direct current (and possibly alternating current if it is rectified by films) electromagnetic pumps, as well as thermoelectric potentials. The cutting of magnetic lines of force by a flowing liquid metal is also the source of small potentials. No evidence of such effects has so far been observed in liquid metal heat-transfer systems (see Page 25) although there is some evidence that application of a potential can be used to inhibit attack (see Page 100).

The solution type of attack can also be accelerated by the presence of impurities in the liquid metal, especially oxygen, but the mechanism is not understood (see Page 22).

Another type of attack, namely that of chemical compound formation, is brought about by the presence of impurities in the liquid metal. For example, in oxygen-contaminated systems, the container metal may become coated with a layer of its own oxide provided its oxide is more stable than that formed by the liquid metal with which it is in contact.

The free energies of formation of the oxides⁽⁷⁸⁾ will indicate whether or not an oxide film can be expected to form. The oxide layer is sometimes tenacious and adherent and acts as a diffusion barrier in which case it inhibits attack. In other cases it is nonadherent so that drastic weight loss ensues especially under dynamic conditions (see Page 22). Unfortunately, quantitative study of the influence of oxygen on the aggressiveness of most of the liquid metals under study has been hampered by the lack of adequate sampling and analytical techniques (see Pages 23, 70).

Attack on steels by mercury is completely inhibited by the addition of titanium or zirconium (see Page 63). These inhibitors were found after very extensive and expensive laboratory investigations, and, though possible explanations have been offered, the mechanism by which they act is not known. Where oxygen is known to accelerate attack by liquid metals, inhibitors are being sought which will tie up the oxygen as an insoluble oxide (see Page 23).

Grain boundary penetration by a liquid metal can drastically alter the physical properties of a metal without appreciably changing its weight or appearance. This type of attack is often accelerated by application of stress during exposure to the liquid metal. Attack on brass by mercury is a classic example of the intergranular penetration type of attack.

General Considerations on Testing

Laboratory tests should be carried out to simulate as closely as possible expected service conditions, and the time of test should be for an appreciable fraction of the expected life of the material under test. First, however, materials that are drastically attacked can be eliminated from consideration by simple static tests. The limitations of accelerated tests have been discussed in detail elsewhere and need not be repeated here.⁽¹⁵⁶⁾ Methods of preparing specimens are also dealt with in this reference.

Methods of testing are often governed by properties of the liquid metal under consideration. The container should be made of the same material as that under test, or it should be made of an inert material. For example, quartz has been used as a container for gallium tests, but it cannot be used for most of the prospective liquid metal heat-transfer fluids. Care must be taken to ensure that atmospheres are inert (i.e., nitrogen can be used over sodium and potassium but not over lithium). Relying on molten salts or graphite on the liquid surface as the sole protection against the atmosphere often leads to questionable conditions (see Page 72). Thermal convection test loops or "harps," were originally used extensively and very successfully to study the attack by mercury under dynamic conditions of flow and thermal gradients (see Page 58). Heat is applied at the bottom and extracted at the top of a closed loop of pipe and specimens can be located in both the high- and low-temperature regions so that mass transfer can be followed. These same techniques have been used recently to study the aggressiveness of sodium and sodium-potassium alloys (see Page 18). Other laboratory methods that have been used to simulate flow of fluids past metal surfaces consist of rotation of specimens under a bath of the liquid metal and rotation of the container so that gravity causes relative motion between the liquid and the specimens. Except for mercury systems, large-scale handling experience is as yet very limited although observations on the aggressiveness of sodium and sodium-potassium alloys are now being made in large heat-transfer systems.⁽⁹⁴⁾ Chattering has been noted in dynamic sodium-potassium systems operated at temperatures where the vapor pressure of the liquid metal is appreciable indicating that cavitation erosion and other dynamic effects should be looked for.⁽¹⁶⁵⁾

Wetting of container walls, a prerequisite for maximum heat transfer, is usually no problem for oxygen-avid liquid metals such as the alkali metals. However, the study of wetting became a major portion of the mercury-vapor turbine program (see Page 65) and is also important in the study of lead and bismuth alloys.⁽¹¹⁾

Methods of measuring the extent of damage due to exposure to corrosive media and precautions to be observed in reporting results have been discussed in detail elsewhere.⁽¹⁵⁶⁾ Where structural members of engineering heat-transfer systems are exposed to liquid metals, it is desirable to

measure attack in terms of changes in mechanical properties as well as the usual changes in weight, dimensions, surface appearance, and microstructure. Stress-rupture tests during exposure to liquid metals and tensile and bend tests after exposure have been used for some studies (See Pages 19, 73).

Most of the test data available are weight change data which are valuable for screening out materials obviously lacking in resistance to attack but which have limited value to the design engineer. These data are usually reported in terms of weight change per unit area per unit time which can be very misleading and are often misused. Data obtained from short-time tests (a few hours or days) are often reported as $\text{mg}/\text{cm}^2/\text{mo}$ (mcm) and these in turn are converted for engineering use to mils penetration per year (mpy) with no regard for the fact that such attack is usually not linear with time. In fact, comparison of data from short- and long-time tests in both static and dynamic systems often shows that rate of attack decreases rapidly with time (see Page 31). There will be less chance for misuse if weight change data are reported as mg/cm^2 with the time and temperature of test and the ratio of solid surface to liquid volume given. Conversion of weight change data to penetration per unit time can be made only when attack by uniform solution is known to be the only form of attack. Otherwise measured penetrations are the only reliable penetration data. Where the mechanism of attack is straight solution, static test data might best be reported as apparent solubility such as might be calculated from weight losses. This is independent of time and takes into account the ratio of solid surface to liquid volume.

It should be kept in mind that increases in dimensions or weight due to the formation of reaction products such as oxides or intermetallic compounds imply penetration attack. The minimum extent of penetration depends upon the amount of base metal in the compound, but considerably greater penetration can occur by diffusion to form solid solutions.

Evaluation of Available Data

Data are given in the following sections which were used as a basis for evaluating materials according to their resistance to attack by liquid metals as shown in the bar charts on pages 15, 48, 57, 69, 109. In many heat-transfer applications where very high thermal fluxes must be contended with (i.e., nuclear piles), very thin-walled metallic containers are desirable. For this reason rather stringent limits of attack have been used in rating materials (these were arrived at in cooperation with engineers who must design such systems). For example, materials that can be considered for long-time use (rated "good" resistance) must not be attacked at a rate of more than 1 mpy; for 1 to 10 mpy attack, the material should be considered for short-time use only (rated "limited" resistance); and where attack is greater than 10 mpy, the material has no structural possibilities (rated "poor" resistance). Where other criteria were used to measure attack, ranges

were selected in conformance with these penetration attack figures. It is obvious that, for specific uses where conditions are accurately known, the reader may interpret the data in such a way as to arrive at a different rating.

The bar charts must be used with caution since they present only a cursory outline of what is known about the resistance of materials to attack by liquid metals as a function of temperature. They have value only in that, through their use, one can immediately eliminate from consideration those materials which are definitely incompatible and can obtain leads on materials that have a chance of being useable at a specified temperature. Even after following up these leads by referring to the relevant portions of the text, the reader will find that in many cases the data serve only to point out what further tests are needed.

In general it was not feasible to indicate on the bar charts test conditions under which the data were obtained. The discussion in the text must be consulted to avoid misinterpretation since it is pointless to compare the results of the charts without assurance that the data are truly comparable. For example, it would be wrong for a user of a chart to compare a value based on the consistent results of several painstaking tests with another value, seemingly of equal weight on the chart, but actually the result of a single exploratory screening test. Also, the charts do not always distinguish between the results of static and the results of dynamic tests. Where static and dynamic test data were not in agreement, the latter were given more weight. Unfortunately, lack of dynamic test data made it necessary to evaluate container materials for several liquid metals on the basis of static tests alone.

The charts are, for the most part, self-explanatory. However, where the degree of attack can be changed by altering the conditions of test or where the data are particularly conflicting, questionable, or meager, it was expedient to show a mixed rating for a given temperature range or to use question marks. It is intended that the reader consult the text in order to clear up questions raised by this equivocal treatment. Uncertainty about the exact temperature at which the resistance changes from "good" to "limited" or from "limited" to "poor" made it necessary to indicate that the transition occurs over a range of temperatures (a slanted line on the charts).

The summarizing chart compares the resistance of materials at two temperatures--300°C (572°F) and 600°C (1112°F)--to attack by all the liquid metals considered as possible heat-transfer media (see Page 14). It is evident at a glance which of the liquid metals are most aggressive. The chart can also be used to indicate the liquid metals that can be contained by any given material.

The accompanying table from a report by L. Brewer⁽²¹⁾ should be a useful supplement to the bar charts. The report provides guidance for some cases in which experimental evidence is lacking. Although Brewer's evaluation is based largely on theoretical considerations, it coincides so well with almost all the experimental evidence now available that it is reasonable to place some confidence in his predictions. Among the possible exceptions is a general statement that W, Ta, Re, and Nb are not resistant to attack by lead. Evidence to the contrary is adduced -- for some of these metals -- in some of the following pages. Metals for possible use as containers are listed by Brewer in order of decreasing preference, based on "availability" and extent of attack, as follows:

MOLTEN METALS

Alkali Metals

Mg

Zn

Cd

Hg

Pb

Sn

Bi

Ga

Tl, In

CONTAINER METALS

Fe, Co, Cr, Nb, W, Ta, Mo, Re

Fe, Nb, Be, W, Ta, Re, Mo, Cr

Nb, Zr, Ta, W, Cr, Ti, Ir, V

Nb, Ta, W, Mo, Fe, Cr

Fe, W, Ta, Re, Mo, Nb, Rh, Ni, Be, Co

Fe, Co, Ir, Zr, Rh

W, Mo, Ta, Nb, Cr

W, Zr, Fe, Ta, Rh, Cr, Ti, V, Co

W, Ta, Mo, Nb, Os, Ir

Fe, W, Ta, Mo, Nb, Co

CONDENSED SUMMARY OF RESISTANCE OF MATERIALS TO ATTACK BY LIQUID METALS AT 300°C AND AT 600°C *

LIQUID METAL →		Na-K mp -97.8	Li mp -35.1	Hg mp -38.8	Pb mp 327	Bi mp 271.3	Bi-Pb mp 125	Bi-Pb-Sn mp 97	Mg mp 651	Cd mp 321	Tl mp 231.9	In mp 156.6	Sn mp 231.9	Zn mp 419.5	Sb mp 590.5
MATERIAL	C	1	2	3	4	5	6	7	8	9	10	11	12	13	14
FERROUS METALS															
Pure Iron	600														
Carbon Steel (Low-C & Mild-C)	600														
Gray Cast Iron	600														
High-Cr Steel (12 to 20 Cr)	600														
2-9 Cr Steel (with Ti, Mo & Si as required)	600														
Low-Cr Steel (with V or Mo & Si as required)	600														
Cr-Ni Austenitic Stainless (with Nb or Mo as required)	600														
High-Speed High-W Tool Steel (with Cr, Mo and V)	600														
High-Nickel Steel	600														
NON-FERROUS METALS															
Aluminum	600														
Bi, Co, Cd, Pb, Sb, Sn	600														
Beryllium	600														
Chromium	600														
Copper (with Si or Be as required)	600														
Al Bronze	600														
Brass, Tin, Bronze etc.	600														
Manganese	600														
Molybdenum	600														
Nickel	600														
Hastelloys A, B & C	600														
Inconel, Nichrome & Chromel	600														
Monel Metal & Other Ni-Cu Alloys	600														
Niobium	600														
Platinum, Gold & Silver	600														
Rhenium & Silicon	600														
Stellite & Other Co-Cr Alloys with W or Mo	600														
Tantalum	600														
Titanium	600														
Wolfram & Vanadium	600														
Zirconium	600														
NON-METALS															
Al ₂ O ₃ & BeO (dense)	600														
Graphite	600														
MgO (porous)	600														
Porcelain & Other Silicate Refractories	600														
Pyrex Glass	600														
TiO ₂ & ZrO ₂	600														
Quartz (fused SiO ₂)	600														
LIQUID METAL →		Na-K mp -97.8	Li mp -35.1	Hg mp -38.8	Pb mp 327	Bi mp 271.3	Bi-Pb mp 125	Bi-Pb-Sn mp 97	Mg mp 651	Cd mp 321	Tl mp 231.9	In mp 156.6	Sn mp 231.9	Zn mp 419.5	Sb mp 590.5

DEGREE OF RESISTANCE

- GOOD - Consider for long-time use.
- LIMITED - For short-time use only.
- POOR - No structural possibilities.
- UNKNOWN - No data for these temperatures.

* See text for discussion of these data.
□ Inhibitor used. See text.

RESISTANCE OF MATERIALS TO ATTACK BY SODIUM AND SODIUM POTASSIUM ALLOYS *

* Degree of Resistance: (See text for discussion of these data)

	GOOD	- consider for long-time use
	LIMITED	- for short-time use only
	POOR	- no structural possibilities
	UNKNOWN	- no data for these temperatures

RESISTANCE OF MATERIALS TO ATTACK BY SODIUM AND SODIUM-POTASSIUM ALLOYS

Until recently there were relatively few uses for liquid sodium and potassium as high-temperature engineering fluids, and consequently little was known about the resistance of engineering materials to attack by these metals. For years producers of sodium have contained the liquid metal at 110°C (230°F), just above its melting point, in a number of metals and alloys with no evidence of attack at this low temperature. Liquid sodium has been transferred continuously for 12 years in a 2 1/2-in. I.P.S. mild steel pipe line 1/3 miles long without any signs of deleterious attack on the pipe wall.⁽⁶²⁾ Sodium has been used as a coolant in the hollow stem of aircraft valves for about 18 years where a standard Cr (13-15), Ni (13-15), W (1.75-3) alloy valve steel is in contact with the liquid metal at an estimated maximum temperature of 538°C (1000°F).⁽¹³⁷⁾ In this application no attempt is made to prevent contamination of the sodium with oxygen and some attack on the containing metal has been observed. However, the attack is not progressive and is not of much concern to the valve manufacturer.

Probably the most drastic conditions for handling sodium and potassium have been those experienced in the production of high potassium alloys of these metals by a distillation process starting with potassium chloride and sodium.⁽⁹²⁾ *Types 304 and 316 stainless steels have been used up to about 900°C (1652°F) and the reported attack that could be attributed to the alkali metal and/or chloride was limited to an unexplained carburization.

Recent engineering experience in handling NaK ** at elevated temperatures indicates that a large number of ordinary metals of construction can be used successfully as container materials. The 18-8 type austenitic stainless steels are used most extensively at present to contain NaK, with the stabilized stainless steels, especially Type 347 (Nb), preferred because of their better welding characteristics and resistance to air corrosion. Type 310 stainless steel (25 Cr-20 Ni) is preferred by one investigator because of its superior physical properties at elevated temperatures.⁽¹⁷³⁾

Results of long-time tests in convection systems have been particularly encouraging. Type 347 stainless steel, nickel, SAE 1020 steel, aluminum bronze, molybdenum, and beryllium specimens have been exposed together for 6 months in the hot zones, 450°C (842°F), and cold zones, 150°C (302°F), of 3 different convection systems made respectively of Type 347 stainless steel, nickel, and SAE 1020 steel.⁽⁸⁶⁾ The SAE 1020 steel was

---

*AISI (American Iron and Steel Institute) designations will be used for all stainless steels referred to in this survey.

**Unless otherwise noted, the term NaK will be used in this section as a general term when referring to sodium, potassium, or sodium-potassium alloys of any composition.

18

decarburized and the beryllium suffered small weight losses due to oxidation. Otherwise the specimens were not at all attacked. A 5000-hour NaK convection test in a unimetallic system wherein Type 310 stainless steel specimens were located in temperature zones ranging from 593°C (1100°F) to 316°C (600°F) gave equally encouraging results in that attack was hardly measurable.⁽¹⁰⁾ Equipment, for studying the attack of containing materials, made of stainless steel and nickel has been operated for as long as a year at temperatures from 450°C to 800°C (842 to 1472°F) with no appreciable difficulties that could be attributed to the NaK.⁽⁸⁶⁾ Welds, made by ordinary techniques, appear to be as resistant to NaK as is the base metal. Care should be taken to make clean welds free of inclusions since sodium has been observed to rapidly remove oxides and slag that were purposely formed in a Type 347 stainless steel weld bead.⁽³⁶⁾

The four laboratories that have been studying the NaK container problems include Mine Safety Appliances Company (MSA), Knolls Atomic Power Laboratory-General Electric Company (KAPL), Babcock and Wilcox Company (B & W), and Argonne National Laboratory (ANL). They have investigated, on a laboratory scale, a number of variables including the effects of temperature (up to 900°C, 1652°F), time (up to 5000 hours), impurities in the NaK, ratio of specimen area to NaK volume, thermal gradients, and rate of fluid flow. The effect of one metal on the rate of attack on other metals in multimetallic systems has also been studied.

Practically all of the tests by KAPL were made using 100% duPont sodium, whereas the other laboratories used various alloys of sodium and potassium prepared by MSA. Examination of all test results reveals that NaK alloys, ranging from 100% sodium to 100% potassium, are very similar in their aggressiveness toward containing materials. Therefore, reference will not be made in the following discussions to the liquid metal composition used for each test.

In an effort to remove the oxygen that is invariably present (see Page 21), some of the investigators heated their NaK in the presence of "gettering" materials (KAPL used beryllium and calcium and ANL used uranium turnings). This is the NaK referred to in the following discussions as "relatively pure" or "clean" NaK. Removal of oxygen by these methods is not quantitative, and, unfortunately, the purity of the NaK could not be determined accurately because adequate analytical techniques were not available.

Static tests at the various laboratories were, for the most part, made in individual "bombs" using argon, helium, or nitrogen atmospheres and were fairly similar. The difficulties encountered in multimetallic systems (see Page 20) were observed in early tests so that most of the later tests were made with this in mind. These were weeding out tests used to determine which materials showed enough promise to warrant further testing in dynamic systems.

19

Dynamic tests have been carried out in thermal convection test loops after the technique used for mercury (see Page 58). The high coefficient of expansion of NaK and its low viscosity make it an ideal liquid for this type of test. Also, tighter systems can be more easily maintained with convection units than in mechanical systems which are more complicated. The test conditions used by various investigators have been summarized⁽³⁶⁾ and are given in Table I. Flow velocities of 2 ft./sec. were attained in these systems which, for NaK, is in the turbulent flow region for the pipe diameters that were used.⁽⁹⁸⁾ A few dynamic tests have been made where flow of NaK past the specimen at predetermined velocities is obtained by rotation of the specimen under a bath of the liquid metal.⁽³⁶⁾ Present test programs include plans to study dynamic flow effects, such as erosion due to suspended solids, high velocity flow, and cavitation, which might arise in engineering systems; and emphasis is being given to test conditions simulating those to be found in specific large-scale applications.

Table I

NaK THERMAL CONVECTION TEST CONDITIONS AT
VARIOUS LABORATORIES⁽³⁶⁾

	ANL	MSA	B & W	KAPL
Max. Temp. (°C)	450	590	592	525 and 520
Min. Temp. (°C)	150	370	348	425 and 440
Velocity (ft/sec)	1-2	1-2	2.3	1 and 2
Time (hours)	340-4400	457-1954	5000	1212 and 232
Specimen Area (cm ²)	~25	10-100	17.5	25 and 44.5
Harp Area (cm ²)	12000	2050	8300	625 and 700
Harp Length (cm)	340	250	775	160 and 175
Harp Height (cm)	125	90	318	18 and 75
Mean Pipe Diam. (cm)	~7	~2.5	3.3	1.3
Na in NaK (%)	56	56	20	100 and 56
Vol. of NaK (cm ³)	13000	2000	7540	200 and 225

Tests have been made to study possible effects exposure to NaK at elevated temperatures might have on the room temperature properties of several stainless steels (Types 302, 304, 310, 316, 318, and 347), inconel, nickel, and low-carbon steel.⁽¹⁰⁾ ⁽⁸⁶⁾ The strength of the low-carbon

20

steel was appreciably lowered corresponding to the very extensive decarburization which occurred. However, no changes ascribable to attack by NaK were noted for any of the other metals. These tests were not conclusive in that changes in properties due to very slight surface attack by NaK would be masked in the massive specimens used. Stress-rupture and slow-fatigue tests⁽³⁶⁾ as well as tests of highly prestressed metals⁽⁸⁶⁾ have been made in an effort to observe possible acceleration of attack by NaK due to stresses in specimens during exposure at elevated temperatures. Here again, no deleterious effects could be ascribed to the NaK.

Mechanism of Attack by NaK

The basic mechanisms involved in the attack on metals by liquid NaK, are recognized but not thoroughly understood. Straightforward solution is observed for metals, the oxides of which are readily reduced by NaK, such as iron and copper. However, NaK always contains some oxide so that metals which are capable of reducing Na_2O become coated with films of their own oxides when exposed to NaK. NaK will also selectively remove a constituent of some metals, as for example, hot NaK will decarburize plain-carbon steels. Fortunately, most common metals of construction do not form solid solutions or compounds with NaK, so metallic surface reaction layers are not involved. Reported alloying of small quantities of sodium with stainless steel, nickel, and Monel⁽²⁸⁾ is believed to be based on questionable evidence⁽¹⁵⁰⁾. There is very little evidence of pit-type attack or intergranular attack of any of the metals tested in NaK. Observations to date reveal no attack by NaK due to electrical effects. The above processes that do apply to attack by NaK are sensitive to a number of variables which makes it difficult to predict the extent of attack in engineering systems.

Very little is known about the equilibrium solubilities in NaK of most of the metallic elements that have been considered as possible container materials. The solubility of iron in liquid potassium is not known but the formation of Fe-K alloys is considered improbable.⁽⁶⁹⁾ The equilibrium solubility of iron in sodium has been reported as 2 ppm at 100°C (212°F) and 18.3 ppm at 700°C (1292°F).⁽³⁵⁾ Although these are relatively low solubilities, they are considerably higher than those of iron in mercury. This has been the source of considerable worry in view of the difficulties with iron transfer that has been experienced in mercury systems (see Page 58). However, actual tests indicate that the rate of attack on iron by flowing NaK is exceedingly small, and no deposition of iron has been observed in the cold zone of any iron or plain-carbon steel dynamic system.

It has been shown that iron dissolves in sodium at a very slow rate resulting in extremely long times to attain equilibrium solubility.⁽³⁵⁾ On the other hand, iron dissolves very rapidly in mercury (see Page 59).

A mechanism of attack on iron by sodium has been proposed wherein the low rate of solution is considered the rate-determining step. According to this theory, equilibrium solubility of iron is never attained in sodium flowing at finite rates.⁽³⁵⁾

Another possible explanation of the low rate of attack on iron by flowing NaK is suggested by the apparent tendency for iron, which is dissolved in NaK at a high temperature, to remain in the NaK at room temperature. The iron content of NaK samples at low temperatures is invariably found to be greater than the equilibrium solubility. Commercially available brick sodium is reported to contain 9 to 20 ppm iron.⁽¹⁵⁹⁾ NaK that had been allowed to stand at room temperature for several weeks contained approximately 20 ppm iron.⁽⁸⁵⁾ This is approximately equal to the equilibrium solubility of iron in sodium at 700°C (1292°F) and far greater than the solubility at room temperature (see Page 19). It is conceivable that, in a dynamic system containing temperature gradients, iron particles which precipitate in the cold zone will be carried in suspension into the hot zone where, because of their large exposed surface, they will redissolve thereby protecting the pipe walls.

Crystalline deposits of iron and of copper which formed in the cold zones of static systems have been described by many investigators.^(24, 85, 92, 173) However, an anomaly was encountered when an attempt was made to study this effect in a dynamic system. After obtaining large weight losses of copper in static tests at 450°C (842°F) (indicating comparatively high solubility of copper in NaK), an investigator⁽¹⁰⁾ circulated NaK for 2677 hours through 150 feet of copper tubing having a hot zone of 329°C (625°F) and a cold zone of 52°C (125°F). The copper in the hot zone showed negligible attack, and no deposition of copper could be found in the cold zone. A plug that was found in the cold zone of a Type 316 stainless steel harp in which several different materials had been tested was found to contain iron, chromium, and nickel in about the ratio found in 18-8 stainless steels.⁽¹⁵²⁾

According to the solution mechanism, weight loss in static tests should increase with increasing temperature, it should be independent of time after equilibrium solubility is attained and, it should increase with increasing ratio of NaK volume to specimen area. The temperature effect has been verified for a number of metals. However, data on the attack as a function of time and of NaK volume-specimen area ratio have usually been difficult to obtain either because of negligibly small changes in weight or because of variables which were much more effective. Where weight changes were large, as in the case of copper, such effects were verified.⁽¹⁰⁾

If copper and nickel are immersed in hot NaK, the copper is found to lose considerably more weight than when copper is the only metal in the system, and the weight gain of the nickel indicates a quantitative transfer

of copper to nickel (see Page 36). Because of this mass transfer of copper (and, to a lesser extent, similar transfer of iron) multimetallic tests systems containing these elements yield data that are often difficult to interpret.^(24, 86) Transfer of silicon to form an alloy with low-carbon steel and with stainless steel by this same mechanism has been observed (see Page 44). The carburization of stainless steel when exposed to NaK is another aspect of this same mass-transfer phenomenon (see Page 24).

Influence of Oxygen in NaK

The above discussed solution mechanism is, in general, applicable when most metals are exposed to NaK containing no oxide. However, experience to date indicates that the propensity of NaK for combining with oxygen makes it difficult if not impossible to obtain oxygen-free NaK and to maintain this condition in an engineering heat-transfer system. Therefore, users of NaK must be cognizant of the influence of appreciable amounts of oxygen.

Sodium oxide (Na_2O), for example, drastically attacks most metals and oxides.⁽²²⁾ Molybdenum, wolfram, iron, cobalt, and nickel are reported as being attacked by Na_2O , the listing being in increasing order of resistance. Crucibles of BeO , ZrO_2 , ThO_2 , MgO , Al_2O_3 , and NiO were rapidly attacked at 1000°C (1832°F). It has been pointed out⁽¹⁶³⁾ that the acceleration of attack by liquid sodium attributed to the presence of NaOH is probably due to the Na_2O which forms on reaction of sodium with NaOH .

Metals such as chromium, beryllium, aluminum, titanium, tantalum, and zirconium are capable of reducing Na_2O . Therefore, alloys in which these elements are major constituents become coated with a layer of the metal oxide when exposed to NaK. The chromium-nickel stainless steels, which are being used most widely to handle NaK in engineering systems, have been studied the most extensively in this regard.⁽³⁶⁾ When exposed to NaK containing small amounts of oxide, stainless steel acquires a chromium oxide film which is tenacious and shows no tendency to spall off. The result is a weight gain. Negligibly small weight gains and sometimes weight losses have been reported for stainless steels when exposed to NaK containing less than 0.01% oxygen.⁽³⁶⁾ The weight changes in stainless steel specimens exposed to 760°C (1400°F) static NaK were essentially independent of time in tests for 200, 500, 1000 and up to 5000 hours.⁽¹⁰⁾ Apparently, a protective oxide film forms on initial exposure if it is not already present. Studies of the films formed on Type 347 stainless steel show that they consist only of Cr_2O_3 and that they are greater than 500 Å thick when formed by exposures of a week or more to calcium-purified sodium at 500°C (932°F).⁽³⁶⁾

Exposure of stainless steel to NaK of relatively high oxygen content results in weight losses. This indicates that the oxide layer is nonadherent if allowed to become thick.⁽⁸⁶⁾ The gray film that forms on beryllium when

exposed to relatively pure NaK has been shown to be BeO.⁽⁸⁶⁾ It is very friable and easily detached from the base metal so that beryllium always loses weight when exposed to NaK.^(36, 86) Acceleration of attack on beryllium occurs under dynamic flow conditions, and this process appears to proceed with time at a fairly uniform rate.^(36, 86) The attack on oxygen-sensitive metals is accelerated by an increase in the ratio of NaK volume to specimen area due chiefly to the resulting increase in oxygen available to form oxide films.⁽³⁶⁾

Oxygen accelerates the attack by NaK on most metals that have been studied regardless of whether they form oxide films or not. The equilibrium solubility of iron in sodium at 320°C (608°F) is not changed by the addition of 0.5% oxygen.⁽³⁶⁾ However, the rate of solution of iron in sodium increases with increasing oxygen content in the range 0.07 to 1% oxygen. Based on these observations it has been proposed that the slow mechanism whereby pure sodium dissolves iron (see Page 19) may be replaced or augmented when oxygen is present by a more rapid process; namely, the formation of $2\text{Na}_2\text{O} \cdot \text{FeO}$ ⁽²²⁾ and subsequent rapid reduction by sodium.⁽³⁵⁾

The rate of decarburization of plain-carbon steel is also accelerated by the presence of oxygen in the NaK.⁽⁸⁶⁾ Attack on low-carbon steel as a function of oxygen in the NaK has been studied in thermal convection test units at 538°C (1000°F) for 500 hours.⁽¹⁵²⁾ Additions of up to 0.3% oxygen (added as Na_2O_2) resulted in rates of weight loss as high as 100 times greater than when no oxygen was added in similar tests.

The influence of oxygen (1 to 3%) on the rate of attack of several metals by static NaK at 600°C (1112°F) has been studied.⁽⁸⁶⁾ Nickel was the only metal tested that was insensitive to oxygen additions, and Inconel and aluminum bronze were only slightly affected. Low-carbon (SAE 1020) steel, Type 303 (18-8 free machining) stainless steel, Invar (36 Ni-Fe), tantalum, molybdenum, and tungsten showed very large weight losses as a result of the oxygen additions. The rates of weight loss of Monel (30 Cu-Ni), 2% beryllium-copper, and titanium were also appreciably accelerated by the presence of oxygen. Several metals sometimes lost and sometimes gained weight indicating that they formed oxide films that were either non-adherent or unstable under some conditions. These include the 18 Cr-8 Ni austenitic stainless steels, aluminum (tested at 450°C, 842°F) and beryllium. Zirconium was the only metal tested which showed a large weight gain as the result of the formation of a heavy but very tenacious oxide film.

In another series of tests, the presence of small amounts of oxygen in NaK has no noticeable influence on the rate of attack on Type 310 (25 Cr-20 Ni) stainless steel, whereas the rate of attack on plain-carbon steel was accelerated by even slight oxygen contamination.⁽¹⁷³⁾ The high rates of attack in most early tests were undoubtedly due to the impurity of the NaK used.^(24, 36, 85, 92) First test results indicated that sodium

was more aggressive than alloys of sodium and potassium. However, more recent work using sodium of lower oxygen content has resulted in lower rates of attack similar to those observed with NaK. It is evident that oxygen contamination is much more effective than many other variables in increasing the aggressiveness of NaK toward containing metals. Satisfactory analytical techniques for traces of oxygen in NaK are needed before a quantitative study of the container problem is possible. At present the amount of oxygen that can be tolerated in NaK under a given set of conditions is not known.

Leaks in NaK systems must be avoided, not only because of the fire hazard, but also because the containing metals are drastically attacked.⁽¹⁷³⁾ Heat liberated by the reaction of NaK with the oxygen and moisture in air results in high temperatures, approximating the boiling point of the NaK,⁽¹⁰⁸⁾ and the oxides and hydroxides that form eat large holes very rapidly through most metal walls.

Methods of minimizing the deleterious effects of oxygen that have been studied include removal of the oxygen from the NaK and the addition of inhibitors. Oxygen has been removed from NaK by filtering, gettering, distilling, and settling with varying degrees of success.⁽⁷⁸⁾ Attempts to minimize attack by NaK by tying up the oxygen as an insoluble oxide indicate that any additive used for this purpose must be capable of reducing Na_2O , it should have some solubility in NaK at the temperature of test, and it should not of itself increase the aggressiveness of the NaK. Magnesium, zirconium, and titanium have been studied as possible inhibitors to attack on low-carbon steel by oxygen-contaminated NaK at 538°C (1000°F), and only magnesium showed any promise.⁽¹⁵²⁾ In order to inhibit the effect of an addition of 0.1% oxygen, it was necessary to dissolve some magnesium in the NaK at the test temperature before adding the oxygen. When the magnesium and oxygen were added before heating, no inhibition of attack occurred. When calcium is used as a getter in NaK, it is important to remove excess calcium to prevent attack on nickel and nickel alloys.⁽³⁶⁾

Solid phase bonding, a phenomenon which is related to attack on metals by NaK, is in some cases promoted and in other cases inhibited by exposure of metal surfaces to NaK before they are brought into contact.⁽¹²¹⁾ Apparently, NaK thoroughly cleans the surfaces of metals whose oxides are easily reduced, such as iron and nickel, and thereby insures intimate contact and diffusion welding. However, when exposed to NaK, metals high in chromium, such as stainless steel and stellite, acquire oxide films which prevent intimate contact and thereby inhibit diffusion welding.

Other Phenomena

Decarburization of plain-carbon steels has been observed by all investigators who have metallographically examined these steels after exposure to NaK at elevated temperatures.(10, 24, 36, 85, 92) The mechanism whereby NaK decarburizes steels is not understood. It is possible that oxygen plays an important role in this process since systems in which decarburization has been observed invariably have been contaminated with oxygen. Also, the rate of decarburization has been found to increase with increasing oxygen content (see Page 22). The reaction of the alkali metals with carbon has been the subject of several investigations.(33, 55, 56, 131, 140) Graphite, when immersed in a relatively small quantity of NaK at room temperature, is rapidly and completely dispersed resulting in a mushy slurry. This has been attributed to penetration of the graphite by potassium to form weakly-bonded interlamellar compounds. There is no appreciable solubility of carbon in sodium or potassium at their melting points, and no information exists about such solubility at elevated temperatures. However, potassium has a markedly greater affinity for carbon in any form than has sodium.

Since decarburization is a diffusion process, the rate of decarburization should increase with increasing temperature and with time of exposure, and this is found to be the case. However, one investigator has noted more rapid weight loss and more extensive decarburization of SAE 1020 steel when exposed to impure NaK at 700°C (1292°F) than at 800°C (1472°F).(85) This apparent anomaly is probably due to the greater rate of diffusion of carbon in ferrite at 700°C (1292°F) than in austenite at 800°C (1472°F).(149, 164) The weight losses for plain-carbon steel specimens are actually quite small; and, in fact, decarburization is extensive enough in some cases to account for most of the weight losses. In these cases, iron removal by the NaK is negligible.(85)

If carbon is appreciably soluble in NaK at elevated temperatures, then the lack of solubility at low temperatures might lead to plugging of small openings in the cooler zones of plain-carbon steel systems. The action of NaK on carbon limits the usefulness in NaK of materials containing free graphite. NaK has been handled at low temperatures in cast iron equipment, such as pumps, with no obvious deleterious effects.(93) However, exposure at high temperatures results in impregnation of cast iron by NaK with attendant swelling and distortion.(85)

Carburization of austenitic (Types 304, 347, and 310) stainless steels has been observed by several investigators; however, the source of the carbon is not known.(92, 150, 173) One investigator has shown that low-carbon steels, in the same system as Type 347 stainless steel, can be the source of carbon.(36) In another case Carboloy (WC) was believed to be the source of carbon.(47) However, several tests indicate that the NaK alloy itself cannot be excluded as a possible source of carbon. Heavy carburized

cases have been put on stainless steels when exposed at high temperatures to NaK to which 3 1/2 to 4% carbon had been purposely added.⁽⁴⁵⁾ The results of one test on low-alloy (up to 9 Cr) steels indicate that decarburization and subsequent carburization can occur but the mechanism was not satisfactorily explained.⁽⁴⁴⁾ In view of the dependence of many physical properties of steel on the carbon content, an understanding of these effects is important. Analytical techniques for carbon in NaK are now being developed so that the above phenomena can be quantitatively studied.⁽¹⁰⁾

The many sources of electrical potentials in engineering liquid metal systems have caused many investigators to suggest that electrolytic diffusion resulting in mass transfer should be looked for (See Page 9). Other investigators feel this is not a source of concern.⁽³⁵⁾ In the few NaK systems that have been examined for these effects no attack has been observed. For example, the inner pipe walls of direct current electromagnetic pumps have been examined carefully after 1000 hours of operation with a potential of 0.2 volts impressed across a stream of 300°C (572°F) NaK in a Type 347 stainless steel pipe with a current of 5000 amps, but there was no evidence of attack.⁽¹⁴⁾ An investigation of possible galvanic potentials between dissimilar metals in NaK has been made, and negative results were reported.⁽¹⁰⁰⁾ Thermoelectric potentials between NaK and several metals have been measured.^(101, 132)

Studies of the NaK container problem have resulted in a large mass of weight change data which are summarized in Table II. The source of all data is noted along with the temperature, time of test, composition of NaK, and whether the test was under static or dynamic conditions. The total number of measurements made under each set of conditions is noted along with the minimum, maximum, and average rate of weight change in mg/cm²/mo (mcm). Although the equivalent penetration, calculated from the weight loss data, is given in mils penetration per year (mpy), data so expressed should be used with discretion in light of the discussion on Page 11. Wherever they were available in the literature, descriptions of the specimens as well as special test conditions are also given. The available test data which have been used to evaluate the resistance of individual materials to attack by NaK as shown in the bar chart on Page 15 are discussed in the following sections.

Table 11a
RESISTANCE OF FERROUS METALS TO ATTACK BY RAE
Weight Change Data

27

Weight Change Data																
Material	Approximate Composition	Laboratory	Reference	W. S. No. in Ref.	Stress Dynamic	Temp. (°C)	Time (hrs)	No. of Tests	W. Change Rate (mg/cm ² /hr.)		Equivalent Penetration (mil/yr.)		Specimen Description	Remarks		
									Range	Average	Range	Average				
IRON AND PLAIN-CARBON STEELS																
Anne Iron	0.01 C	AHL	86	56	D	400	144	1	-	-	- 0.2	-	Dull gray	Tested with other metals		
		AHL	86	56	D	450	470-500	9	-0.08	-0.10	- 0.08	0.025	0.050	Unaltered	Tested alone	
		AHL	86	56	D	600	144	1	-	-	- nil	-	-	Unaltered	Tested with other metals	
Temple Iron	0.05 C	AHL	92	56	D	-225	100	1	-	-	- 95	-	38	Smooth and shiny. Decarburized	Relatively impure RAE	
		AHL	92	56	D	-225	500	1	-	-	- 150	-	90	Smooth and shiny. Decarburized	Relatively impure RAE	
		AHL	92	56	D	-225	500	1	-	-	- 150	-	90	Smooth and shiny. Decarburized	Relatively impure RAE	
SAE 1020 Steel	0.20 C	AHL	86	56	D	300	320	1	-	-	- 0.7	-	0.40	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	2	-0.02	-0.21	- 0.24	0.025	0.193	0.083	Unaltered	Tested with other metals
		AHL	86	56	D	450	2100	1	-	-	- 0.14	-	0.083	Bright	Tested with other metals. RAE impure	
Low-Carbon or Mild Steel (P-SAE 1020)	~0.20 C	AHL	86	56	D	300	144	1	-	-	- 0.2	-	0.30	Unaltered	Tested alone	
		AHL	86	56	D	300	144	1	-	-	- 0.2	-	0.30	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.2	-	0.30	Unaltered	Tested with other metals	
SAE 1095 Steel	0.95 C	AHL	86	56	D	300	144	1	-	-	- 1.6	-	0.95	Dull gray. Decarburized	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 1.6	-	0.95	Dull gray. Decarburized	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 1.6	-	0.95	Dull gray. Decarburized	Tested with other metals	
LOW-ALLOY (CHROMIUM) STEELS																
SAE 52100 Steel	1.45 Cr, 1.0 C	AHL	86	56	D	450	144	2	-0.2	-0.9	- 0.5	0.13	0.54	0.20	Unaltered	Tested with other metals
		AHL	86	56	D	600	144	2	-1.8	-1.7	- 3.7	1.1	3.6	2.2	Unaltered	Tested with other metals
		AHL	86	56	D	600	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
2 Cr, 1 Mn Steel Crucible 2 1/4	2 Cr, 1 Mn 2.25 Cr, 1 Mn	AHL	86	56	D	300	144	1	-	-	- 0.1	-	0.05	Gray	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.1	-	0.05	Gray	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.1	-	0.05	Gray	Tested with other metals	
Crucible 5 0.5 Ti Crucible 5	5 Cr, 0.5 Mn, 0.5 Ti 5 Cr, 0.5 Mn	AHL	86	56	D	300	144	1	-	-	- 0.1	-	0.05	Gray	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.1	-	0.05	Gray	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.1	-	0.05	Gray	Tested with other metals	
Stearns 55	5 Cr, 0.5 Mn, 1.5 Ni	AHL	86	56	D	300	144	1	-	-	- 0.1	-	0.05	Gray	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.1	-	0.05	Gray	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.1	-	0.05	Gray	Tested with other metals	
Crucible 7	7 Cr, 0.5 Mn	AHL	86	56	D	300	144	1	-	-	- 0.1	-	0.05	Gray	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.1	-	0.05	Gray	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.1	-	0.05	Gray	Tested with other metals	
Crucible 9	9 Cr, 1 Mn	AHL	86	56	D	300	144	1	-	-	- 0.1	-	0.05	Gray	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.1	-	0.05	Gray	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.1	-	0.05	Gray	Tested with other metals	
STAINLESS STEELS																
Type 302 S.S.	18 Cr, 8 Ni	AHL	86	56	D	300	144	2	-0.1	-0.3	- 0.2	0.05	0.20	0.10	Unaltered	Tested with other metals
		AHL	86	56	D	300	144	10	-1.0	-1.1	- 0.3	gain	0.05	gain	Unaltered	Tested with other metals
		AHL	86	56	D	600	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 303 S.S.	18 Cr, 8 Ni, (P, S, or Se)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 304 S.S.	18 Cr, 8 Ni (low C)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
		AHL	86	56	D	300	144	1	-	-	- 0.4	-	-	Unaltered	Tested with other metals	
Type 316 S.S.	18 Cr, 8 Ni (Mo)	AHL	86	56	D	300										

Table IIb

RESISTANCE OF NICKEL AND NICKEL ALLOYS TO ATTACK BY NaK

Weight Change Data[illegible]

BIGGEL - CONTINUED - IRON ALLOYS															Tested with other metals. Relatively improves Fe.	
Zincum	6.5 Fe, 12 Cr	40L	96	22	0	400	2000	1	-	-	nil	-	nil	Lead tested	Tested with other metals. Relatively improves Fe.	
		40PL	96	200		500	170-2500	5	-0.01	-0.07	0.04	gain	0.04	0.02		
		40L	96	96		400	144	3	+0.3	+0.6	0.5	gain	gain	Unaltered		
		40	10, 48	30		760	300	2	-0.2	-0.3	0.3	0.30	0.15	Sooty-like, smooth		
		40	10, 48	30		760	300	2	-0.1	-0.1	0.05	0.05	0.05	Sooty-like, smooth		
		40L	92	30		-225	380	1	-	-	30	-	16	Slightly pitted		
		40L	92	30		-225	380	1	-	-	6	-	gain	Slightly pitted		
		40L	96	96		400	144	2	+0.5	+0.5	0.5	gain	gain	gain		
		40L	96	96		400	144	2	+0.5	+0.5	0.5	gain	gain	gain		
		40L	96	96		400	144	2	+0.5	+0.5	0.5	gain	gain	gain		
Nickelium	25 Fe, 12 Cr	40L	96	96		400	144	2	+0.5	+0.5	0.5	gain	gain	gain	Slightly dull	
		40L	96	96		400	144	2	+0.5	+0.5	0.5	gain	gain	gain	Slightly dull	

BIDGEL - COPPER ALLOYS														
Name	30 Cu				300	125-368	8	+ 0.1	- 2.1	- 0.6	gain	1.10	0.20	
8APL	36	300			300	125-368	8	+ 0.1	- 2.1	- 0.6	gain	1.10	0.20	Tested with Ni
8AL	86	36			620	164	1	-	-	-	-	-	-	Tested alone
86	36	36			620	164	1	-	-	-	-	-	-	Tested with Ni
86	36	36			620	164	1	-	-	-	-	-	-	Tested alone
86	36	300			700	164	1	-	-	-	-	-	-	Tested with other metals including Ni
8F	64, 173	30			760	200	1	-	-	-	-	-	-	

OTHER NICKEL ALLOYS																
Hastelloy "A"	20 Wb, 20 Fe	SAFL	36	36		300	144	1	-	-	+ 0.3	-	-	gain	Partly dull	Relatively improves PdE
Hastelloy "B"	20 Wb, 5 Fe	SAFL	36	360	2	300	144	1	-	-	+ 0.2	-	-	gain		
		SAFL	152	36	36	300	144	1	+ 0.1	+ 0.2	-	-	gain			
		SAFL	36	360	2	300	144	1	-	-	+ 0.1	-	-	0.25 gain		
		SAFL	36	36		300	144	1	-	-	+ 0.2	-	-	gain	Underlaid	
		SAFL	36	36		300	144	1	-	-	+ 0.2	-	-	gain	Bright	
Hastelloy "C"	19 Wb, 17 Cr, 6 Fe	SAFL	36	360	2	300	144	1	-	-	+ 0.2	-	-	gain		
		SAFL	152	36	36	300	144	1	+ 0.1	+ 0.4	-	-	gain			
		SAFL	36	360	2	300	144	1	-	-	+ 0.1	-	-	gain		
		SAFL	36	36		300	144	1	-	-	+ 0.9	-	-	gain	Dull	
		SAFL	36	36		300	144	1	-	-	+ 0.1	-	-	gain	Hard green deposit	Relatively improves PdE
Hastelloy "D"	18 Wb, 2 Cr	SAFL	36	360	2	300	144	1	-	-	+ 0.3	-	-	gain		
		SAFL	152	36	36	300	144	1	-	-	+ 0.1	-	-	gain		
		SAFL	36	360	2	300	144	1	-	-	+ 0.1	-	-	gain		
		SAFL	36	36		300	144	1	-	-	+ 0.2	-	-	gain	Dull	
Ni-40 Bracing Alloy	20 and 40 Wb	SAFL	36	360		300	144	6	+ 0.17	+ 0.6	+ 0.3	gain	gain	gain	Strength of joints not impaired	
Ni-40 Bracing Alloy	30 Wb	SAFL	36	360		300	144	7	+ 0.7	+ 0.9	+ 0.9	gain	gain	gain	Strength of joints not impaired	
Ni-P Bracing Alloy	10 P	SAFL	36	360		300	144	6	+ 0.6	+ 2.4	+ 2.0	gain	gain	gain	Strength of joints not impaired	

Table IIc

RESISTANCE OF COPPER AND COPPER ALLOYS TO ATTACK BY NaOH

Weight Change Data

[illegible][illegible][illegible]

COPPER - RICHES ALLIERS																
Copper Nickel	30 Ni	Gr	64, 173	30		700	300	1	-	-	+ 36	-	-	gms	Light green deposit. Incipient attack	Treated with directionally attached Cu alloys
Copper Nickel	30 Ni	Gr	64, 173	30		700	300	1	-	-	+ 30	-	-	gms	Light green deposit. Incipient attack	Treated with directionally attached Cu alloys

COPPER - 110% ALLOY												
Specimen	Temp	Strain	Stress	Strain	Stress	Strain	Stress	Strain	Stress	Strain	Stress	Notes
Brass	40 Zn	0.01	56	56	0.01	144	2	- 6.7	- 6.6	- 6.6	6.10	Uniaxial Crystalline Ductility studied
		0.01	56	56	0.01	144	2	<0.1	<0.1	<0.1	6.10	
		0.01	56	56	0.01	144	2	-	-	-	6.10	
Micro Silver	17 Zn, 83 Ni	0.01	64, 173	30	700	200	1	-	-	-	14.0	No metallographic evidence of attack
	17 Zn, 83 Ni	0.01	64, 173	30	700	200	1	-	-	-	4.0	No metallographic evidence of attack

OTHER SUPPORT ALLOYS														
Drumbar	3 3/4, 1 lb	50	44, 173	50	760	500	1	-	+ 53	-	-	gain	Crystalline, Co color	Tested with directionally attached Co alloys
	1 1/2, 1 lb	50	50	100	500	500-504	2	- 2.7	- 15.4	- 36	-	-	6.5	

* N-K tests worked much better than tests in dynamic "Thorn" systems and should be given more weight than other tests which were in static NaK systems.

31

Table 114

RESISTANCE OF REFRACTORY METALS TO ATTACK BY NaK

Weight Change Data

Material	Approximate Composition	Laboratory	Reference	No. 1 Na in NaK	Static Dynamic	Temp. (°C)	Time (hrs)	No. of Tests	Wt. Change Data (mg/g/yr.)		Equivalent Penetration (mils/yr)		Specimen Description	Remarks
									Range	Average	Range	Average		
Niobium		EAPL	36	100		500	168	1	-	+ 0.1	nil	2.50	Gray	Tested with other metals. Relatively impure NaK NaK probably contaminated with oxygen
		ANL	85, 86	56		600	144	7	nil	- 4.6 - 1.1	nil	0.60	Varied-unaltered to dull gray	
Molybdenum		ANL	86	56	D	450	384-4370	4	nil	nil	nil	nil	Unaltered	
		EAPL	36	100		500	168	1	-	- 0.1	nil	0.05	Bright	
		ANL	86	56		600	144	4	+ 0.1	- 4.3	nil	0.10	Unaltered	
		ANL	173	20		760	200	1	-	- 42	-	19.5	Unaltered	
Tantalum		ANL	86	56		450	144	1	-	- 0.6	-	0.15	Black	
		ANL	86	22	D	450	2160	1	-	- 22.9	-	6.80	Black	
		ANL	153	34	D	538	500	1	-	Disintegrated	-	-	Disintegrated	
		ANL	86	56		600	144	2	- 1.6	- 1.6 - 1.6	0.45	0.45	Dull gray	
Titanium		ANL	86	22		600	144	2	- 2.9	- 2.9 - 3.4	0.80	1.10	Dull gray	
		EAPL	36	100		500	168	2	+ 0.6	+ 1.0	0.8	gain	Dark	
		ANL	86	22		600	144	1	-	- 1.0	-	1.0	Dull gray	
		ANL	10	20		760	200	1	-	+ 7.5	-	gain	Green and brown layers	
Zirconium		ANL	86	56		400	144	2	nil	nil	nil	nil	Unaltered	Zirconium contained 25 C
		ANL	153	34	D	385	500	1	-	- 490	-	100	Unaltered	
		ANL	86	56		600	144	3	nil	nil	nil	nil	Unaltered	
Vanadium		EAPL	36	100		500	168	2	- 0.2	- 1.3	0.2	0.15	Bright	Tested with other metals. Relatively impure NaK
		ANL	86	22	D	450	2160	1	-	+ 1.67	-	gain	Black tenacious film	
Zirconium		EAPL	36	100		500	168	2	+ 0.5	+ 0.7	gain	gain	Bright	
		ANL	86	56		600	144	2	+ 0.2	+ 0.9	gain	gain	Unaltered	

Table 115

RESISTANCE OF OTHER METALS AND ALLOYS TO ATTACK BY NaK

Weight Change Data

BIRM - COBALT ALLOYS														
Cobalt		ANL	86	56		600	144	1	-	+ 0.6	-	-	gain	Slight tarnish
Stellite No. 1	43 Co, 34 Cr, 14 W	EAPL	36	100		500	168	1	-	- 0.3	-	-	0.15	Unaltered
		ANL	86	56		600	144	1	-	- 0.1	-	-	0.05	
Stellite No. 6	55 Co, 33 Cr, 6 W	EAPL	36	100		500	168	1	-	+ 0.4	-	-	gain	
		ANL	153	34	D	538	500	1	-	nil	-	-	nil	
Stellite No. 12	47 Co, 34 Cr, 10 W	EAPL	36	100		500	168	1	-	+ 0.9	-	-	gain	
Stellite No. 21	~58 Co, 30 Cr, 6 Mo	ANL	152, 153	34	D	538	500	3	+ 6.0	+ 2.0 - 2.2	gain	gain	gain	Scale on specimen before test
		ANL	92	56		~825	500	1	-	- 11	-	-	6.3	
Tungsten	45 Co, 30 Cr, 15 W	EAPL	36	100		500	720	4	nil	- 6.07	nil	0.03	nil	Bright
Vitallium	~62 Co, 37 Cr, 4 Mo	EAPL	36	100		500	184	1	-	+ 5.8	-	-	gain	
Multimet N-155	21 Co, 21 Cr, 21 Ni, 30 Fe	ANL	152	34	D	538	500	1	-	+ 0.7	-	-	gain	
		ANL	92	56		~825	500	1	-	+ 90	-	-	gain	Green deposit
ALUMINUM ALLOYS														
Aluminum - 25	99.0 Al (min.)	ANL	86	56		200	144	1	-	nil	-	-	nil	Dull
		EAPL	36	100		400	168	1	-	- 2.4	-	-	4.20	Dull
		ANL	86	56		450	144	1	-	+ 0.6	-	-	gain	
		EAPL	36	100		500	168	1	-	- 2.7	-	-	4.65	Thin opaque dark film
		ANL	44, 173	20		538	200	1	-	- 15	-	-	22.5	
Aluminum - 35	1.2 Mn	ANL	173	20		538	200	3	- 2.6	- 5	- 4	4.5	8.6	Clean
Aluminum - 245	4.5 Co, 0.6 Mo, 1.5 Mg	ANL	44, 173	20		538	200	3	- 3.9	- 15.7	- 9	6.6	27	Mottled black
Aluminum - 525	2.5 Mg, 0.25 Cr	EAPL	36	100		450	168	7	- 3.5	- 61.5	- 32	6.2	108	56
		EAPL	36	100		500	168	4	- 2.7	- 300	- 100	4.8	530	175
		ANL	173	20		538	200	2	- 12.1	- 14	- 14	21.3	29	24.5
														Thin opaque dark film
BERYLLIUM														
Beryllium - (extruded)		ANL	86	56		200	144	2	nil	nil	nil	nil	nil	Slightly dull
		ANL	86	22	D	450	336-4370	8	- 0.05	- 1.3	- 0.19	0.140	0.860	Black film
		ANL	86	22	D	450	2160	1	-	-	-	-	-	Black film
		EAPL	36	100		500	156-2950	13	+ 0.7	- 2.1	- 0.1	gain	3.0	0.470
		EAPL	36	100		525	1717	2	-	-	-	0.10	-	Gray film
		ANL	86	56		600	144	4	+ 0.4	- 0.1	- 0.1	gain	5.0	0.25
														Varied-unaltered to gray

* NaK tests marked with "D" were made in dynamic "harp" systems and should be given more weight than other tests which were in static NaK systems.

7428 76

33

FERROUS METALS WITH NaK

m.p. Range -12.3 to 97.9°C (10 to 208°F)

Iron and Plain-Carbon Steels with NaK

Armco iron (0.01 C) has good resistance to attack by NaK at 600°C (1112°F).

The maximum equivalent penetration of 9 Armco iron specimens was only 0.05 mpy when exposed for up to 1000 hours to flowing NaK at 450°C (842°F) in uni- and multimetallic systems.⁽⁸⁶⁾ In static 6-day NaK tests at 600°C (1112°F) the maximum and average equivalent penetrations of 20 specimens were 0.10 and 0.05 mpy.⁽⁸⁶⁾ Hot NaK readily wets Armco iron surfaces leaving them bright and clean.

The extreme susceptibility of plain-carbon steels to decarburization by NaK is the reason for rating them as having limited resistance to NaK above 450°C (842°F). If decarburization is of no concern, plain-carbon steels have good resistance to NaK up to 600°C (1112°F) and moderate to poor resistance at higher temperatures.

Low-carbon steels (SAE 1010 and 1020) are extensively decarburized by NaK at and above 450°C (842°F) (see Page 24) and some decarburization has been observed at as low as 200°C (392°F).⁽⁸⁶⁾ However, weight loss rates are low on exposure to either static or dynamic NaK. On exposure to flowing NaK in a large number of tests ranging from 384 to 4370 hours, the maximum equivalent penetration at 450°C (842°F) was less than 0.2 mpy,⁽⁸⁶⁾ and it was about 0.6 mpy at 538°C (1000°F).⁽¹⁵³⁾ Exposures to static 600°C (1112°F) NaK for short times resulted in equivalent penetrations as high as 1 mpy^(36, 86) whereas similar tests at 760°C (1400°F) resulted in weight losses 2 to 3 times as great.⁽¹⁷³⁾ A test in boiling sodium, 883°C (1621°F) resulted in complete decarburization and equivalent penetration, calculated from weight loss, of 9 mpy with deposition of iron crystals at the surface of the liquid metal bath.⁽⁹²⁾ Under similar conditions, wrought iron was even more drastically attacked (equivalent penetration of 90 mpy) and iron crystals were found. The freedom from oxygen contamination in the latter tests is questionable.

The only reported test of high-carbon steel (SAE 1095) was one of 6 days in static 600°C (1112°F) NaK in which extreme decarburization occurred and the equivalent penetration was about 1 mpy.⁽⁸⁶⁾

Iron oxide on plain-carbon steel is rapidly reduced by NaK resulting in thoroughly wetted surfaces which are clean and bright. The rate of weight loss as well as the rate of decarburization are accelerated by oxygen contamination of the NaK (see Page 22). Early evidence that the presence of stainless steel accelerated the attack on low-carbon steel⁽⁸⁵⁾ has not been substantiated in more recent tests.^(10, 86) The early test results are believed to be due to oxygen contamination since very impure NaK was used. There is some evidence that magnesium dissolved in NaK will inhibit the deleterious effects of oxygen (see Page 23).

Transfer of small amounts of iron from plain-carbon steels to nickel has been observed in multimetallic NaK systems.⁽⁸⁶⁾

Low-Alloy (Chromium) Steels with NaK

The low-alloy steels containing chromium have, in general, good resistance to NaK at 500°C (932°F) and good to limited resistance up to 760°C (1400°F). They form oxide films which are not always adherent and, therefore, can cause weight gains as well as losses.

Ball-bearing steel (SAE 52100 lost the equivalent of as much as 0.5 mpy at 450°C (842°F) and 3.6 mpy at 600°C (1112°F) in 6-day static NaK tests.⁽⁸⁶⁾ The microstructure was not altered in these tests or in numerous long-time bearing tests at lower temperatures.⁽⁴⁶⁾

Sicromo 5S (5 Cr, 1.5 Si, 0.5 Mo) gained up to 5 mg/cm² when exposed to flowing NaK at 538°C (1000°F) for 500 hours⁽¹⁵²⁾ presumably because of the formation of an oxide layer. However, short-time exposures to 500°C (932°F) static NaK of Sicromo 5S and 5 Cr, 0.5 Mo steels resulted in very slight weight gains and in one case a slight weight loss.⁽³⁶⁾ Short-time exposures to static NaK at 760°C (1400°F) of several Croloys (2 1/4 to 9 Cr) resulted in relatively high weight losses, the maximum (expressed as equivalent penetration) being 6 mpy.⁽¹⁷³⁾ These specimens were covered with rust-like areas and also were peculiarly decarburized and carburized. Until further work is done, these Croloy steels are not recommended for long-time use in NaK at 760°C (1400°F).

Stainless Steels with NaK

The 18-8 type austenitic stainless steels, as well as similar steels of higher alloy content, are extremely resistant to attack by NaK at, and possibly above, 760°C (1400°F). When exposed to ordinary NaK, they acquire thin tenacious Cr₂O₃ films which usually lead to small weight gains.

35

Several 18-8 type austenitic stainless steels have been tested in clean NaK at temperatures as high as 871°C (1600°F) with no significant attack. They include Types 302, 303 (P, S or Se), 304 (low C), 316 (Mo), 318 (Mo, Nb), 321 (Ti), and 347 (Nb). Similar steels of higher alloy content, such as 25 Cr-20 Ni (Type 310) and 35 Cr-15 Ni, behave similarly toward NaK and are grouped with the austenitic stainless steels as having excellent properties as well as resistance to NaK. There is no evidence that the stabilized stainless steels are more resistant than those that are unstabilized, the former (especially Type 347) being preferred only because of better welding characteristics and resistance to air corrosion at elevated temperatures.

Slight weight losses are observed when stainless steels are exposed to very pure NaK, whereas contamination of the NaK with small amounts of oxygen results in small weight gains due to the adherent Cr₂O₃ films that form (see Page 21). The rate of weight change decreases rapidly with time. For example, Type 310 stainless steel, when exposed to clean static NaK at 760°C (1400°F), lost weight equivalent to 1 mpy in 50 hours, 0.2 mpy in 1500 hours, and nil in 5000 hours.⁽¹⁷³⁾

Attack of stainless steels by NaK is not influenced by the presence of other metals in the same system nor do the stainless steels influence attack of the other metals by NaK (see Pages 20 and 30). However, carburization of stainless steels can occur in NaK and there is evidence that plain-carbon steel in the same system can be the source of carbon (see Page 24). Tensile tests at room temperature of several stainless steels after exposure to static NaK at 760°C (1400°F) for up to 1000 hours revealed no appreciable change in mechanical properties that could be attributed to attack by NaK.⁽¹⁰⁾ Also, NaK has no deleterious effects on the high temperature stress-to-rupture or fatigue strength of Type 347 stainless steel.⁽³⁶⁾

The meager data available on the ferritic type (Cr) stainless steels indicates that they are not much different from austenitic stainless steels in their behavior toward NaK.⁽⁸⁶⁾

Other Ferrous Metals with NaK

Numerous other iron-base alloys had good resistance to hot NaK. In most cases, only one or two tests in static NaK were made for each alloy so that not many conclusions can be drawn from the data.

Worthite (20 Cr, 24 Ni, 3.5 Si, 3 Mo, 1.75 Cu) behaved much like stainless steel when exposed for 7 days to static 500°C (932°F) NaK in that it gained slightly in weight because of a thin oxide film.⁽³⁶⁾

High-speed tool steel (18 W, 4 Cr, 1 V) also gained slightly in weight when exposed for short times to static 500°C (932°F) and 600°C (1112°F) NaK.⁽³⁶⁾ However, exposure to flowing NaK for 500 hours at 595°C (1103°F) resulted in a weight loss equivalent to 3 mpy.⁽¹⁵²⁾ The presence of several carbide specimens as well as a 2% C-W specimen which was drastically attacked (see Page 41) may have complicated this test.

Invar (36 Ni) was practically unaltered by exposure for 6 days to 600°C (1112°F) static NaK.⁽⁸⁶⁾ However, Invar was drastically attacked when 2-3% of oxygen was added to the NaK in a similar test, the equivalent penetration being 26 mpy.⁽⁸⁶⁾ Fernico (28 Ni, 18 Co) showed slight weight losses (equivalent penetrations of 0.5 mpy) in short-time exposures at 500°C (932°F) and 700°C (1292°F), and Alnico 5 (14 Ni, 24 Co, 8 Al, 3 Cu) was practically unaltered in a similar test at 500°C (932°F).⁽³⁶⁾ A nickel-iron alloy (9 Ni) showed limited resistance to 760°C (1400°F) static NaK in that it lost the equivalent of 3 mpy when exposed for 200 hours.⁽¹⁷³⁾

Hadfield's manganese steel (12 Mn) was covered with a light gray film and lost the equivalent of 0.8 mpy after a 6-day exposure to 600°C (1112°F) static NaK.⁽⁸⁶⁾

The nitrided surface of Nitralloy G was badly cracked after 300°C (572°F) and 600°C (1112°F) exposures to static NaK.⁽⁸⁶⁾ It is difficult to say how aggressive the NaK was in this case since thermal expansion differences could have caused much of the observed results. However, pending further study, nitrided steels are not recommended for use in NaK at elevated temperatures.

An iron-phosphorus brazing alloy (20P) showed negligible attack by static sodium at 500°C (932°F), and the mechanical strength of joints brazed with this alloy was not impaired by the sodium exposure.⁽⁵⁷⁾

NICKEL AND NICKEL ALLOYS WITH NaK

m.p. Range -12.3 to 97.9°C (10 to 208°F)

Nickel and Nickel Alloys of Low Alloy Content with NaK

Nickel has excellent resistance to attack by NaK at, and probably above, 760°C (1400°F) and is highly recommended for use as a container material. Small alloy additions to the nickel do not alter its resistance, and it is comparatively insensitive to oxygen contamination of the NaK.

Nickel would be used more extensively as a container for NaK at high temperatures were it not for its relatively poor high-temperature properties. It has been tested in NaK under a wide range of conditions, and the available test data are uniformly encouraging. The weight changes of nickel specimens were hardly detectable when they were exposed to flowing NaK at 450°C (842°F) for up to 4370 hours⁽⁸⁶⁾ and at 538°C (1000°F) for 500 hours.⁽¹⁵²⁾ Many short-time static tests at 600°C (1112°F)^(36, 86) and 760°C (1400°F)⁽¹⁷³⁾ yielded similar results, and contamination of the NaK with as much as 3% oxygen did not result in attack on nickel by NaK.⁽⁸⁶⁾

When nickel is exposed to NaK in the presence of low-carbon steels, iron is transferred from the steel to the nickel and reacts with it to form a thin dull-gray nickel-iron alloy film.⁽⁸⁶⁾ The thickness of the film increases with increasing ratio of exposed iron to nickel surface and also with temperature. At 450°C (842°F) in a steel convection system in which the iron-to-nickel surface ratio was very large, the weight increase of the nickel was hardly detectable.⁽⁸⁶⁾ When specimens were exposed to 600°C (1112°F) static NaK for 6 days in low-carbon steel containers, the maximum weight increase was 0.1 mg/cm² of nickel surface.⁽⁸⁶⁾ However, similar tests at 760°C (1400°F) resulted in weight gains as high as 8 mg/cm² of nickel surface.⁽¹⁷³⁾ A similar phenomenon occurs when copper and most copper alloys are exposed in a NaK system containing nickel except that the transfer of copper to nickel is considerably more extensive.⁽⁸⁶⁾ The transfer of iron and of copper to nickel is accelerated by the presence of oxygen⁽⁸⁶⁾ (see Page 20).

Seven-day tests in 500°C (932°F) static NaK of nickel-base alloys of small alloy content indicate that they are similar to nickel in their resistance to NaK.⁽³⁶⁾ These alloys contained small additions of Mn, Si, Ti, Mg, Zr, and B and include Inco Alloys No. 83, 77, and HF 4065 as well as nickel welding rod.

Inconel and Nichrome with NaK

Inconel (6.5 Fe, 13 Cr) and Nichrome (25 Fe, 15 Cr) behave much like stainless steel when exposed to NaK in that they have excellent resistance at temperatures as high as 760°C (1400°F), and they acquire thin adherent oxide films.

In flowing NaK at 450°C (842°F) for 2160 hours, Inconel showed no detectable weight change.⁽⁸⁶⁾ Very slight weight gains and losses of Inconel and Nichrome were noted in static tests at 500°C (932°F)⁽³⁶⁾ and at 600°C (1112°F),⁽⁸⁶⁾ and the maximum weight loss of Inconel in a 1000-hour static test at 760°C (1400°F) corresponded to 0.05 mpy.⁽¹⁰⁾ Some data indicate that attack on Inconel by NaK is relatively insensitive to oxygen contamination of the NaK,⁽⁸⁶⁾ but other data throw doubt on this point.^(86, 92) Tensile tests at room temperature of Inconel after exposure to static NaK at 760°C (1400°F) for up to 1000 hours revealed no appreciable change in mechanical properties that could be attributed to attack by NaK.⁽¹⁰⁾

Monel with NaK

Monel (30 Cu) has good resistance to attack by NaK at 600°C (1112°F) and limited resistance at 700°C (1292°F) and at 760°C (1400°F).

Monel showed no evidence of attack and negligible weight change when exposed for 6 days to static NaK at 600°C (1112°F).⁽⁸⁶⁾ Similar tests by other investigators at 700°C (1292°F)⁽³⁶⁾ and 760°C (1400°F)⁽¹⁷³⁾ resulted in weight losses corresponding to penetrations of 3 and 5 mpy. The surface of the specimen tested at 760°C (1400°F) appeared to be richer in copper. The investigator attributed this enrichment to selective nickel solution by the NaK.⁽¹⁷³⁾ This does not appear to be compatible with the excellent resistance to NaK attack exhibited by nickel in a large number of tests (see Page 33).

Another investigator found that tests of Monel and nickel in the same NaK system resulted in the formation of a nickel-copper solid solution layer on the nickel because of transfer of copper from the Monel.⁽⁸⁶⁾ The addition of oxygen to the NaK accelerated the rate of transfer of copper and resulted in large weight losses. In a similar static NaK test of Monel in a low-carbon steel container, a heavy nonadherent film was formed on the Monel which was found to consist of iron, nickel, and copper.

Hastelloys A, B, C, and D with NaK

Hastelloys A, B, C, and D have good resistance to attack by NaK at 600°C (1112°F) and one test indicates that Hastelloy B is drastically attacked by boiling NaK.

Hastelloys A (20 Mo, 20 Fe) and B (30 Mo, 5 Fe) showed very small weight changes and negligible attack when exposed to flowing NaK at 538°C (1000°F)⁽⁹²⁾ and static NaK at 600°C (1112°F).^(36,86) However, after 500 hours in static boiling NaK, approximately 825°C (1517°F), Hastelloy B was drastically attacked, the attack resulting in a weight loss corresponding to about 50 mpy. Hastelloy D (10 Si, 3 Cu) also showed negligible weight changes as the result of exposure to static NaK at 600°C (1112°F).^(36, 86) Hastelloy C (19 Mo, 17 Cr, 6 Fe) specimens acquired thin oxide films and gained slightly in weight when exposed to NaK at 600°C (1112°F).^(36, 86) However, contamination of the NaK with oxygen resulted in hard green deposits and corresponding weight gains as was found in a flowing NaK system at 538°C (1000°F) and static NaK boiling at approximately 800°C (1472°F).^(92, 153)

Nickel-Base Brazing Alloys with NaK

Several nickel-base brazing alloys including 20 Mn-Ni, 40 Mn-Ni, 50 Mo-Ni, and 10 P-Ni alloys showed negligible attack and slight weight gains when exposed to static sodium at 500°C (932°F). The physical properties of joints brazed with these alloys were not impaired by the sodium exposure.⁽⁵⁷⁾

COPPER AND COPPER ALLOYS WITH NaK

m.p. Range -12.3 to 97.9°C (10 to 208°F)

Copper with NaK

Phosphorus deoxidized copper and * OFHC copper appear to have good resistance to NaK at 450°C (842°F) and limited to poor resistance at higher temperatures. However, the resistance of copper to attack by NaK is greatly reduced by impurities in the copper, by nickel in the same test system, and by oxygen in the NaK.

Copper appears to be appreciably soluble in NaK at elevated temperatures as evidenced by the extremely large weight losses and drastic attack that have been observed, as high as 92.5 mpy at 760°C (1400°F) in static NaK.^(10, 173) This is further borne out by the same investigator who noted an increase in weight loss with increasing ratio of volume of NaK to area of copper exposed. However, when tested for 6 days in a unimetallic static system containing clean NaK at 600°C (1112°F), deoxidized copper appeared slightly etched, gained slightly in weight, but was otherwise unaltered.⁽⁸⁶⁾ Similar tests at 450°C (842°F) resulted in even less attack. Results of the long-time dynamic test described on Page 20 are further evidence that copper resists NaK at moderate temperatures.

When nickel is exposed in NaK systems containing copper, the nickel surfaces acquire films which have been identified as copper-nickel solid solutions.⁽⁸⁶⁾ As a result, copper tested in a nickel container loses considerably more weight than when tested in a copper container. For example, the presence of nickel caused copper to lose weight at rates equivalent to 45 mpy at 600°C (1112°F) and 2.5 mpy at 450°C (842°F) in 6-day static tests.

When exposed to oxygen-contaminated NaK at elevated temperatures, copper is drastically attacked and deposition of copper crystals on the container at the NaK surface often occurs.^(24, 85, 152, 173)

Electrolytic copper was not attacked by static NaK at 300°C (572°F) but was intergranularly attacked at 450°C (842°F) and completely honey-combed by intergranular penetration at 600°C (1112°F).⁽⁸⁶⁾ Silver-bearing copper (trace Ag) was similarly penetrated throughout by static NaK at 760°C (1400°F).⁽¹⁷³⁾

---

*Oxygen-free high-conductivity copper

41

Beryllium Copper with NaK

Beryllium copper (2 Be) has reasonably good resistance to attack by pure NaK under static conditions at 600°C (1112°F). However, it is sensitive to oxygen and should not be considered for use at 450°C (842°F) in contaminated flowing NaK, and probably not even at somewhat lower temperatures.

Beryllium copper gained slightly in weight when exposed for 6 days to static deoxidized NaK at 600°C (1112°F) and lost slightly in weight under conditions which were the same except for the presence of nickel. However, it was drastically attacked, losing the equivalent of 14.5 mpy, when exposed for 2160 hours to flowing oxygen-contaminated NaK at 450°C (842°F).⁽⁸⁶⁾ Similar attack was noted on specimens statically tested at 600°C (1112°F) in NaK to which 2-3% of oxygen was purposely added.⁽⁸⁶⁾ After test, these specimens had gray, powdery, nonadherent films remindful of those that form on beryllium when exposed to hot NaK.

Aluminum Bronze with NaK

Aluminum bronze (8 Al) and Ambraloy 901 (5 Al) have good resistance to NaK at 600°C (1112°F) and 760°C (1400°F).

The aluminum bronzes resist attack by NaK better than any of the copper alloys tested. Specimens were unaltered on exposure to flowing NaK at 450°C (842°F) for 4370 hours and were only slightly attacked by 600°C (1112°F) static NaK⁽⁸⁶⁾ and 760°C (1400°F) static NaK.⁽¹⁷³⁾ The presence of nickel in the same system had no effect, and contamination of the NaK with 2-3% oxygen caused only slight attack.⁽⁸⁶⁾

Copper-Nickel Alloys with NaK

Super nickel (30 Ni) and Cupro nickel (20 Ni) acquired light green deposits and gained 4.4 and 2.7 mg/cm² of metal surface on exposure for 200 hours to 760°C (1400°F) static NaK.⁽¹⁷³⁾ These specimens were tested in a multimetallic system containing Cu-Ni-Zn alloys which lost considerable weight as a result of the exposure to NaK (see Page 38). When metallographically examined, these alloys showed only incipient attack. Based on this meager information and also by comparison with the resistance to attack by NaK of Cu-Ni alloys rich in Ni (see Page 34), these alloys are rated as having good resistance up to 600°C (1112°F) and lower resistance at higher temperatures.

Copper-Zinc Alloys with NaK

Brass (30 and 40 Zn) has good resistance to NaK at 200°C (392°F) but is drastically attacked at 600°C (1112°F).

Brass appeared to be unaltered by NaK at 200°C (392°F), whereas tests of brass in 600°C (1112°F) static NaK resulted in large weight gains as the result of impregnation of the specimens with NaK.⁽⁸⁶⁾ Similar tests with nickel present result in extreme weight loss of the brass (130 mpy) and corresponding weight gain of the nickel.⁽⁸⁶⁾ Nickel silver (17 Zn, 18 Ni) and Ambrac (5 Zn, 20 Ni) also lost considerable weight, the equivalent of 14 and 4.8 mpy, when exposed to 760°C (1400°F) static NaK, but they showed no metallographic evidence of attack.⁽¹⁷³⁾

Other Copper Alloys with NaK

Everdur (3 Si, 1 Mn) gained 9 mg/cm² of surface area when exposed to 760°C (1400°F) static NaK and had a crystalline copper appearance.⁽¹⁷³⁾ There was no metallographic evidence of attack. The specimen was tested in a multimetallic system with copper alloys that were drastically attacked. This accounts for the weight gain.

Trovaloy No. 1 (2.5 Co, 0.5 Be) lost the equivalent of 8.5 mpy when exposed to 500°C (932°F) static NaK⁽³⁶⁾ and therefore has limited to poor resistance to attack at that temperature.

A 10% tin bronze was drastically attacked by 650°C (1202°F) static NaK, the tin-rich phase being removed.⁽⁸⁵⁾

A 30% Mn-Cu 5-mil foil weighing 1.2 grams was completely dissolved in about 100 grams of impure NaK at 600°C (1112°F) leaving copper-colored crystals on the container wall.⁽³⁵⁾

REFRACTORY METALS WITH NaK

m.p. Range -12.3 to 97.9°C (10 to 208°F)

Chromium with NaK

Chromium has good resistance to NaK at 600°C (1112°F) and probably at higher temperatures. It forms an adherent protective oxide film.

Chromium appeared dull but otherwise unaltered after exposure to clean static NaK at 600 and 800°C (1112 and 1472°F).⁽⁸⁶⁾ Weight changes were meaningless for these tests because of the type of specimens used. Chromium plates on nickel showed excellent resistance to attack and negligible weight changes on 6-day exposures to static NaK at 600°C (1112°F).⁽⁸⁶⁾

Niobium with NaK

Niobium has good resistance to NaK at 500°C (932°F) and good to limited resistance at 600°C (1112°F) depending on the purity of the NaK.

In static tests of relatively short duration at 500°C (932°F) and 600°C (1112°F), niobium sometimes remained bright and sometimes acquired a gray film.^(36, 86) The gray film had only limited adherence and resulted in weight losses which ranged from nil to 2.5 mpy when expressed as equivalent penetration.

Molybdenum with NaK

Molybdenum has good resistance to clean NaK at 600°C (1112°F), but is extremely sensitive to oxygen contamination of the NaK.

Molybdenum was not at all altered by several long-time exposures (up to 4370 hours) to flowing NaK at 450°C (842°F) in systems containing several other metals.⁽⁸⁶⁾ Also, no attack was found as the result of short-time exposures to clean static NaK at 500°C (932°F)⁽³⁶⁾ and 600°C (1112°F).⁽⁸⁶⁾ Similar tests in which oxygen was purposely added to the NaK resulted in large weight losses of the molybdenum specimens.⁽⁸⁶⁾ This probably explains the extreme loss in weight (19.5 mpy) reported by one investigator who exposed molybdenum to static NaK at 760°C (1400°F).⁽¹⁷³⁾

Tantalum with NaK

The resistance of tantalum to pure NaK is good at 450°C (842°F) and limited at 600°C (1112°F) because of its extreme sensitivity to even slight oxygen contamination. It is not recommended for use even at 450°C (842°F) in systems contaminated with oxygen.

The loss in weight observed in all tests of tantalum in NaK is due to the nonadherent black oxide film that always forms on tantalum when exposed to even relatively pure NaK. Short-time exposures to pure static NaK resulted in small weight losses at 450°C (842°F) and appreciable weight losses at 600°C (1112°F).⁽⁸⁶⁾ However, exposures to oxygen-contaminated static NaK at 600°C (1112°F) and flowing NaK for 2160 hours at 450°C (842°F) resulted in very large weight losses.⁽⁸⁶⁾ The complete disintegration of tantalum in both static and dynamic exposures at 538°C (1000°F) reported by one investigator is probably due to use of impure NaK.⁽¹⁵²⁾

Titanium with NaK

The resistance of titanium to attack by relatively clean NaK is probably good at 500°C (932°F) but titanium has limited resistance at 600°C (1112°F) and poor resistance at higher temperatures.

The rating of titanium is probably influenced by the purity of the NaK because the extent of oxide contamination was not sufficiently known in the few tests that have been made. The titanium acquired dark gray films that caused small weight gains in 500°C (932°F) static NaK,⁽³⁶⁾ but it lost the equivalent of 1 mpy at 600°C (1112°F).⁽⁸⁶⁾ A titanium specimen lost weight equivalent to 3.5 mpy when exposed to 600°C (1112°F) static NaK to which 2 to 3% oxygen had been added.⁽⁸⁶⁾ Another investigator observed a large weight gain due to the formation of a nonadherent green layer over an adherent dark brown film when titanium was exposed to 760°C (1400°F) static NaK for 200 hours.⁽¹⁰⁾

Wolfram with NaK

Wolfram has excellent resistance to attack by pure NaK up to 600°C (1112°F) but it is sensitive to oxygen in the NaK.

Exposure of wolfram to purified static NaK for 6 days at 400°C (752°F) and 600°C (1112°F) resulted in no discernible attack, the metal having remained unaltered both in appearance and weight.⁽⁸⁶⁾

45

Although wolfram was unaltered in appearance on exposure for 6 days at 600°C (1112°F) to static NaK to which 2-3% of oxygen had been added, it lost the equivalent of 6 mpy.⁽⁸⁶⁾ Drastic attack was observed when wolfram containing 2% carbon was exposed for 500 hours to flowing NaK at 595°C (1103°F).⁽¹⁵²⁾

Vanadium with NaK

The only test that has been made on vanadium, indicates that it has good resistance to attack by NaK at 500°C (932°F).

The specimen remained bright and only lost the equivalent of 0.15 mpy when exposed to 500°C (932°F) static NaK.⁽³⁶⁾

Zirconium with NaK

Zirconium has good resistance to attack by NaK at 600°C (1112°F) but gains weight when exposed to even relatively pure NaK because of the formation of a very tenacious and adherent oxide film.

Zirconium specimens were unaltered in appearance but gained up to 0.2 mg/cm² in 6 and 7-day exposures to relatively clean static NaK at 500°C (932°F)⁽³⁶⁾ and 600°C (1112°F).⁽⁸⁶⁾ A shiny black adherent film formed on zirconium when it was exposed for 2160 hours to 450°C (842°F) flowing NaK which was believed to be contaminated with oxygen.⁽⁸⁶⁾ This specimen gained 5 mg/cm² of zirconium surface. A weight gain with formation of a similar film resulted when zirconium was exposed for 6 days to static 600°C (1112°F) NaK to which 2-3% of oxygen had been added.⁽⁸⁶⁾

OTHER METALS AND ALLOYS WITH NaK

m.p. Range -12.3 to 97.9°C (10 to 208°F)

High-Cobalt Alloys with NaK

Cobalt and a number of high-cobalt alloys have good resistance to attack by NaK in the range 500°C to 600°C (932°F to 1112°F).

Cobalt and several alloys high in cobalt, chromium, and wolfram have been exposed to static and dynamic NaK at 500°C, 538°C, and 600°C (932°F, 1000°F, and 1112°F), and, in general, they show either negligible weight loss or small weight gains.^(36, 85, 153) The alloys tested include Stellites No. 1, 6, 12, and 21, Tantung, Vitallium, and Multimet N-155 (Fe, Ni, Co, Cr alloy). The specimens usually were bright and unaltered in appearance. Oxygen contamination of the NaK was probably responsible for the formation of a heavy green deposit with resultant large weight gain (62 mg/cm²) reported for a Multimet N-155 specimen after a 500-hour exposure to boiling NaK.⁽⁹²⁾

Aluminum Alloys with NaK

The aluminum alloys tested have, in general, good resistance to attack by NaK at 200°C (392°F), limited resistance at 400°C (752°F), and poor resistance at higher temperatures.

Aluminum, when exposed to even clean NaK, acquires an oxide film which is relatively nonadherent and results in erratic weight changes. Aluminum (2S) was dulled but otherwise unaltered by a 6-day exposure to 200°C (392°F) static NaK, and similar results, with slight weight gains, were observed at 450°C (842°F).⁽⁸⁶⁾ However, weight losses equivalent to 4 to 5 mpy were reported in similar tests at 400 and 500°C (752 and 932°F) by another investigator, who also noted that aluminum lost more weight when tested in stainless steel than in low-carbon steel containers.⁽³⁶⁾ At 538°C (1000°F) drastic attack (22.5 mpy) has been reported.⁽¹⁷³⁾

Weight losses equivalent to 7, 15.5, and 24.5 mpy were reported for 3S, 24S, and 52S aluminum after 200-hour exposures to 538°C (1000°F) static NaK.⁽¹⁷³⁾ Even greater attack on 52S aluminum was found by another investigator at 450 and 500°C (842 and 932°F).⁽³⁶⁾

Aluminum-silicon eutectic alloy (12 Si), when exposed for 6 days to 450°C (842°F) NaK, was drastically attacked and completely impregnated with NaK due to removal of the silicon.⁽⁸⁶⁾

47

Beryllium with NaK

The resistance of beryllium to attack by clean static NaK is excellent at 200°C (392°F), good at 450°C (842°F) and limited at 500°C (932°F) and 600°C (1112°F). However, beryllium is very sensitive to oxygen contamination of the NaK.

Sintered (porous) beryllium becomes impregnated with NaK whereas extruded beryllium does not, so the latter has been used to study the resistance of beryllium to attack by NaK. When exposed to purified NaK, beryllium acquires a nonadherent BeO film which always results in weight losses (see Page 22). The weight loss is negligible at 200°C (392°F), but it is equivalent to as much as 3 mpy in clean static NaK in the range 500 to 600°C (932 to 1112°F).^(36, 86) The nonadherent BeO film is removed by NaK flowing at 10 to 20 ft/sec. More BeO forms on the freshly exposed beryllium surface resulting in progressive attack with time.⁽³⁶⁾ Short-time exposures at 600°C (1112°F) to static NaK contaminated with oxygen resulted in weight losses equivalent to as high as 20 mpy.⁽⁸⁶⁾

Metals Which Have Poor Resistance to Attack by NaK

Several elements have poor resistance to NaK even at low temperatures, and alloys containing appreciable amounts of these elements, especially in the free state, should be used with caution. The following elements are eliminated from consideration as container materials because available phase diagrams indicate high solubility in sodium and potassium at low temperatures:⁽⁶⁹⁾ antimony, bismuth, cadmium, calcium, gold, lead, selenium, silver, sulfur, and tin. Magnesium might have limited resistance to NaK at very low temperatures in view of the rate at which the solubility decreases with decreasing temperature from a reported 1-1/2 to 2% in sodium at 638°C (1180°F) (lower solubility in potassium).⁽⁶⁹⁾

The above evidence is supported by available laboratory test results. Brazing alloys containing large amounts of silver were drastically attacked by NaK at 300°C (572°F).⁽⁸⁶⁾ Copper containing a trace of silver was penetrated throughout by NaK at 760°C (1400°F) (see Page 36). The tin-rich phase of a 10% tin bronze was removed by NaK at 650°C (1202°F) (see Page 38).

Platinum has been reported as being readily attacked by sodium and potassium vapors but there is no evidence of solubility in the liquid metal.⁽⁶⁹⁾ At 600°C (1112°F) NaK drastically attacked platinum leaving a black fibrous mass.⁽⁸⁶⁾ Spectrographic analysis revealed no platinum in the NaK at room temperature.

No phase diagrams of silicon with sodium or potassium were found in the literature; however, laboratory tests conclusively eliminate silicon from consideration as a container for NaK. Silicon specimens were completely dissolved at 600°C (1112°F) and alloyed with the containing vessels (Type 347 stainless steel and Armco iron) forming heavy brittle layers. When tested in a low-carbon steel container at 800°C (1472°F), all the silicon was transferred to the container wall where it was found as a 12% Si-Fe layer of uniform thickness.⁽⁸⁶⁾ The drastic attack on Al-Si eutectic alloy (12 Si) was due to removal of the silicon by the NaK (see Page 42).

49

NON-METALS WITH NaK

m.p. Range -12.3 to 97.9°C (10 to 208°F)

Ceramic Materials with NaK

Ceramics, which, from free energy considerations should be reduced by NaK, are not always attacked; whereas those that should not be reduced are sometimes penetrated, depending on the temperature of exposure to NaK, on the binder in the ceramic, and on various factors contributing to porosity of the ceramic (particle size, firing temperature, etc.). Porous refractory oxides, regardless of their purity or stability of the oxide, are impregnated by NaK and often disintegrate.

Synthetic sapphire (single crystal Al_2O_3) had good resistance to 500°C (932°F) static NaK⁽³⁶⁾ and limited resistance to 600°C (1112°F) flowing NaK.⁽¹⁵²⁾ Alumina (Al_2O_3), fired at 1750°C (3182°F) for 1 hour, had good resistance at 500°C (932°F) whereas high-alumina ceramics such as Haenium, (fired at 1800°C (3272°F) and BG Aluminite, (fired at 1600°C (2912°F)), had good resistance to 243°C (470°F) NaK but disintegrated on exposure to 500°C (932°F) NaK.⁽³⁶⁾

Beryllia (BeO) was unaltered by 500°C (932°F) and 600°C (1112°F) NaK only when very dense and highly vitrified. Otherwise it was impregnated with the liquid metal and often badly distorted on exposure to NaK.^(36, 86)

Magnesia (MgO) was slightly discolored but otherwise not altered by 200°C (392°F) NaK, whereas it was darkened and gained considerable weight due to impregnation with NaK at 600°C (1112°F).⁽⁸⁶⁾

Thoria (ThO_2), zirconia (ZrO_2) with silicate binder, and McDanel refractory porcelain were thoroughly impregnated and completely disintegrated on exposures to NaK at 500°C (932°F) and 600°C (1112°F).^(36, 86)

Glasses with NaK

In a discussion of laboratory handling of sodium,⁽⁷⁸⁾ it is pointed out that "Sodium does not react with glass below 300°C (572°F), and, though Pyrex is rapidly attacked at higher temperatures, some glasses are more resistant or can be made resistant by suitable coatings." Oxides in NaK cause glass to fail at much lower temperatures than otherwise.

Pyrex acquired a light tan hue but was otherwise unaltered by a 3-day exposure to 300°C (572°F) NaK. Pyrex, alkaline resistant glass, and Vycor were etched but resisted NaK in the order listed at 400°C (752°F) and they were drastically attacked at higher temperatures.⁽⁸⁶⁾

50

Cemented Carbides with NaK

The resistance of cemented carbides to attack by NaK appears to be related to the composition of the carbide, rates of weight loss from good to poor at 538°C (1000°F) being reported.⁽¹⁵²⁾ The carbides tested were high in WC with cobalt binder, and some contained varying amounts of TiC and TaC. Weight losses were very high for some of the carbides tested, but not enough information was reported to allow correlation of attack with composition.

Protective Materials with NaK

The protective qualities of certain items of safety equipment when in contact with hot NaK have been studied.⁽⁹⁷⁾ Various materials were exposed to NaK (32 Na) and pure sodium at 150, 350, and 550°C (302, 662, and 1022°F) under controlled conditions, and the materials were rated according to the degree of attack as summarized in Table III. The case-hardened glass lens (chipper's goggles), plain glass lens (welder's goggles), chrome leather, and laminated bakelite (skull protector) gave 100 % protection against NaK and Na at 550°C (1022°F). The rubber (gloves) and * cellulose acetate (face shield and goggles) protect against NaK at 150°C (302°F) and Na at 350°C (662°F), but they do not protect against NaK at the latter temperature. Wool affords slight protection at 150°C (302 °F) but not at higher temperatures, and cotton can only be used momentarily at room temperature.

In some cases the above results indicate that at 350°C (662°F) NaK is more aggressive than Na. This may in part be due to solidification of the higher melting sodium on contact with the material.

Other Non-Metals with NaK

Darkoid (a rubber impregnated asbestos gasket material) is not attacked by NaK at 110°C (230°F) and is used extensively at that temperature.⁽⁶²⁾

Plain asbestos can be used for packing to seal static shafts against NaK at temperatures up to 162°C (324°F) and pressures up to 50 psi but not at 204°C (400°F).⁽¹⁰⁾

Some silicone rubbers were found to retain their flexibility after 96 hours exposure in NaK at 250°C (482°F), whereas others disintegrated or lost all flexibility.⁽³⁶⁾

Teflon (tetrafluoroethylene polymer) was reduced to a black powder by 200°C (392°F) NaK.⁽⁸⁶⁾

---

*Type of acetate not reported but probably cellulose.

51

Table III

PROTECTION EXHIBITED BY MATERIALS WHEN EXPOSED TO
40 ml OF Na OR NaK⁽⁹⁷⁾

MATERIALS	TEMPERATURE (°C)			
	150 NaK	350 Na NaK		550 Na NaK
Case-hardened Glass Lens (Chipper's Goggles)	---	--	---	Exc. Exc.
Plain Glass Lens (Welding Goggles)	---	--	---	Exc. Exc.
Leather (Chrome)	Exc.	Exc.	Exc.	Exc. Exc.
Laminated Bakelite (Skull Protector)	Exc.	Exc.	Exc.	Exc. Exc.
Rubber (Gloves)	Exc.	Exc.	None	None None
Acetate-probably Cellulose (Face Shield and Goggles)	Exc.	Exc.	None	None None
Wool (Cloth)	Fair	None	None	None None
Cotton (Cloth)	None	None	None	None None

7422 45

RESISTANCE OF MATERIALS TO ATTACK BY LITHIUM*

*Degree of Resistance: (See text for discussion of these data)

	GOOD	- consider for long-time use
	LIMITED	- for short-time use only
	POOR	- no structural possibilities
	UNKNOWN	- no data for these temperatures

RESISTANCE OF MATERIALS TO ATTACK BY LITHIUM

Lithium differs in its properties from other alkali metals as it is more like the alkaline-earth metals in its chemical properties. Test results indicate that lithium is more aggressive in its attack on many metals than either sodium or sodium-potassium alloys, although the questionable purity of the lithium used in these tests may make these results somewhat misleading.

Data concerning the attack by molten lithium on solid metals can be expected to be influenced by the amount of contaminants in the lithium and by the nature of these contaminants. Among those commonly occurring (dissolved and mechanically dispersed) in lithium are compounds with lithium of nitrogen, oxygen, chlorine, and hydrogen, and metals such as calcium, aluminum, iron, and silicon. Carbon is also apt to be present. There are, however, no data for quantitative evaluation of the attack by lithium on solid metals as a function of the contamination of lithium by these impurities.

Lithium nitride, which is readily formed by the reaction of nitrogen with liquid or solid lithium,^(19, 23, 109, 120) is a very reactive compound. No metal or ceramic material has been found resistant to attack by molten lithium nitride,^(23, 34, 109, 120) although it has been tested with all the common metals and with their oxides, nitrides, and silicides--as well as with porcelain. Lithium nitride attacks pure iron⁽⁵⁸⁾ at 280°C (536°F), is more effective than lithium in attacking mild steel,^(58, 59, 109) and, although believed deleterious to stainless steel, is less detrimental to stainless steel than it is to mild steel or to iron.^(59, 120, 125) This distinguishes it from lithium, which attacks stainless steel more readily than it attacks iron^(58, 89, 117) or low-carbon steel.⁽¹⁷¹⁾

Oxygen is more often present in lithium as a hydroxide than as an oxide, if the lithium has been exposed in the solid state to air, since traces of moisture in the air promote the oxidation of lithium.^(109, 110) Molten lithium hydroxide is very corrosive,^(89, 109, 117, 125) no refractory nor metal having been found suitable for handling it. On being heated above its melting point, 455°C (851°F), the hydroxide tends to decompose to form the oxide.^(84, 162)

Lithium hydroxide or oxide can combine with or "flux" many refractories,⁽¹⁰⁹⁾ and in this way may either remove protective oxide films from metals or, conversely, add to their thickness. The hydroxide also attacks metals, in particular those which form acidic ions^(34, 109, 110) (probably including ferrates and platinates).

The fact that the free energy of formation of lithium oxide below 900°C (1652°F)⁽¹⁸⁾ does not surpass that of sodium oxide (which, per oxygen atom, is of the same order as that of chromium oxide) makes it difficult to explain thermodynamically the fact that lithium attacks stainless steel more aggressively than does sodium. Lithium at 900°C, however, should reduce any protective oxide films on stainless steel, whereas it is questionable whether sodium can reduce this type of oxide film--particularly at temperatures above 900°C (1652°F). An additional explanation of the effect of lithium is based on the fact that nickel is more soluble in molten lithium than in sodium.

Molten lithium chloride attacks iron and copper.⁽¹²⁵⁾ This compound is rather generally found in commercial lithium, although some lithium is chloride-free.

Lithium hydride, which is apt to be present in molten lithium that has been exposed to moisture or to hydrogen, is reactive with metals and ceramics at high temperatures.^(33, 129)

Lithium has a greater solubility for nickel, in particular, as well as for iron, and probably for chromium than does sodium.⁽¹⁷¹⁾ Lithium also has the property of attacking steels intergranularly^(59, 171) if the temperature is high enough for any attack at all to occur, although it is not known the extent to which this propensity for intergranular attack is due to the presence of contaminants.

Molten lithium, which is the only alkali metal that forms a true carbide, reacts readily with metal carbides,^(109, 110, 125) and, if added as a calcium alloy to molten stainless steel, reacts with impurities in the steel and also causes the intergranular carbide content of the solidified steel to be unusually low. The affinity of lithium for carbides, for carbon, and for impurities in steel probably is related to the tendency of lithium to decarburize metals and to attack steels intergranularly. It has therefore been suggested that a steel that has been decarburized in the molten condition by treatment with lithium (or possibly by other means) would not be subsequently subject to intergranular attack by lithium.⁽²³⁾

Particles of contaminants suspended in the lithium, such as oxides, hydroxides, nitrides, or hydrides, can be removed by filtration. It has been found, however, that a sintered stainless steel filter is attacked by lithium,⁽¹⁷¹⁾ and the resulting high nickel content of the lithium is apt to complicate the evaluation of test results.

The data for the bar chart, page 48, showing the resistance of various materials to attack by lithium were obtained from various sources. In some cases (Argonne National Laboratory, Mine Safety Appliance Company) the lithium used for the tests on which the data are based was

first freed from oil by treatment with petroleum ether, and then passed through a sintered stainless steel filter. In other cases (Aerojet Engineering Corporation) no attempt was made to free the lithium from inorganic contaminants or from traces of protective oil.

Samples of lithium from different ingots have been known to vary somewhat in the percentages of contaminants different batches are reported to contain. One batch (nominally 99+% pure), which was analyzed spectrographically at Argonne National Laboratory, was reported to contain 0.01% of iron, less than 0.01% of boron, and no other metallic impurities in measurable amounts; but the lithium used for the tests at Argonne contained 0.1% calcium, less than 0.1% silicon, and no other metallic impurities in measurable amounts. Although this lithium contained no detectable amount of chloride, lithium obtained from the same producer for use by another organization is reported by them to contain traces of chloride.

The lithium used at Argonne National Laboratory and at Mine Safety Appliance Company was protected during tests by an atmosphere of argon, which had been dried but not otherwise purified. The chief impurity remaining in the argon is believed to be a trace of nitrogen.

At Argonne, the ratio of area of solid test material to volume of liquid lithium, expressed as sq. cm. per cc., was in each case about 5. In the tests at Mine Safety Appliance Company the proportion of lithium was greater.

In spite of widely differing test conditions, data from different sources appear to be in qualitative agreement wherever there is any reasonable basis for comparison. The following indicates the basis upon which each of the materials in the bar chart on page 48 was evaluated for its resistance to attack by molten lithium.

FERROUS METALS WITH LITHIUM

m.p. 186°C (367°F)

Armco Iron with Lithium

Armco iron has good resistance to attack by lithium at temperatures up to 600°C (1112°F).

A micrograph at 500X of a specimen of Armco iron exposed to lithium at 600°C (1112°F) for six days showed no significant attack.⁽¹⁷¹⁾ A slight gain in weight and dimensions is attributable to deposition from solution (the deposit is presumably largely nickel dissolved from a stainless steel filter). Aerojet Engineering Corporation has found iron to be resistant at 426°C (800°F) during repeated short-time exposures.⁽¹³⁵⁾

Molten lithium-aluminum alloy "dissolves" as much as 0.5% of iron by weight from a cast iron container. The high apparent solubility is attributable to the presence of aluminum in the melt.⁽⁶⁶⁾

Stainless Steels with Lithium

Type 347 (18-8, Nb) stainless steel has good resistance to attack by lithium at 538°C (1000°F), and limited resistance at 600°C (1112°F).

There is no change in weight or dimensions to Type 347 stainless steel in lithium at 300°C (572°F) for six days, and no metallographic evidence of intergranular penetration.⁽¹⁷¹⁾ Welds in a Type 347 container (a 2-inch pipe, butt-welded at the bottom) that held lithium at 538°C (1000°F) for 672 hours appeared to be unaffected.⁽⁷⁹⁾ Type 347 specimens in lithium at 600°C (1112°F) for six days gained slightly in weight and dimensions and acquired a reaction or deposition zone about 0.25 mils in depth.⁽¹⁷¹⁾ A 30-gram Type 347 sphere in lithium at 704°C (1300°F) gained 0.9 mg. in 2 hours.⁽⁷⁹⁾ If the weight gains can be attributed to deposition of nickel from the filter, Type 347 stainless steel may actually have good resistance to attack by lithium at 600°C (1112°F).

Straight-chromium stainless steels have good resistance to attack by lithium at 426°C (800°F) and poor resistance at 600°C (1112°F).

There was no change in weight or dimensions of Type 430 steel in lithium at 300°C (572°F) for six days nor any evidence of intergranular attack; but at 600°C (1112°F) there was appreciable gain in weight and dimensions as well as intergranular penetration in six days to a depth of 10 mils.⁽¹⁷¹⁾ Type 416 steel is resistant at 426°C (800°F) on repeated short-time exposure.⁽¹³⁵⁾

57

Timken 16-25-6 (16 Cr-25 Ni-6 Mo) steel is not attacked by lithium at 426°C (800°F) on repeated short-time exposure.⁽¹³⁵⁾

Type 302 (18 Cr-8 Ni) stainless steel has limited resistance to attack by lithium at 300°C (572°F), and poor resistance at 600°C (1112°F).

The apparent solubility of Type 302 stainless steel is 0.024% by weight at 300°C (572°F), and 3.0% at 600°C (1112°F) at which temperature there is slight intergranular penetration.⁽¹⁷¹⁾

Low-Chromium Steel with Lithium

Type 4130 (1 Cr-0.2 Mo) steel has good resistance to attack by lithium at temperatures up to 426°C (800°F) except at welds.

This steel was subjected to repeated short-time exposures at 426°C (800°F). It has been suggested that welds in this steel may give better service with lithium at this temperature if nickel plated,⁽¹³⁵⁾ but tests with pure nickel (see Page 54) indicate that any long-time improvement would probably be slight.

Low-Carbon Steel with Lithium

SAE 1020 (low-carbon) steel has good resistance to attack by lithium at 300°C (572°F), but limited resistance at 600°C (1112°F).

With SAE 1020 steel in lithium at 300°C (572°F) for six days there is no significant change. At 600°C (1112°F) there is incipient intergranular attack. The maximum depth of the attack is about 0.1 mil.⁽¹⁷¹⁾

NON-FERROUS METALS AND ALLOYS WITH LITHIUM

m.p. 186°C (367°F)

Beryllium with Lithium

Beryllium has good resistance to attack by lithium at 600°C (1112°F).

Beryllium in lithium for six days at 600°C (1112°F) was not significantly attacked by lithium itself; but nickel dissolved in the lithium forms a 1 to 2-mil coating on the beryllium consisting principally of a nickel-beryllium compound, NiBe, which was identified micro-chemically, spectrographically, and roentgenographically. This coating, which is loosely adherent, was contaminated by iron (1%) and by traces of several other elements but by only 0.01 to 0.1% of lithium. Although beryllium is not attacked by lithium, itself, at 600°C (1112°F), beryllium in lithium in a stainless steel container is attacked by the nickel that dissolves in the lithium.⁽¹⁷¹⁾

Molybdenum with Lithium

No attack was observed on molybdenum in lithium on repeated short-time exposure at temperatures up to 426°C (800°F).⁽¹³⁵⁾

Nickel and Nickel Alloys with Lithium

Nickel has good resistance to attack by lithium at 225°C (437°F), limited resistance at 300°C (572°F), and poor resistance at higher temperatures.

A nickel specimen heated in lithium at 300°C (572°F) for six days gained slightly in weight, but molten lithium poured from the specimen was found to contain about 0.09% of nickel. A nickel specimen similarly heated at 600°C (1112°F) was intergranularly attacked.⁽¹⁷¹⁾ An "electroformed" nickel lining on a steel vessel was used at temperatures up to 225°C (437°F) for melting lithium. After 50 one-hour exposures the vessel was in good condition.⁽²³⁾

Inconel has good resistance to attack by lithium at 300°C (572°F), and poor resistance at 600°C (1112°F).

At 300°C (572°F) Inconel in lithium for six days does not change significantly in weight or dimensions nor is there indication of intergranular attack. At 600°C (1112°F) the apparent solubility of Inconel in

59

lithium is 2.1% by weight, and there is intergranular penetration and increase of dimensions.⁽¹⁷¹⁾ An Inconel wire in lithium at 704°C (1300°F) parted in less than two hours while being used to hold a 30-gram stainless steel sphere in lithium during a specific-gravity determination.⁽⁷⁹⁾

A Chromel wire had poor resistance to attack by lithium at 704°C (1300°F).

This wire failed under the same conditions as did the Inconel wire.⁽⁷⁹⁾

Monel metal has poor resistance to attack by lithium at 300°C (572°F) as its apparent solubility at that temperature is 18% by weight.⁽¹⁷¹⁾

Copper and Copper Alloys with Lithium

Copper and copper alloys such as aluminum bronze have poor resistance to attack by lithium.

Six-day tests show that the apparent solubility of aluminum bronze in lithium at 300°C (572°F) is extremely high.^(136, 171) Copper dissolves in molten lithium without compound formation.^(120, 125)

Other Metals with Lithium

Aluminum, barium, bismuth, calcium, cadmium, gold,⁽⁹⁹⁾ lead, magnesium, platinum,^(109, 110, 120) silicon, silver,^(109, 110, 120) strontium, thallium, tin, and zinc react with molten lithium to form products of no structural usefulness.⁽¹²⁵⁾

NON-METALS WITH LITHIUM

m.p. 186°C (367°F)

Quartz reportedly has good resistance to lithium (but not to lithium oxide or nitride) at temperatures up to 285°C (545°F) but at higher temperatures reacts to form lithium silicide.^(109, 130) However, attempts to melt most commercial lithium in quartz are apt to result in almost immediate failure of the container.⁽¹⁷¹⁾ Glass has no resistance to attack by lithium at 150°C (302°F), and porcelain and other silicate materials are attacked by molten lithium.^(99, 105, 109, 110, 125, 130) Molten lithium penetrates magnesia, but does not otherwise attack it,^(110, 144) whereas molten lithium attacks most other oxides of structural metals, and also attacks carbides, silicides, rubber, and plastics.^(109, 110) Near its melting point lithium does not attack Dow-Corning silicone fluid D.C. 550.⁽²³⁾

RESISTANCE OF MATERIALS TO ATTACK BY MERCURY*

*Degree of Resistance: (See text for discussion of these data)

- GOOD - consider for long-time use
- LIMITED - for short-time use only
- POOR - no structural possibilities
- UNKNOWN - no data for these temperatures

- - Dynamic mercury "harp" tests and industrial boiler tests
- D - Dynamic mercury "harp" tests
- S - Static mercury tests

RESISTANCE OF MATERIALS TO ATTACK BY MERCURY

Our present knowledge concerning the resistance of engineering materials to attack by mercury at elevated temperatures can be attributed almost entirely to the efforts of A. J. Nerad and his associates in connection with the development of the mercury-vapor turbine by the General Electric Company. They were concerned chiefly with ferrous alloys. In most cases, only equilibrium solubility data are available upon which to judge the resistance of other materials to attack by mercury.

Early short-time experiments near the normal boiling temperature of mercury indicated that iron and steels were practically unaltered by mercury. However, over long periods of operation it was found that the inside tube walls in the cooler zones of large mercury-vapor boilers became plugged with a crystalline deposit, resulting in overheating due to the restriction of mercury circulation. It soon became evident that the mercury was dissolving great quantities of iron in the hot zone and depositing it in the cold zone and that full-scale operation was impossible under these conditions.⁽¹⁴⁶⁾

The laboratory studies which followed were aimed at a practical solution to this specific problem.^(37, 67, 146) Dynamic laboratory tests were carried out in hundreds of so-called "harps" wherein mercury was circulated by thermal convection through the heating of one leg and cooling of the top and other leg of a closed loop of pipe. Most tests were carried out at 649°C (1200°F) and some tests as high as 800°C (1472°F), and the 10°C (18°F) temperature differences which were maintained between the hot and cold zones resulted in very slow flow of the mercury (approximately 0.1 ft/sec).⁽³⁷⁾ In the following discussions where resistance to flowing or dynamic mercury is referred to, it will be understood that the specimens were tested in these "harps."

Studies in these systems were made of the rate of attack by mercury as a function of alloying elements in the steel, of additives to the liquid metal, and of such variables as time and temperature. It was found that some low-alloy steels (i.e. Sicom 5S: 4-6 Cr, 0.45-0.65 Mo, 1-2 Si) had better resistance to attack by mercury than low-carbon steel. However, of even greater importance was the discovery that the controlled addition of certain elements to the mercury (i.e., Ti and Mg) resulted in negligible attack on even low-carbon steel.

63

FERROUS METALS WITH MERCURY

m.p. -38.9°C (-38.0°F)

Mechanism of Attack on Steels by Mercury

Whereas ferrous alloys are practically unaltered by mercury in static systems, they are drastically attacked in dynamic systems where mercury flows very slowly and where even slight temperature gradients exist. In this regard mercury differs from NaK where it was found that ferrous alloys were, in general, not attacked in static or dynamic systems even though relatively high flow velocities and extreme temperature differentials were maintained (see Page 16). This is true in spite of the comparatively higher equilibrium solubility of iron in NaK than in mercury (see Page 19). A theoretical discussion of the differences in the mechanism of attack by mercury and that by NaK has been offered by Epstein (see Page 8 and 20).⁽³⁷⁾

The attack on steels by mercury appears to be largely governed by a solution mechanism whose rate is determined by the rate of diffusion of iron in mercury. Since attainment of equilibrium solubility of iron in the liquid boundary layer is extremely rapid, the rate of attack is determined by the rate of diffusion of the dissolved iron from the solid-liquid interface into the bulk of the liquid.⁽³⁵⁾ The most recent information indicates that the equilibrium solubility of iron in mercury is very low but that an appreciable temperature coefficient of solubility exists--the solubility varies from 0.015 ppm at 25°C (77°F) to 0.96 ppm at 700°C (1292°F).⁽³⁷⁾ Unlike the case for iron in NaK (see Page 19), calculations for dynamic systems, taking the flow rate of mercury into account and assuming that equilibrium solubility is achieved in both the hot and cold zones, give rates of attack on steel that are in good agreement with experimental observations.⁽³⁷⁾

The rate of transfer of iron from the hot to the cold zones is found to be a function of time, temperature gradient and level, rate of flow of mercury, temperature coefficient of solubility of iron in mercury, and geometry of the system. At 500°C (932°F), and above, the rate of attack increases approximately by a factor of five for every 100°C (180°F) rise in the mercury temperature.⁽⁶⁷⁾ For example, the rate of attack (based on weight changes) on low-carbon steel in a "harp" test increased from 5 mpy at 500°C (932°F) to 560 mpy at 800°C (1472°F).⁽³⁷⁾ Available test data for steels that are appreciably attacked by mercury bear out the direct relationship between amount of attack and time. Where steels were only slightly attacked, the time effect was overshadowed by the inaccuracies of the test data.⁽³⁷⁾

The Effect of Alloying Elements in Low-Carbon Steel

A large number of tests were made in an effort to develop low-alloy steels which would resist attack by flowing mercury. Selected test data are given in Table IV. The following discussion is based almost entirely on these data. The steels were prepared in the laboratory by melting portions of a large low-carbon steel billet and adding the desired amounts of alloying elements.

Low-carbon steels have good resistance to attack by flowing mercury below about 400°C (752°F), limited resistance up to about 540°C (1004°F), and poor resistance at higher temperatures.

Averages of a large number of laboratory "harp" tests as well as long-time exposures in operating mercury boilers resulted in weight losses of low-carbon steel specimens equivalent to 4 mpy at 482°C (900°F) and increasing to 53 mpy at 649°C (1200°F).^(37, 146) The low solubility of iron in mercury at 700°C (1292°F), 0.96 ppm, makes it probable that iron would have good resistance to attack by static mercury at these temperatures in systems having no thermal gradients. Only slight attack was noted in one test where low-carbon steel was exposed to static mercury at 550°C (1022°F).⁽³⁷⁾

Alloying elements which, when added in small amounts, make low-carbon steels more resistant to attack by mercury in dynamic systems include chromium, silicon, titanium, and possibly molybdenum, whereas aluminum shows little promise. Various combinations of these elements, in small amounts, especially chromium, silicon, and molybdenum, result in several steels which have good resistance to attack by flowing mercury up to about 600°C (1112°F).

Additions of up to 4% aluminum to low-carbon steel resulted in little if any improvement in its ability to resist attack by flowing mercury. The aluminum is apparently preferentially dissolved from the steel resulting in erratic pitting and scale formation somewhat similar to the type of attack which occurs when aluminum has been purposely added to the mercury (see Page 65). For example, supposedly similar tests of 4%-aluminum steel specimens at 630°C (1166°F) and 650°C (1202°F) resulted in a tenfold greater weight loss at the lower than at the higher temperature.

Chromium, in amounts as low as 0.2 and 0.4%, increased the resistance of low-carbon steel to attack by dynamic mercury by a factor of about six. A 4% chromium addition was much less effective "probably because of the formation of nonadherent chromium oxide films."⁽³⁷⁾ Averages of a

Table IV

DYNAMIC "HARP" TESTS ON FERROUS ALLOYS IN MERCURY

A. J. Nerad, et al., Unpublished G.E. Data (Compiled by L. F. Epstein)⁽³⁷⁾

Material	Major Alloying Elements (wt.%)	Time of Test (Hrs.)	Maximum HARP Temp. (°C)	Rate of Attack (Wt. Change Date) Mg/cm ² /Mo mil/yr	
Low-C Steel (Mild Steel)	~ 0.2 C	**	482	- 7	4
		**	538	-15	9
		**	593	-37	22
		**	649	-88	53
Low-C Steel + Al	• 0.1 Al	162	625	-28	17
	• 0.2 Al	48	650	-18	11
	• 0.5 Al	257	625	-64	40
	• 1 Al	95	620	-52	32
	• 4 Al	113	630	-69	43
	• 4 Al	48	650	- 7	4
Low-C Steel + Cr	• 0.2 Cr	46	650	-13	8
	• 0.5 Cr	138	615	- 7	4
	• 4 Cr	138	625	-23	14
5% Cr Steel	5 Cr	**	482	- 3	2
		**	538	- 7	4
		**	593	-17	10
		**	649	-42	25
Low-C Steel + Mo	• 0.5 Mo	161	670	-86	53
	•20 Mo	64	650	<- 0.5	< 0.3
Low-C Steel + Si	• 1 Si	67	640	- 7	4
	• 2 Si	107	640	-11	7
	• 3 Si	67	640	- 7	4
Low-C Steel + Ti	• 1 Ti	329	620	- 9	6
	• 1 Ti	329	675	-39	24
	• 2 Ti	329	625	- 7	4
	• 2 Ti	329	640	-15	9
Low-C Steel + Al + Cr	• 0.1 Al, 0.1 Cr	136	625	-46	29
	• 0.5 Al, 0.5 Cr	137	630	-37	23
	• 2 Al, 2 Cr	48	620	-44	27
	• 2 Al, 2 Cr	142	650	-13	8
Nitalloy (Not Nitrided)	1.23 Al, 1.49 Cr	165	650	- 7	4
		2	615	6	4
Low-C Steel + Cr + Cu	• 5.7 Cr, 1.2 Cu	161	670	- 8	5
Low-C Steel + Cr + Mo	• 0.5 Cr, 0.5 Mo	140	650	- 6	4
	• 4.5 Cr, 4.5 Mo	140	640	- 6	4
	4.9 Cr, 0.5 Mo	161	670	-86	53
Low-C Steel + Cr + W	5.7 Cr, 1.2 W	100	660	-26	16
Low-C Steel + Mo + Si	*15 Mo, 3 Si	89	655	- 1	0.6
	*20 Mo, 3 Si	88	655	<- 0.5	< 0.3
Low-C Steel + Al + Cr + Mo	• 0.5 Al, 8 Cr, 0.3 Mo	140	640	- 1	0.6
Low-C Steel + Cr + Mo + Si	*44.6 Cr, 0.5 Mo, 1.23 Si	140	640	- 6	4
	4-6 Cr, 0.45-0.65 Mo, 1-2 Si (Sicrom 5 S or Croloy 5 Si)	**	482	- 0.3	0.2
		**	538	- 0.80	0.5
		**	593	- 1.8	1.1
		**	649	- 4	2.5
	• 5.5 Cr, 6.4 Mo, 1.4 Si	280	588	- 0.7	0.4
		982	620	- 0.8	0.5
		111	650	- 0.8	0.5
Low-C Steel + Al + Cr + Mo + Si	• 0.8 Al, 5 Cr, 0.5 Mo, 0.9 Si	450	650	-64	38
Type 304 S. S.	18 Cr, 8 Ni	460	652	-32	20
Type 310 S. S.	25 Cr, 20 Ni	400-500	650	-77	47

*Alloys made in G.E. Laboratory by melting portions of a single low-carbon steel billet and adding desired alloying elements.

**Average of a large number of laboratory tests as well as samples from large-scale boiler operations, exposures of up to 10,000 hours.

large number of "harp" tests as well as long-time exposures in operating mercury boilers resulted in weight losses of a 5%-chromium steel which were half those of low-carbon steel. (37, 146)

The addition of 0.5% molybdenum to low-carbon steel had little if any influence on its ability to resist attack by dynamic mercury, but a 20%-molybdenum addition reduced the attack by mercury at 650°C (1202°F) to a negligible amount.

Additions of 1, 2, and 3% silicon to low-carbon steel were uniformly successful in lowering the rate of attack by flowing mercury at 640°C (1184°F) by about a factor of ten.

Titanium additions of 1 and 2% to low-carbon steel resulted in a four- to fivefold increase in the resistance of the latter to attack by flowing mercury.

The resistance of low-carbon steel to attack by dynamic mercury was somewhat improved by addition of small amounts of aluminum plus chromium; however, in general the benefits were not as great as those derived from chromium additions alone. The best of these alloys was a commercially available Nitralloy (not nitrided, containing 1.23 Al and 1.49 Cr) which had limited resistance to attack by flowing mercury (4 mpy) at 650°C (1202°F), better than a tenfold improvement over ordinary low-carbon steel. The equilibrium solubility of iron from Nitralloy was found to be practically the same as that found when pure iron was exposed to mercury (see Page 59). (102) Other steels were investigated in which the major alloying additions were chromium and one other element - copper, molybdenum, or wolfram. A 5.7 Cr, 1.2 Cu steel and two Cr-Mo steels resisted attack by flowing mercury at least ten times better than did low-carbon steel. However, the Cr, Mo steels were erratic in their behavior in that a third steel of this type had much poorer resistance to attack by mercury. A 5.7 Cr, 1.2 W steel resisted attack by flowing mercury somewhat better than did low-carbon steel, however, its resistance was still poor at 660°C (1220°F) (16 mpy).

Steels containing 15 to 20% molybdenum together with 3% silicon had good resistance to mercury in dynamic "harp" tests, the weight losses being equivalent to 0.6 and less than 0.3 mpy.

Low-alloy steels containing 4-6% chromium, 0.45-0.65% molybdenum, and 1-2% silicon (Sicromo 5 S or Croloy 5 Si) were about 20 times as resistant to attack by flowing mercury as was low-carbon steel over a wide temperature range. (37, 146) Steels of this type are used extensively in mercury boilers because of their good high-temperature properties and resistance to oxidation as well as their resistance to attack by mercury in dynamic systems. Similar steels of higher chromium or higher molybdenum content were found to have even better resistance to attack by mercury and should be considered for use where long-time service is desirable.

67

The high-chromium ferritic stainless steels had good resistance to attack by static mercury at 550°C (1022°F), but these steels were not tested in "harps." The chromium-nickel austenitic stainless steels showed poor resistance to attack by dynamic mercury at 650°C (1202°F). Other high-nickel ferrous alloys, however, resisted attack by static mercury at 550°C (1022°F).

Delhi Tough Steel (18 Cr, 1 Si) showed no evidence of attack and Ascoloy (13 Cr) was only slightly attacked when exposed to static mercury at 550°C (1022°F). Types 304 (18 Cr, 8 Ni) and 310 (25 Cr, 20 Ni) stainless steel lost weight equivalent to 20 and 47 mpy when tested in "harps" at about 650°C (1202°F). The poor resistance of these alloys at these temperatures may possibly be attributable to the appreciable solubility of nickel in mercury at elevated temperatures. However, when other ferrous metals high in nickel were exposed to static mercury, at 550°C (1022°F), they showed no signs of attack. These alloys included Calite A (15 Cr, 35 Ni), Invar (35 Ni), and a 35 Ni, 2 Mn alloy.⁽³⁷⁾

The Effect of Additives to the Mercury on Attack on Ferrous Metals

Attack by mercury on ferrous alloys can be reduced to negligible amounts by the addition of an inhibitor to the mercury, the best of which is titanium. In order to insure good heat transfer and to prevent excessive use of the inhibitor, it is also necessary to add a wetting agent, the best of which is magnesium.*

The results of a series of "harp" tests in which the effect of additives in mercury on the rate of attack on low-carbon steel was studied are summarized in Table V.⁽³⁷⁾ Titanium and zirconium were found to be the best inhibitors with the former preferred since smaller quantities are required. The presence of 10 ppm titanium dissolved in the mercury reduces the rate of attack on ferrous metals at 650°C (1202°F) to an inappreciable value and as little as 1 ppm titanium is similarly effective at 454°C (850°F). About ten times as much zirconium is required to give the same degree of inhibition.⁽³⁷⁾

---

*The Ti-Mg treatment for mercury is covered, for commercial and industrial uses, by General Electric Company, U.S.A. patents 1964592, 1964593, 1964594 (A. J. Nerad - 1934).

Table V

THE EFFECT OF ADDITIVES IN MERCURY ON THE RATE
OF ATTACK ON LOW-CARBON STEEL

A. J. Nerad, et al., Unpublished G.E. Data (Compiled by L. F. Epstein)⁽³⁷⁾

ADDITIVE	TIME (HOURS)	TEMP. (°C)	RATE OF ATTACK*	
			mg/cm ² /mo	mils/yr
None	Testing periods ranging from 40 to 175 hours	482	- 6.5	4
None		649	- 88	53
None		800	- 990	560
0.1% Sn		640	-4200	2590
1% Cu		650	- 360	222
1% Pb		650	- 280	173
10% Pb		700	- 280	173
1% Na		650	- 80	49
0.25% Al		650	- 0.6	0.37
0.25% Cr	--	600	< - 0.5	< 0.3
1% Ni	--	600	< - 0.5	< 0.3
0.0001% Ti	Tests of 100 to 2000 hours	454	< - 0.5	< 0.3
0.001% Ti		538	< - 0.5	< 0.3
0.04% Zr		625	< - 0.5	< 0.3
0.02% Zr		625	- 1	0.66

*There is evidence that the rate of attack does not change appreciably with time.

The theory of inhibition by titanium is not completely understood and has been the subject of considerable speculation. It has been suggested that a titanium-bearing film forms on the steel surfaces which is relatively impermeable to the diffusion of iron atoms. Accordingly, the rate of attainment of the equilibrium solubility in the liquid immediately adjacent to the solid surface is slowed down to the point where the mechanism of attack is limited by this process rather than by the rate of diffusion away from the liquid film.⁽³⁷⁾ There is evidence that such a titanium-bearing film exists and that it is less than 250 Å thick, but the structure of the film is known only to the extent that the titanium is not in the form of the free element.^(37,67) Titanium is added to the mercury as a dry, finely divided powder (may be prewetted) and heated with good agitation or it may be added as titanium hydride which subsequently dissociates on heating and liberates hydrogen.⁽³⁸⁾

69

Chromium or nickel, when added to mercury in considerably larger amounts, 0.25% chromium or 1% nickel, at 600°C (1112°F), also inhibit attack by mercury. Aluminum was intensively studied and found to be effective in only a narrow concentration range. No more nor less than a very definite quantity could be used at any one temperature level with increasing amounts needed as the temperature is increased. At 650°C (1202°F) 0.25% aluminum was very effective in reducing the attack on low-carbon steel. If there is insufficient aluminum dissolved in the mercury at any given temperature, it does not protect; if there is too much, the aluminum deposits out on the steel surfaces forming a coating that has a tendency to build up and pit or flake off.(37)

The presence of 1% copper or lead in mercury made it considerably more aggressive toward low-carbon steel at 650°C (1202°F). As little as 0.1% tin in mercury resulted in very drastic attack under similar conditions. Sodium had little or no effect as an inhibitor (however, see discussion of wetting at the bottom of this page).

In addition to an inhibitor it was found desirable to have a wetting agent present in the mercury. Its function is twofold; to reduce oxides on steel surfaces so that wetting and optimum heat transfer may be realized and to react with the free oxygen, nitrogen, and water vapor in the mercury in order to keep the inhibitor active. Wetting agents must, therefore, have a greater affinity for oxygen and nitrogen than both the inhibitor material (titanium) and iron.

The alkaline earths, especially magnesium and calcium, have been found to be very effective wetting agents and do not have any deleterious effects. Magnesium is preferred on the basis of low cost and higher solubility in mercury. Approximately 20 ppm magnesium is required at 650°C (1202°F) to effectively tie up free oxygen thereby allowing titanium to remain active as an inhibitor. The magnesium is added to mercury as bar metal and reduces iron oxides resulting in very rapid wetting of steel surfaces. The proper amount of magnesium must be carefully maintained since air leaks cause it to be gradually used up. The resulting MgO forms a film on the walls of the system which has pronounced thermal insulating properties thereby reducing heat transfer. This property of the film is used to advantage in industrial applications to indicate when replenishment of the magnesium is necessary.(37, 67)

The alkali metals, especially sodium, are less satisfactory as wetting agents. They tend to form compounds such as $\text{Na}_2\text{O} \cdot \text{Fe}_2\text{O}_3$ which are both insoluble in mercury and resistant to reduction. This material tends to plug up openings in dynamic systems and can be very troublesome.(37, 67)

70

NON-FERROUS METALS WITH MERCURYm.p. -38.9°C (-38.0°F)

The dearth of experimental evidence that is available makes it difficult to judge non-ferrous metals as containing materials for mercury at elevated temperatures. The only metals tested in dynamic "harp" systems were molybdenum, wolfram, and Stellite. Several metals have been tested in static mercury, but the results are only qualitative and may be misleading if used as a basis for the design of dynamic systems. Solubility data, much of it at room temperature only, are also available; however, experience regarding mercury attack on ferrous metals indicates that these data are probably of limited usefulness to the designer of an engineering system.

Sufficient experimental evidence is available to indicate that wolfram, molybdenum, chromium and beryllium can be considered for long-time use as containers for mercury at elevated temperatures.

No significant attack on wolfram occurred upon exposure to mercury at $600-625^{\circ}\text{C}$ ($1112-1157^{\circ}\text{F}$) for 5-1/2 days in a mercury "harp," and a static test in mercury at its normal boiling point, 357°C (675°F), gave similar results.⁽³⁷⁾ The solubility of wolfram in mercury is reported as 0.1 ppm at 25°C (77°F).⁽⁶⁹⁾

Molybdenum has somewhat less resistance to attack by mercury than has wolfram. Molybdenum showed a weight loss equivalent to 2 mpy when tested in a mercury "harp" for 2 days in the range $590-650^{\circ}\text{C}$ ($1094-1202^{\circ}\text{F}$). No significant attack occurred on exposure to static boiling mercury at 550°C (1022°F).⁽³⁷⁾ The solubility of molybdenum in mercury is reported as 0.2 ppm at 25°C (77°F).⁽⁶⁹⁾ Vacuum distillation of mercury from amalgams with molybdenum has been described.⁽⁶⁹⁾

Static tests of chromium in mercury at 550°C (1022°F) resulted in no observable attack.⁽³⁷⁾ The solubility of chromium in mercury is reported to be a maximum of 0.5 ppm at 25°C (77°F).⁽⁶⁹⁾

Beryllium is reported to be unaffected or, at most, only superficially amalgamated when exposed to mercury up to its normal boiling temperature.^(20,104,133,138) After exposure for 330 hours at 316°C (600°F), no attack on or amalgamation with beryllium by mercury was noted. Under similar conditions, but with the test vessel open to the atmosphere (air), a slight attack on the beryllium was noted, which was attributed to the mercury; and the specimen was coated with a white powdery substance (probably BeO).⁽¹³⁸⁾ The solubility of beryllium in mercury has been estimated as increasing

uniformly from 0.01 ppm at 100°C (212°F) to 0.4 ppm at 800°C (1472°F).⁽³⁷⁾

Although the available information is very meager, there is reason to believe that the following elements might resist attack by mercury at elevated temperatures: tantalum, niobium, silicon, titanium, and vanadium.

Attempts to amalgamate tantalum and niobium with mercury have been unsuccessful.⁽⁶⁹⁾ Based on theoretical considerations, tantalum and niobium have been suggested for use as containers for mercury at elevated temperatures. (See Page 13).⁽²¹⁾

There is disagreement concerning attack on silicon by mercury. A reaction both at room temperature and at elevated temperatures has been reported by one investigator;⁽⁶⁹⁾ however, another investigator observed no reaction up to the normal boiling point of mercury, 357°C (675°F).⁽³⁷⁾ It has been suggested that the reported reaction of mercury with silicon may actually have been a reaction between their oxides if the system were contaminated with oxygen.⁽³⁷⁾

Reported solubilities for titanium and vanadium at 25°C (77°F) are 0.11 and 0.5 ppm respectively.⁽⁶⁹⁾ Unpublished data indicates low solubility of titanium in mercury at elevated temperatures.⁽³⁷⁾

The following metals sometimes can be used to contain mercury at low temperatures, but they have limited resistance to attack by mercury at elevated temperatures: nickel, Inconel, and Monel, copper and copper-base brazing alloys, cobalt and Stellite, platinum, manganese, and zirconium.

Nickel, copper, and their alloys (i.e. Monel-70 Ni, 30 Cu) have been recommended for use with mercury at "moderate temperatures."^(107,109,156) However, even at room temperature they should be in an annealed condition in order to avoid embrittling intercrystalline penetration.^(107,156) In 15-day exposures to mercury at about 400°C (752°F), amalgamation of nickel, copper, and Monel was noted.^(107,156) In static tests at 550°C (1022°F), one investigator found that pure copper was only slightly attacked by static mercury after a 24-hour exposure at 400°C (752°F). Thus, the reported high solubility of copper in mercury⁽⁶⁹⁾ appears to be in error. Much lower solubilities are indicated by unpublished data.⁽³⁷⁾ The latter investigator's data also shows solubilities for nickel in mercury that are lower than those for copper.

Attack on Inconel (79.5 Ni, 13 Cr, 6.5 Fe) by mercury is reported as ten times greater than that on low-carbon steel.⁽³⁷⁾ Treatment of the mercury with titanium and magnesium (see Page 63) improves this situation.

In boiling mercury at 357°C (675°F) the following copper-base brazing alloys resisted attack in the order given: Cu-Ni, Cu-Ni-Fe, Cu, Cu-Fe, Cu-Ni-Cr, Cu-Mn, Cu-Cr, Cu-Cr-Fe.⁽³⁷⁾

Cobalt was darkened when exposed to static mercury at 550°C (1022°F), but attack appeared to be slight.⁽³⁷⁾ The best figure for the solubility of cobalt in mercury at 25°C (77°F) taken from several reported values appears to be about 0.06%.⁽⁶⁹⁾ The poor resistance exhibited by Stellite (Co, Cr, W) when exposed to flowing mercury in a "harp" at 600°C (1112°F) (weight loss equivalent to 86 mpy)⁽³⁷⁾ is probably attributable to the high cobalt content.

Amalgams of platinum with mercury have been described by a number of investigators; however, no quantitative data have been published.⁽⁶⁹⁾ One investigator states that mercury does not amalgamate with platinum except in the presence of tin, zinc, copper sulfate, or acids.⁽¹⁰⁴⁾ Unpublished data indicate relatively low solubility at the normal boiling point of mercury.⁽³⁷⁾

Manganese formed a pasty amalgam with static mercury at 550°C (1022°F).⁽³⁷⁾ Its solubility at room temperature has been reported as approximately 30 ppm.⁽⁶⁹⁾

Zirconium (Bureau of Mines) formed a distinct amalgam layer on exposure to static mercury for 330 hours at 316°C (600°F).⁽¹³⁸⁾ The equilibrium solubility of zirconium in mercury has been found to vary from 5 ppm at 350°C (662°F) to 16 ppm at 550°C (1022°F).⁽³⁷⁾

Several elements are relatively soluble in mercury including aluminum, bismuth, cadmium, cerium, gold, lead, magnesium, silver, tin, and zinc.^(2,69,103,104,107,109,156)

Alloys containing appreciable amounts of these elements, especially in the free state, are not recommended for use with mercury. For example, silver solder (Ag, Cu, Zn) was drastically attacked on exposure to mercury for 24 hours at 400°C (752°F).⁽³⁷⁾

NON-METALS WITH MERCURY

m.p. -38.9°C (-38.0°F)

In the laboratory, mercury is ordinarily handled in glass. From free energy considerations⁽⁷⁸⁾ it is evident that ceramic materials can be expected to withstand attack by mercury. The negligible solubility of carbon in mercury at its normal boiling point⁽⁶⁹⁾ indicates that graphite might also be used as a containing material.

73

RESISTANCE OF MATERIALS TO ATTACK BY LEAD, BISMUTH, EUTECTIC
BISMUTH-LEAD ALLOY, AND EUTECTIC BISMUTH-LEAD-TIN ALLOY.*

LEAD*

BISMUTH*

EUTECTIC BISMUTH-LEAD ALLOY*

EUTECTIC BISMUTH-LEAD-TIN ALLOY*

* Degree of Resistance: (See text for discussion of these data)

- GOOD - consider for long-time use
- LIMITED - for short-time use only
- POOR - no structural possibilities
- UNKNOWN - no data for these temperatures

7428 67

RESISTANCE OF MATERIALS TO ATTACK BY LEAD, BY BISMUTH,
AND BY ALLOYS OF LEAD AND BISMUTH

Tests with lead, with bismuth, and with binary and ternary bismuth-lead alloys can have quantitative meaning only to the extent that the purity of the liquid metal and of the test material can be determined, to the extent that the test conditions can be controlled and reproduced, and to the extent that the degree of attack can be suitably measured and evaluated. Many of the tests that have been carried out with these metals have been difficult to interpret even qualitatively because conformance with the requirements mentioned has rarely been satisfactory.

General considerations applying to tests that have been made with lead will be considered first. Oxygen and particularly antimony⁽¹⁵⁴⁾ (as well as arsenic, tin, and zinc) are among the impurities in commercial lead believed to be detrimental in their action on steel, iron, and certain other structural metals, but experiments to date have not been controlled in such a way as to give sufficient quantitative information on the effects of contaminants. Obtaining such information hinges on the development of satisfactory methods of determining the oxygen content of lead, and this is a problem that needs further study.⁽¹¹⁾

The nominal purity of a certain grade of lead does not always correspond with that found on analysis, and the purity is apt to change, one way or another, during the course of an experiment. In some tests a molten salt covering on a melt was the only protection against contamination by air--even when the melt was stirred.⁽¹⁵⁴⁾ Here the concentration of oxygen present as entrained gas and dispersed oxides far exceeds the saturation value, which is 0.0025% oxygen at 650°C (1202°F) and probably about 0.002% near the melting point.⁽¹³⁾ Even when considerable vigilance was employed, perhaps involving the use of commercial argon or helium, several laboratories have observed dross or evidence of oxidation at the conclusion of tests in which the inert gas was used as a protective blanket for lead alloys. This indicates contamination of the inert gas or, perhaps, some undetected fault in apparatus or technique. It has been observed that a lead alloy in a stainless steel container simultaneously increased in purity with respect to iron, magnesium, calcium, and silicon (perhaps by sludge formation in connection with selective oxidation and other reactions) while it decreased in purity with respect to nickel, which it dissolved from the container.⁽⁶⁴⁾ At Argonne National Laboratory specimens have been tested with lead in evacuated quartz containers. While this method prevents increased contamination by the external atmosphere and prevents metallic contamination from the walls of the container, it is probably unsuitable (above a certain limiting temperature) for the testing in lead of metals, such as zirconium, that are more oxygen-avid than silicon. Even when less oxygen-avid metals are tested in

75

quartz, the possibility of forming protective silicate films should be explored, and also any volatilization of components that are gettered by the quartz. The latter reaction appears to take place in an evacuated system but not always in a sealed system containing argon⁽¹⁶⁷⁾--at least not to the same extent.

To date the methods that have been used to determine the degree of attack--even assuming that the amount of contamination is known and controlled--are not unimpeachable. When it is desired to determine dimensional changes and weight losses or gains of a specimen in lead, a correction should be made for any solubility of the base metal in the selective solvent used to remove the lead or for any loss of base metal involved in the mechanical separation of the lead. The lead itself should be sampled for analysis at temperature and with due regard for contamination and for segregation on cooling. In many cases filtration during sampling may be necessary.

Data obtained with these precautions are still incomplete unless it is known, usually through metallographic examination, that no alloying attack or intergranular penetration has taken place. In this connection it has been reported that lead or bismuth in heavily attacked materials may be identified by an electrolytic ammonium-acetate etch.^(143C) Micro spot tests for lead, tin, and bismuth also seem feasible.

Minor variations in the composition and structure of the materials tested are important. For example, the miscibility and alloying reaction of pure iron with pure lead are probably insignificant (the solubility of iron in lead at 1528°C (2782°F) is 0.0003% by weight,⁽⁶⁹⁾ but inclusions and intergranular deposits (notably carbides) are often readily attacked by lead⁽¹⁵⁴⁾ or bismuth, by lead-bismuth alloys, and by some of their contaminants. Pit-type attack has been observed in a steel having sulfide inclusions⁽¹⁶⁷⁾ (perhaps through the mechanism of lead sulfide, sulfite, or sulfate formation) and has been observed (but to a limited degree) in a steel having spheroidized carbides.⁽⁶⁴⁾ Pit-type attack also has occurred when intergranular attack has resulted in the removal of entire grains. Intergranular iron cementite is relatively susceptible to attack, iron-chromium cementite has exhibited better resistance, and niobium perhaps improves this resistance up to a certain temperature. Observations that large-grain steel is in general less resistant to attack by lead alloys than fine-grain steel⁽⁴⁰⁾ and that welds are particularly susceptible to attack^(143B,167) are probably related to the susceptibility of intergranular contaminants to attack as well as to the prevalence of large grains and intergranular contaminants in cast and insufficiently hot-worked steel, and to the likelihood that the continuity of the network of intergranular contaminants is impaired by the production of fine grains by hot working.

More information is needed on the effects of stresses, electrical effects, wetting, and film formation in their relationship to attack by lead

and lead alloys. A molten bismuth-lead alloy treated with hydrogen and maintained in a helium atmosphere was found to wet carbon steel but not Types 347 and 316 stainless steels at 538°C (1000°F),⁽⁶⁴⁾ whereas wetting under semi-oxidizing conditions (a bath protected only by powdered carbon) was incomplete with all unstressed steels. Stressing specimens beyond a critical value appears to promote wetting and intergranular surface attack, perhaps by destroying the continuity of a protective film. The seemingly anomalous condition is also indicated in which an environment can favor the formation of a film that is protective against transgranular attack, but which also can promote intergranular attack. There is evidence (see page 100) that the maintenance of an electrical potential between a solid and a liquid metal, made possible by the presence of a separating film, influences the degree of attack. The role played by films and scale in systems heated by passage of an electric current through the systems, themselves, should be clarified before attempts are made to interpret broadly the results obtained with such systems.

The foregoing comments on lead and lead alloys apply, in general to bismuth except that bismuth is believed to act as tin (though much less aggressively) in forming a reaction product with iron, attacking it most readily above the austenite transformation temperature.⁽⁶⁴⁾

Tests have been carried out in which bismuth that had been heated with a particular metal in an evacuated quartz container was prepared for analysis by melting the bath after quenching, causing a substantial amount of bath metal to flow away from the solid specimen.⁽⁸³⁾ Because of the possibility of liquation and segregation during this melting, it is difficult to estimate the accuracy of these results.

Preliminary investigations of the attack on structural metals by bismuth-lead eutectic alloy were conducted at Battelle Memorial Institute by means of short-time tests. In these tests⁽¹⁶⁾ specimens of known section were immersed a measured distance into a bismuth-lead (eutectic alloy) bath contained in a pot and protected somewhat against oxidation by a layer of graphite powder. (It has been shown that this procedure does not afford complete protection against oxidation.)⁽⁶⁴⁾ After the system was maintained at temperature for one hour, the specimens were withdrawn and the bath frozen. Samples from the top and bottom of the ingot were analyzed, the average of the resulting values for the concentration of elements dissolved from the specimen was computed, and from this the average amount of attack per unit area was calculated. Some of the specimens were examined metallographically.

Several different types of static tests conducted with bismuth and lead alloys at Argonne National Laboratory are described on pages 74, 91, and 96. Also bismuth-lead alloy and bismuth-lead-tin were circulated at this laboratory for extended periods in heat-transfer studies.

77

The method of heating utilized the self-resistance of a portion of the system to the passage of electric current. A number of different metals were present in the same system. A certain amount of dross was found in the melt despite the use of an argon atmosphere, and scale developed in varying thicknesses on the outside of one of the resistance tubes. These observations, plus several doubtful features of fabrication, introduce so many questions that attack data based on this heat-transfer system cannot be readily extended to general interpretation.

Since an important purpose of studying the attack of bismuth-lead alloy is to determine its effect on the physical properties of structural materials, Stanford University and the University of California at Berkeley employed stress-rupture tests of structural materials in the liquid alloy.

The initial stress-rupture studies at Berkeley used a 3-inch layer of refined carbon (with an ash content of 0.3%) on the surface of the molten bath.⁽¹²⁾ The eutectic alloy was heated electrically by tubular Calrod immersion heaters. Later, use was made of a 4-inch thick surface layer of carbon with an ash content of less than 0.15%. After three months of operation, lead oxide, PbO, was observed, indicating that the carbon blanket had not served its function well enough.

There was no general evidence of carburization or decarburization of AISI-C1021 steel at 538°C (1000°F) after 805 hours. Carbon on the surface of the bath (in a Type 347 stainless steel container) therefore did not cause carburization of the specimen. Use of helium at the surface of the bath, instead of carbon, did not significantly affect the stress-rupture relations for AISI stainless steel Types 316 and 347.

Helium was used instead of carbon for protecting the bath in the stress-rupture tests at Stanford. (In special tests no attack was found in partially immersed specimens at the helium-liquid alloy interface.) Control stress tests in helium were regularly conducted for otherwise identical tests in bismuth-lead alloy.

In the construction of the bar chart for resistance to attack by bismuth-lead alloy, the data obtained from the stress-rupture tests at Stanford and Berkeley were given more weight than differing data from other tests.

Most of the tests with eutectic bismuth-lead-tin alloy were conducted at Argonne National Laboratory,⁽¹⁶⁷⁾ and the material before remelting had approximately the following per cent composition: 50.3 Bi, 29.8 Pb, 18.3 Sn, 0.01 Fe, 0.05 Mg (possibly as MgO), 0.01 Ca (possibly as CaO), 0.005 each of Ti and Zr (introduced with the Mg and present possibly as oxides), 0.005 Zn, and less than 0.01 of any other metal. That used in the dynamic test formed a dross despite an attempt to maintain an argon atmosphere.

Analysis of the dross indicated oxidation of tin, lead, and bismuth in that order of preference.

The alloy for the vacuum-sealed static tests at Argonne was prepared by heating the initial alloy in an outgassed vacuum system and vacuum-casting into a Pyrex tube which did not appear to be wet by this alloy. Portions from the middle of the casting were used, and were obviously of higher purity than the original material. The alloy used in several other static tests at Argonne was not specially prepared, and is believed to have had the same initial oxygen content as that of the alloy used for the dynamic test.

The quartz containers for the standard vacuum-sealed test specimens were "necked-in" in the middle so that the liquified metal, which was added as a solid, could flow through this portion on inverting the container, but so that the solid specimen itself could not pass. On being heated for the required period of time in a constant-temperature bath (with the specimens and alloy in the lower portion), the containers were inverted without removal from the bath. This permitted the liquid metal to be decanted away from the specimens at temperature. As the entire decantate was used in the analysis, there were no errors due to segregation. The specimens were run in duplicate but in separate containers. One of each pair was examined metallographically, and the other was examined for changes in weight and dimensions, after removal of traces of adhering alloy with due consideration to the possible loss of base metal in the selective solvent.

The question has arisen as to whether tin remains corrosive when added to a bismuth-lead alloy. In a study of the dissolution of copper and iron in alloys of lead with antimony (and in other metals) it was established that the presence of an inert metal did not change the value of the interaction between the active components but merely slowed the reaction.⁽⁴⁰⁾ It therefore seems reasonable that tin should remain corrosive to most metals even when added to bismuth-lead alloy. Evidence of this is given in the data for attack on aluminum (see Page 100).

The general procedures and considerations just outlined for lead, bismuth, and their alloys should be kept in mind when evaluating specific data. The data in the following sections (on static tests with lead, bismuth, bismuth-lead, and bismuth-lead-tin) constitute the basis for the chart on the resistance of materials to attack by the liquid metals just mentioned (see Page 69). It should be evident that most of the data are merely suitable for screening out metals that are obviously lacking in resistance to attack by these liquid metals, and are not suitable for use in designing dynamic systems.

79

FERROUS METALS WITH LEAD

m.p. 327°C (621°F)

Carbon Steel with Lead

Steel containing up to 0.51% of carbon has good resistance to attack by lead at temperatures up to 600°C (1112°F) and limited resistance at 1000°C (1832°F).

A specimen of steel (0.51 carbon, 0.08 Si, 0.48 Mn, 0.046 P, and 0.058 S) on exposure to lead at 600°C (1112°F) lost weight at a rate corresponding to 0.144 mpy.^(114,134)

A specimen of SAE 1020 steel vacuum-sealed with lead in a quartz container and heated at 1000°C (1832°F) for 17 days dissolved to the extent of 0.021 grams per 100 grams of lead. This corresponds to a calculated penetration of 3.12 mpy. Metallographic examination indicated additional penetration of about 0.5 mils.

Iron with Lead

Iron has good resistance to attack by lead at 600°C (1112°F) and poor resistance at 1000°C (1832°F).

Data for the attack on iron by lead, whether under static or dynamic conditions, are conflicting. Studies indicate that contamination in one form or another is responsible for most of this disagreement.

Pure iron is reported to have a solubility in lead at 327°C (621°F) to 1528°C (2782°F) of 0.0002 to 0.0003%, respectively,⁽¹¹⁴⁾ and, in the absence of alloying reaction, should therefore have good resistance to attack by lead in this entire temperature range. In tests carried out at 600°C (1112°F) iron was reported^(114,134) not to be attacked. In a 17-day test at 1000°C (1832°F), however, an Armco iron specimen, originally vacuum-sealed with lead in a quartz tube (1 sq. cm. Fe to 2 cc. of Pb) appeared to be intergranularly attacked to a depth of 1.5 mils,⁽¹⁶⁷⁾ and had lost weight and dimensions corresponding to 10 mpy. This result needs confirmation because cracking of the quartz tube (it is not known whether it occurred before or after the lead had frozen) may have admitted enough air to accelerate the attack.

At 500°C (932°F) Armco iron was only partially wetted by lead under a salt cover, but at 600°C (1112°F) wetting was complete. At 750°C (1382°F) in lead + 8% antimony (which was more aggressive than pure lead in these

tests) the iron decreased 2.4 mils in radius when statically tested, and 100 mils in radius when rotated at about one surface foot per second.⁽¹⁵⁴⁾ The increased attack in the dynamic test can be attributed largely to the entraining of air into the system.

The dynamic test specimen had a 0.3 mil reaction zone and a carburized zone adjoining. As the attack progressed after the solution had become saturated with carbon, at least some of the carbon at the reaction boundary apparently escaped oxidation by migrating inward into the metal instead of entering the bath.⁽¹⁵⁴⁾

Mild-Chromium Steel with Lead

Chromium steel has good resistance to attack by lead at temperatures up to 600°C (1112°F).

Chromium steel in lead at 600°C (1112°F) loses weight at a rate corresponding to 0.0034 mils per year.⁽¹¹⁴⁾

Stainless Steels with Lead

Straight high-chromium stainless steels have good resistance to attack by lead at temperatures up to about 600°C (1112°F) and limited resistance at 1000°C (1832°F).

Although published data indicate that molten lead (near 327°C or 621°F) attacks Type 410 and Type 430 stainless steels at a rate of 120 to 420 mpy,⁽¹¹⁴⁾ it is believed that these high rates may have been caused by the presence of oxygen. Lead-bismuth alloy in a helium atmosphere (see Page 88) does not attack straight-chromium stainless steel at 538°C (1000°F),^(143D) and lead at 1000°C (1832°F) in an evacuated Vycor container (9-day test) removes the metal at a calculated rate of 18 mpy. There is, however, at the higher temperature intergranular penetration to a depth of 4 or 5 mils.⁽¹⁶⁷⁾

Sicromal 12 high-chromium steel, which contains some aluminum and silicon, rotated in lead at 750°C (1382°F) under a salt flux for 2 1/2 days (therefore in an oxidizing environment) had a 30-mil intergranular reaction zone and was decarburized in the adjoining area. The attack was stronger than in the case of a lower chromium (Sicromal 6) steel, and the material attacked is presumably "(Cr,Fe)₄C in the grain boundaries."⁽¹⁵⁴⁾

Type 347 (18-8 Nb) stainless steel has good resistance to attack by lead at 538°C (1000°F) and poor resistance at 1000°C (1832°F).

81

Type 347 stainless steel has good resistance to attack by Bi-Pb alloy at 538°C (1000°F) (see Page 89), and should be even more resistant to attack by lead. Lead in an evacuated quartz container (9-day test) at 1000°C (1832°F) removes metal at a calculated rate of 26 mpy and tends to penetrate Type 347 steel intergranularly.⁽¹⁶⁷⁾

Chromium-nickel (18-8 Type) stainless steel has poor resistance to attack by lead at 600°C (1112°F), and good resistance at 327°C (621°F).

Although 18-8 Type stainless steel has exhibited good resistance to lead under certain conditions, it has also exhibited poor resistance at the same temperature under different conditions. More information is needed on the controlling factors. The above estimates are therefore subject to revision when data become available that are based on more closely controlled conditions.

A specimen of V2A steel (Krupp 18-8 stainless) in lead at 600°C (1112°F) lost weight at a rate corresponding to 41 mpy, and Type 302 steel, which is similar, is reportedly attacked by molten lead at about 327°C (621°F) at a calculated rate of 120 to 420 mpy; but the effect of oxygen contamination was not considered in reporting these results. Other tests with Type 302 stainless steel indicate that the rate of attack is only 0.35 to 3.4 mpy,⁽¹¹⁴⁾ depending on conditions, and a test at 1000°C (1832°F) in an evacuated quartz container indicates a weight loss corresponding to 32 mpy, after the lead had been removed with nitric acid. There is also evidence of extensive intergranular penetration at that temperature,⁽¹⁶⁷⁾ and the steel becomes strongly ferromagnetic.

Type 316 (18-8 Mo) stainless steel is reported to be attacked by molten lead at the rate of 120 to 420 mpy.⁽¹¹⁴⁾ Because experimental conditions in the various tests were not comparable, these data do not permit conclusions to be drawn as to the effect of molybdenum in 18-8 Type stainless steel.

Cast Iron with Lead

Gray cast iron has good resistance to attack by lead at 500°C (932°F) and poor resistance at 1000°C (1832°F).

At 500°C (932°F) neither graphite nor steel is attacked by lead except under oxidizing conditions, but both are attacked at 1000°C (1832°F) (see Pages 75 and 83). Gray cast iron vacuum-sealed with lead in a quartz container for 17 days at 1000°C (1832°F) was disintegrated principally through replacement of the graphite by lead,⁽¹⁶⁷⁾ and also by solution of a small amount of ferrite.

Gray cast iron rotated at a rate of one surface foot per second in lead under a salt bath at 750°C (1382°F) for 36 hours had an intergranular reaction zone 7 mils in depth and had lost 2 mils on the radius.⁽¹⁵⁴⁾ Air entrained in the system was undoubtedly a factor in promoting this high rate of attack.

NON-FERROUS METALS WITH LEAD

m.p. 327°C (621°F)

Tantalum with Lead

Tantalum has good resistance to attack by lead at 1000°C (1832°F).

A specimen of tantalum vacuum-sealed with lead (1.1 cc of lead per sq. cm. of tantalum) in a quartz container for 9 days at 1000°C (1832°F) lost weight corresponding to an average penetration of 0.02 mils per month. It gained 0.1 mil on the radius.⁽¹⁶⁷⁾

Metallographic examination revealed no intergranular penetration and slight--almost insignificant--transgranular reaction and solution attack.

Niobium with Lead

Niobium has good resistance to attack by lead at 1000°C (1832°F).

A specimen of niobium vacuum-sealed in a quartz container with lead (2 cc. of lead per sq. cm. of niobium) for 17 days at 1000°C (1832°F) gained slightly in weight and only 0.1 mil in thickness. The gain in thickness corresponds to the gain in weight. It is therefore assumed that solution attack is negligible.

Metallographic observation indicates a reaction zone or lead deposit several tenths of a mil in thickness, but no intergranular attack.⁽¹⁶⁷⁾

Beryllium with Lead

Beryllium has good resistance to attack by lead at 500°C (932°F) and probably at 1000°C (1832°F).

A specimen of beryllium was scratch-brushed and then soaked five hours in lead at 1000°C (1832°F). Subsequent chemical analysis indicated the lead to contain less than 0.01% of beryllium.⁽¹⁶⁾ In another test beryllium was "recovered intact" after having been heated in lead at 700°C (1292°F) for 24 hours.⁽¹¹⁶⁾ The good resistance exhibited by beryllium to lead-bismuth at 1000°C (1832°F), either electrodeposited onto the alloy or immersed in the scratch-brushed condition (see Page 94), and the absence of attack on exposure for one month at 500°C (932°F) to eutectic Bi-Pb-Sn alloy (see Page 99) are further confirmation of the good resistance of beryllium to attack by lead.

While the specimen tested at 500°C (932°F) was examined metallographically, as well as in other ways, the reports do not indicate whether the specimens tested at the higher temperatures were so examined. On the basis of solubility and general appearance beryllium is assumed to have good resistance at 1000°C (1832°F). Although there is no contrary evidence, the assumed good resistance of beryllium to attack at temperatures higher than 500°C (932°F) is subject to confirmation by metallographic examination.

Chromium with Lead

Chromium has limited resistance to attack by lead at 1000°C (1832°F).

Chromium with lead vacuum-sealed in a Vycor container (17-day test) and heated at 1000°C (1832°F) had an apparent solubility in lead of 0.054% and had a weight loss corresponding approximately to 1 to 2 mils per month. The possibility is not excluded that this weight loss occurred through reaction of the chromium with the glass, which was soft at that temperature.⁽¹⁶⁷⁾

Chromium in lead has insignificant⁽⁶⁹⁾ solubility at 327°C (621°F), and a solubility of 15% at 1470°C (2678°F). The chromium used in determining the solubility contained 0.32% Si and 1.20% Fe.

Chromium plate was removed from the base metal by drops of lead in air at 760°C (1400°F).^(143B)

Molybdenum with Lead

A specimen of molybdenum in lead (2 cc of lead per sq. cm. of Mo) vacuum-sealed in a quartz tube and heated for 9 days at 1000°C (1832°F) appeared to be substantially intact at the end of the test, but no confirmatory examination was made.⁽¹⁶⁷⁾ More evidence is needed.

Zirconium with Lead

Specimens of Bureau of Mines zirconium (which is contaminated with substantial amounts of magnesium and carbon), in lead at 1000°C (1832°F) for five days had zones about one mil in thickness--presumably formed by reaction of the lead with impurities in the zirconium, since zirconium crystals extended into the reaction zone without evidence of being attacked and since zirconium from which the impurities had been partially distilled had a thinner zone.⁽¹⁶⁷⁾ It is possible that pure zirconium would have exhibited good resistance at the temperature of the test.

Titanium with Lead

Titanium has poor resistance to attack by lead at 1000°C (1832°F).

Titanium vacuum-sealed with lead (2 cc of lead to 100 sq. cm. of titanium) in a quartz container at 1000°C (1832°F) for 17 days lost weight and dimensions corresponding to about 360 mpy.⁽¹⁶⁷⁾ The moderate resistance of impure titanium to Bi-Pb-Sn alloy (see Page 100) at 500°C (932°F) suggests that pure titanium may have good resistance at that temperature to lead alone (as well as to bismuth-lead and bismuth-lead-tin alloys). More evidence is needed.

Aluminum with Lead

Aluminum has good resistance to attack by lead at 350°C (662°F).

Aluminum of 99.5% purity is not attacked by lead at 350°C (662°F), but lead oxide causes the aluminum to be attacked.^(114,134) Aluminum and lead are immiscible⁽⁶⁹⁾ in the temperature range of 327°C to 658°C (621°F to 1216°F).

Nickel and Nickel Alloys with Lead

Nickel has poor resistance to attack by lead at the melting point of lead, 327°C (621°F).

The solubility of nickel in lead is 0.195% by weight at 327°C (621°F), and 7% at 1340°C (2444°F).⁽⁶⁹⁾ Nickel is not recommended as a container for molten lead.^(114,134)

Monel metal has poor resistance to attack by lead at the melting point of lead, 327°C (621°F).

Monel metal at 360°C (680°F) is attacked by lead at a calculated rate of 36 mpy,^(107,114) and is not recommended as a container for molten lead.

Inconel-type alloys have limited resistance to attack by lead at 600°C (1112°F) and poor resistance at 1000°C (1832°F).

A 60% nickel alloy containing 15% Cr and about 25% Fe is attacked by lead at 600°C (1112°F) at the rate of 0.38 mpy,^(114,134) and a similar alloy containing 66% Ni and 20% Cr is recommended by some for use at temperatures up to 815°C (1500°F) but is not recommended by others.^(107,114)

Alloys containing 80% Ni and 14-20% Cr, 37% Ni and 17% Cr (bal. Fe), and 25 %Cr and 12 % Ni have also been recommended for use with molten lead.

A specimen of Inconel (13 Cr, 6.5 Fe) vacuum-sealed with lead in a quartz container and heated for nine days at 1000°C (1832°F) was severely intergranularly attacked, and gained in weight and dimensions. In this test there were 20 grams of lead per square centimeter of Inconel surface.⁽¹⁶⁷⁾

Hastelloy C has poor resistance to attack by lead at 871°C (1600°F) because of severe alloying attack.^(143D)

Platinum and Platinum Alloys with Lead

Platinum has poor resistance to attack by lead above 290°C (554°F), which is the eutectic temperature.⁽⁶⁹⁾

Platinum alloys used in spark plugs are attacked at the grain boundaries by molten lead provided stresses, applied or internal, are present.⁽⁵⁴⁾ The orientation of the grains parallel to the surface is reported to be necessary for best resistance in wolfram-bearing platinum alloys.

Other Metals with Lead

On the basis of phase diagrams^(69,80) structural materials containing appreciable amounts of copper, wolfram, tin, zinc, and manganese probably should not be used to contain molten lead. The solubility of copper in lead at the eutectic temperature 326°C (619°F) is 0.06% by weight, and at 500°C is of the order of 1%. At higher temperatures molten lead has a slight solubility in solid copper (0.02 to 0.05% Pb).

The solubility of manganese in lead, as indicated by the phase diagram, is very slight at 327°C (621°F), about 1% by weight at 400°C (752°F), and 12% at 1200°C (2192°F).

According to one investigator wolfram is not attacked by molten lead, but another indicates that wolfram has very poor resistance to attack by molten lead even at temperatures near the melting point of lead.⁽⁶⁹⁾

87

NON-METALS WITH LEAD

m.p. 327°C (621°F)

Ceramic Materials with Lead

Most refractory oxides and silicates have good resistance to attack by lead.^(114,134) Sintered beryllia is resistant to attack by lead even at 1000°C (1832°F).⁽¹⁶⁷⁾ Carbides, at least those of an intergranular type, are attacked by lead melts;⁽¹⁵⁴⁾ but in this case the presence of contaminants may be an important factor. Porcelain holders were not attacked by lead at 850°C (1562°F) in an oxidizing environment.⁽¹⁵⁴⁾

Quartz with Lead

Quartz has been satisfactorily used as a container for lead at 1000°C (1832°F) for a period of 9 days. In some cases the lead adheres to the quartz on freezing, causing breakage.⁽¹⁶⁷⁾ Quartz is recommended for general use with molten lead.^(114,134)

Glass with Lead

Glass is unattacked by pure lead at temperatures near the lead melting point, 327°C (621°F).

Carbon with Lead

Carbon (including graphite) has poor resistance to attack by lead at 1000°C (1832°F), but good resistance at 500°C (932°F).

The solubility of carbon in lead⁽⁶⁹⁾ is 0.024 % by weight at 1170°C (2138°F) and presumably is somewhat more than 0.01% at 1000°C (1832°F). When cast iron was heated with lead at 1000°C (1832°F) in an evacuated quartz container (see Page 77) the graphite in the cast iron was completely removed.

When cast iron was heated with bismuth-lead-tin (see Page 97) at 500°C (932°F), the graphite was not attacked; but at a lower temperature in the presence of oxides the graphite was attacked.

FERROUS METALS WITH BISMUTH

m.p. 271.3°C (520.3°F)

Iron and Steel with Bismuth

Ferritic iron and plain steel of low carbon content have good resistance to attack by bismuth up to their transformation temperatures (about 700°C or 1292°F).

Unstressed specimens tested with bismuth under argon show that the reaction zone on SAE 1025 steel at 760°C (1400°F) resembles the reaction zone formed when iron or steel is attacked by tin. At 704°C (1300°F) there was apparent lack of attack by Bi-Pb alloy (see Page 91)(143D) and therefore presumably by bismuth.

A roughly quantitative test indicates the solubility of iron in bismuth to be 0.003% at 482°C (900°F), 0.027% at 732°C (1350°F), and 0.069% at 1010°C (1850°F).(83) Because of the method of sampling there is some question as to the accuracy of these results. Other results indicate the solubility of iron in bismuth at 400°C (752°F) to 1600°C (2912°F) to be 0.0002% to 0.0004%, respectively, by weight.(69) Iron is reported to dissolve 0.081% of bismuth, presumably at a temperature near the melting point of the iron.

89

NON-FERROUS METALS WITH BISMUTH

m.p. 271.3°C (520.3°F)

Molybdenum with Bismuth

Molybdenum has good resistance to attack by bismuth at temperatures up to 1010°C (1850°F).

A roughly quantitative test indicates that the solubility of molybdenum in bismuth is less than 0.011 % by weight at 1010°C (1850°F). Data are needed on the diffusion of bismuth into molybdenum and on the tendency of the two metals to react.⁽⁸³⁾

Chromium with Bismuth

Chromium has good resistance to attack by bismuth at 732°C (1350°F) and limited resistance at 1010°C (1850°F).

A roughly quantitative test indicates that the solubility of chromium in bismuth is less than 0.001% at 482°C (900°F), is 0.0036% at 732°C (1350°F), and 0.065% at 1010°C (1850°F).⁽⁸³⁾ Others have reported chromium to be "insoluble" in bismuth at temperatures up to 1553°C (2827°F),^(69,83) and the phase diagram indicates that the solubility of bismuth in solid chromium is negligible.

Beryllium with Bismuth

Beryllium has good resistance to attack by bismuth at 500°C (932°F) and probably at 1000°C (1832°F).

A specimen of beryllium was scratch-brushed and then soaked 5 hours in bismuth at 1000°C (1832°F).⁽¹⁶⁾ Subsequent chemical analysis indicated the bismuth to contain less than 0.01% of beryllium. In another test beryllium was "recovered intact" after having been heated in bismuth at 700°C (1292°F) for 24 hours.⁽¹¹⁶⁾ For further evidence of resistance, see the data on bismuth-lead (Page 94) and bismuth-lead-tin (Page 99).

Niobium with Bismuth

Niobium has good resistance to attack by bismuth at 482°C (900°F), and limited resistance in the range of 732°C (1350°F) to 1010°C (1850°F).

A roughly quantitative test indicates that the solubility of niobium in bismuth is 0.0024% at 482°C (900°F), 0.0125% at 732°C (1350°F), and 0.0175% at 1010°C (1850°F).⁽⁸³⁾

Data are needed on the tendency of bismuth to react with or diffuse into niobium.

Aluminum with Bismuth

Aluminum has good resistance to attack by bismuth at 300°C (572°F), and poor resistance at 500°C (932°F).

Work with 99.9% aluminum indicates it to have insignificant solubility in bismuth at 274°C (525°F) and a solubility of 1.5% at 656°C (1213°F).⁽⁶⁹⁾ Aluminum of 99.5% purity has been recommended for use with bismuth at the melting point of the latter.^(114,134) The solubility at 300°C (572°F), based on the phase diagram,⁽⁶⁹⁾ is less than 0.01%.

Nickel and High-Nickel Alloys with Bismuth

Nickel and high-nickel alloys have poor resistance to attack by bismuth at temperatures above 271°C (520°F), the melting point of bismuth.

Nickel, even unstressed, is severely attacked by molten bismuth.^(143A) The solubility of nickel in bismuth is 4% at 469°C (876°F), 6.5% at 655°C (1211°F), and 11.78% by weight at 732°C (1350°F). The compound NiBi₃ forms at 437°C (819°F).⁽¹⁶⁰⁾

Hastelloy C and Inconel are subject to alloying attack by bismuth at 650°C (1202°F).^(143B) Neither Monel metal nor Inconel is recommended for resistance to attack by molten bismuth.⁽¹¹⁴⁾

Other Metals with Bismuth

Phase diagrams indicate that copper, manganese, magnesium, zinc, platinum, and tin form respective eutectics with bismuth at 270.3°C (519°F), 268°C (514°F), 260°C (500°F), 254.5°C (492°F), 266°C (511°F), and 139°C (282°F), with corresponding solubilities of 0.2%, 0.6%, 0.54%, 2.7%, 1.0%, and 42% by weight. Structural metals containing appreciable amounts of these elements probably should not be used to contain molten bismuth.⁽⁶⁹⁾

91

NON-METALS WITH BISMUTH

m.p. 271.3°C (520.3°F)

Quartz with Bismuth

Bismuth of ordinary purity can be held for several days in quartz containers at temperatures in the range of 500°C (932°F) to 1000°C (1832°F) but the bismuth tends to wet the quartz and to break it by expansion on freezing.⁽¹⁶⁷⁾

Vycor with Bismuth

Vycor glass appears to be a satisfactory container for bismuth at temperatures up to 900°C (1652°F).⁽⁸³⁾

Carbon with Bismuth

The solubility of carbon in bismuth⁽⁶⁹⁾ is 0.012% by weight at 1385°C (2525°F), 0.017% at 1408°C (2566°F), and presumably is considerably less than 0.01% at 1000°C (1832°F). Graphite crucibles usually last for several days only, when used at temperatures up to 1000°C (1832°F) to contain bismuth exposed to the atmosphere.⁽¹⁶⁷⁾ If the bismuth freezes, the graphite container in many cases will break.

FERROUS METALS WITH EUTECTIC Bi-Pb ALLOY (55.5Bi-44.5Pb)

m.p. 125°C (257°F)

Stainless Steels with Eutectic Bi-Pb Alloy

Type 430 and other straight-chromium stainless steels have good resistance to attack by eutectic Bi-Pb alloy at 538°C (1000°F), and limited resistance at 1000°C (1832°F).

A 0.025-inch thick specimen of 18% Cr steel sheet exposed for one hour to eutectic Bi-Pb alloy (initially containing 0.003% Fe) at 500°C (932°F) exhibited no appreciable solubility when the oxide film was initially intact and about 0.01% solubility of iron plus an average of 0.007% of chromium in the solution for a specimen that was cleaned and fluxed. Another specimen similarly treated at 1000°C (1832°F) exhibited only 0.02% of iron in the solution and 0.01% of chromium.⁽¹⁶⁾ There was, however, in this case evidence of intergranular attack.

A specimen of 0.08% carbon 12% chromium steel containing 0.1 to 0.3% of aluminum had negligible attack and no reduction in stress-rupture life after a 1500-hour exposure to Bi-Pb alloy in a stress-rupture test at 538°C (1000°F).⁽⁶⁴⁾

The conditions for all these tests were semi-oxidizing, as only powdered carbon was used to protect the bath against oxidation.

Type 310 (25 Cr-20 Ni) stainless steel has good resistance to attack by eutectic Bi-Pb alloy at 538°C (1000°F).

When stressed in the range of 56,000 to 44,700 psi (causing rupture in 100 to 1000 hours), Type 310 stainless steel in Bi-Pb alloy at 538°C (1000°F) showed surface cracks (generally of an intergranular nature) near the fracture that on the average extended to a depth of 8 mils. When stressed at 21,730 psi (well within the secondary creep range) for 865.9 hours a longitudinal section showed neither significant evidence of surface attack nor changes in structure. Intergranular surface cracks occurring at the higher stresses can be attributed to a mechanical process associated with the third stage of creep or to a stress-corrosion type of reaction associated with grain boundaries. For a given time before rupture this steel could be stressed more in Bi-Pb alloy at 538°C (1000°F) than it could in air at the same temperature.⁽⁶⁴⁾

Type 347 (18-8 Nb) stainless steel has limited resistance to attack by eutectic Bi-Pb alloy at 648°C (1200°F) if a freshly machined surface is exposed, and good resistance at 538°C (1000°F) if a flame-oxidized surface is exposed.

Micro-examinations of specimens of Type 347 stainless steel that had been immersed in Bi-Pb alloy at 538°C (1000°F) for 100 hours show a flame-oxidized specimen to have been unaffected, and a freshly machined specimen to have undergone substantial attack.^(143C)

At 648°C (1200°F) and 20,000 psi stress in Bi-Pb alloy under argon a Type 347 stainless steel specimen, after 1606 hours, had a general reaction zone 1.5 to 2 mils in depth. Intercrystalline penetration is apt to occur at temperatures above 538°C (1000°F).^(143C)

When stressed in the range of 57,300 psi to 53,700 psi (causing rupture in 100 to 1000 hours), Type 347 stainless steel in Bi-Pb alloy at 538°C (1000°F) showed surface cracks (generally of an intergranular nature) near the fracture that on the average extended to a depth of 3 mils. The time of exposure did not seem to be a factor.⁽⁶⁴⁾ The possibility therefore exists that Type 347 stainless steel, even with oxide-free surfaces, may have good resistance to attack by Bi-Pb alloy at temperatures up to 538°C (1000°F) if the metal is not so highly stressed. Confirming data are needed. From the standpoint of stress-rupture life in Bi-Pb alloy, Type 347 stainless steel is outstanding among the metals tested.

Type 316 (16 Cr-13 Ni-3 Mo) stainless steel has limited resistance to attack by eutectic Bi-Pb alloy at 538°C (1000°F), and good resistance at 232°C (450°F).

After exposure in a Bi-Pb alloy bath, which was frozen and reheated twice per week, Type 316 stainless steel had not changed in weight and appeared unattacked after a total of 1300 hrs. in the bath at 232°C (450°F).⁽²⁹⁾

A specimen of Type 316 stainless steel had a shallow reaction zone after 500-hour exposure to the Bi-Pb alloy in helium, although there was no reduction in stress-rupture life.^(143D) This steel was not wetted under semi-oxidizing conditions (that is, with powdered carbon on the surface of the bath), but the reduced section of a tensile test bar was completely wetted by hydrogen-treated alloy in a helium atmosphere.⁽⁶⁴⁾ This suggests that a protective film on the reduced section is broken by stressing (so as to make wetting possible), but is healed in a semi-oxidizing environment (so as to prevent wetting).

When stressed in the range of 65,000 psi to 45,200 psi (causing rupture in 100 to 1000 hours), Type 316 stainless steel in Bi-Pb alloy at 538°C (1000°F) showed surface cracks (generally of an intergranular nature)

near the fracture that on an average extended to a depth of 2 mils.⁽⁶⁴⁾ There is no real evidence that the surface fissuring is due to attack by the Bi-Pb alloy, and the possibility exists that, as in the case of Type 310 stainless steel, intergranular surface cracks are attributable in substantial measure to stresses that exceed those associated with second-stage creep. If this is true, Type 316 stainless steel may actually have good resistance to attack by Bi-Pb alloy at 538°C (1000°F).

Type 302 and similar (18 Cr-8 Ni austenitic) stainless steels have good resistance to attack by eutectic Bi-Pb alloy at 232°C (450°F), limited resistance at 570°C (1058°F), and poor resistance at 1000°C (1832°F).

A specimen of Type 304 stainless steel in a Bi-Pb alloy bath, which was frozen and reheated twice per week, had not changed in weight and appeared unattacked after a total exposure time of 1300 hours at 232°C (450°F).⁽²⁹⁾

Although 18-8 Type stainless steel with oxide film intact is not attacked by Bi-Pb alloy on exposure for one hour at 500°C (932°F), it is attacked -- dissolving enough metal to yield a concentration of 0.026% Fe (about 0.003% Fe was initially in the melt, 0.011% Ni, and 0.005% Cr) -- if the solid metal has been cleaned and fluxed before the test.⁽¹⁶⁾

When the stainless steel was heated in Bi-Pb alloy at a nominal temperature of 570°C (1058°F) for one week under semi-oxidizing conditions, a reaction layer about two mils in thickness is formed.⁽¹⁶⁷⁾

At 1000°C (1832°F) the cleaned and fluxed stainless steel is intergranularly attacked on similar exposure to the alloy for 1 hour.⁽¹⁶⁾

Type 330 (16 Cr-36 Ni) stainless steel has poor resistance to attack by eutectic Bi-Pb alloy at 538°C (1000°F).

Six specimens of Type 330 stainless steel in helium at 538°C (1000°F) were stressed at 35,500 psi, and six similar specimens in Bi-Pb eutectic were similarly stressed at the same temperature.^(143C) The average life of the specimens in helium was 1637 hours, that of the specimens in Bi-Pb alloy was 1150 hours. These results offer conclusive evidence that Type 330 stainless steel is unsatisfactory in the stressed condition.

Although the visible reaction zone after 1500 hours at 538°C (1000°F) was six mils in depth, calculations based on chemical analysis indicate penetration of lead and bismuth to a depth of over 10 mils. Besides penetration of the solid metal by the liquid, there is evidence of removal of solid metal by solution in the liquid alloy (or by spalling). Nickel was removed to a much greater extent than either chromium or iron. At 981°C (1800°F) the reaction zone was 60 mils after only 46 hours.^(143C)

Low-Carbon Steel with Eutectic Bi-Pb Alloy

Mild steel has good resistance to attack by eutectic Bi-Pb alloy under non-oxidizing conditions at temperatures up to at least 500°C (932°F), and up to the transformation temperature--roughly 700°C (1292°F)--if the carbide structure is spheroidized.

One of the largest manufacturers of lead kettles believes that ferrite remains unaffected by lead and lead-bismuth alloy while cementite is attacked, and recommends Carnegie Illinois Locomotive Firebox Steel (A.S.T.M. SA-30) with 0.12 maximum carbon percentage. Attacks at welds are eliminated by grinding and stress relief. Sharp corners causing stress concentration are avoided. Steel pots for lead alloys have lasted ten years or more. They slowly stretch out of shape without cracking.^(143B)

Mild steel exposed to Bi-Pb alloy for a total time of 1300 hours at 232°C (450°F), with the bath frozen and reheated twice per week, did not change in weight or appear to have been attacked.⁽²⁹⁾

A mild steel container (SAE 1020), approximately ten inches long and four inches ID, somewhat more than half-filled with eutectic Bi-Pb alloy covered with powdered carbon was welded air-tight and placed on its side in a furnace at 500°C (932°F), where it was heated for one month. The only oxygen in the system was thus limited to any oxide film or scale initially on the mild steel surface, any dross initially dispersed in the melt, and the carbon monoxide atmosphere. A polished section of the mild steel did not exhibit any surface reaction. The surface was uneven only to the degree that might be expected on unpolished steel with a normally oxidized surface (that has been subsequently reduced).⁽¹⁶⁷⁾ When the container was rotated 180° on its long axis the liquid did not adhere to the solid.

AISI-C1021 steel in Bi-Pb alloy under carbon exposed to air (semi-oxidizing conditions) could be given a higher stress for a given time before rupture than it could in air at the same temperature, 538°C (1000°F). Although a slight solubility of this steel was observed, the limited degree of attack indicates good resistance. When stressed in Bi-Pb alloy at 538°C (1000°F) so that failure occurred in 95.6 hours, the steel exhibited surface attack to a depth of two mils in a region near the fracture. A similar specimen, stressed so that failure occurred in 805 hours, showed surface attack to a depth of 5 mils. The surface attack resembled that obtained during the third stage of creep and, since only partial wetting had occurred during the stress-rupture test, is not definitely ascribable to the presence of the liquid metal.⁽⁶⁴⁾

At 704°C (1300°F) helium-protected Bi-Pb alloy containing a mild-steel (SAE 1025) specimen with a spheroidized carbide structure apparently

did not attack the specimen during a 250-hour exposure.^(143D) Since at the slightly higher temperature of 760°C (1400°F) the metal is attacked, it is reasonable to assume that austenite forming above the critical temperature, which is 719°C (1330°F) for this steel, is more susceptible to attack than the ferrite structure. Indications of depletion of carbides near the outer edge of the steel also suggest the possibility of oxidation and decarburization by gases dissolved in the molten metal.

In the absence of oxygen in the atmosphere, a small amount of litharge added to a lead bath (in a stainless steel container) did not cause evidence of oxidation of iron (or nickel) at 538°C (1000°F), nor did the small partial pressure of oxygen occurring in commercial helium--although such a pressure will cause oxidation of chromium. It is therefore probable that a critical amount of oxide or pressure of oxygen is necessary for conditions to favor the accelerated oxidation mechanism of attack on iron or steel. Indications are that no base metal can resist this type of attack when conditions favor it.^(143B)

With Armco iron and Bi-Pb alloy, pit-type attack was observed in a dynamic system in a specimen that had been heated electrically by its own resistance (see Page 73) for 1000 hours at an apparent temperature of 550°C (1022°F) at the hot end of the tube. The uncertainties and complexities of the test conditions preclude general application of this result.

Chrome-Molybdenum Steel with Eutectic Bi-Pb Alloy

Chrome-molybdenum steel has good resistance to attack by eutectic Bi-Pb alloy at 538°C (1000°F).

Steels containing 2-1/2 to at least 5% chromium, 0.50 to 1.10% Mo, and up to 1.54% Si (Sicromo 2-1/2 to 5) showed no evidence of surface attack after 1634-hours exposure in Bi-Pb alloy at 538°C (1000°F) in a helium atmosphere, and no reduction in stress-rupture life on stressed exposure for 1000 hours.^(143D)

A specimen of Timken 17-22A (1.25 Cr, 0.5 Mo, 0.25 V, 0.57 Mn, 0.63 Si, 0.46 C, 0.018 P, 0.027 S) steel, that had been heat-treated so as to have a spheroidized structure, was pitted to a depth of 1 mil when stressed in Bi-Pb alloy at 538°C (1000°F) so that failure occurred in 115 hours. A similar specimen was pitted and fissured to a depth of 3 mils when stressed in Bi-Pb alloy so that failure occurred in 693 hours. The Bi-Pb bath for these specimens was covered with powdered carbon.⁽⁶⁴⁾

It is of interest that this steel, which has a spheroidized carbide structure, was subjected to pit-type attack instead of the intergranular attack observed with other steels. Partial wetting of this steel was observed.

It may be noteworthy that slight attack occurred under semi-oxidizing conditions (bath protected by powdered carbon), but did not occur in a bath protected by a helium atmosphere.

Cast Iron with Bi-Pb Alloy

Cast iron pots used for melting lead and lead-bismuth alloys usually fail by cracking after about a year of service.^(143B) They are not considered as satisfactory as steel containers.

96

NON-FERROUS METALS WITH EUTECTIC Bi-Pb ALLOY (55.5 Bi - 44.5 Pb)

m.p. 125°C (257°F)

Beryllium with Eutectic Bi-Pb Alloy

Beryllium has good resistance to attack by eutectic Bi-Pb alloy at temperatures up to 700°C (1292°F), and has limited resistance at 1000°C (1832°F).

In two tests⁽¹⁶⁾ beryllium was scratch-brushed and heated for 5 and 6 hours, respectively, in Bi-Pb alloy at 1000°C (1832°F). The percentages of beryllium by weight found in the melt by analysis were 0.01 and 0.02, respectively. A specimen of beryllium electrolytically deposited on Bi-Pb eutectic alloy was heated at 1000°C (1832°F) for one hour and then cooled to 500°C (932°F) and held at that temperature for 2-1/2 hours. The entire melt, which was presumably saturated or supersaturated by this treatment, was then found to contain less than 0.01% of beryllium. The good resistance to attack exhibited by the electro-deposited beryllium at 500°C (932°F) after prior heating at 1000°C (1832°F) suggests that the presence of an oxide film on the beryllium is unessential to good resistance to attack.

In another test⁽¹¹⁶⁾ beryllium was "recovered intact" after having been heated in lead and in bismuth, respectively, for 24 hours at 700°C (1292°F). On Page 99 it is shown that beryllium also has good resistance to the ordinarily more aggressive Bi-Pb-Sn alloy when tested at 500°C (932°F).

Aluminum with Eutectic Bi-Pb Alloy

Commercially pure (2S) aluminum has good resistance to attack by eutectic Bi-Pb alloy at 300°C (572°F) and limited resistance at 500°C (932°F).

The average solubility of 2S aluminum in Bi-Pb alloy at 300°C (572°F) is 0.004% by weight, and at 500°C (932°F) is 0.037%, as determined by immersing a flux-treated 3/8" diameter rod into a graphite-protected melt for one hour.⁽¹⁶⁾ The oxide film normally present on aluminum retards or reduces the attack. (The Bi-Pb alloy used for this test contained 0.003% of iron.)

A Bi-Pb ingot, frozen after similar exposure to aluminum at 500°C (932°F), contained 0.006% of aluminum at the bottom and 0.067% of aluminum at the top. The aluminum contents were determined by chemical analysis.

22

A 17-ST aluminum specimen on similar exposure at 500°C (932°F) introduced 0.009% of aluminum into the bottom of the melt and 0.060% of aluminum into the top.

A specimen of 2S aluminum was not affected in weight or appearance by a total of 1300 hours of exposure to Bi-Pb alloy at 232°C (450°F). In this test the alloy bath was frozen and reheated twice per week.⁽²⁹⁾

Nickel, Copper, and Their Alloys with Bi-Pb Alloy

Hastelloy C, Monel metal, and Inconel were severely attacked by eutectic Bi-Pb alloy in tests in which specimens in the unstressed condition were heated in the liquid metal at 538°C (1000°F).^(143B)

Nickel is severely attacked, even in the unstressed condition, by molten Bi-Pb alloy.^(143A)

Copper and phosphor bronze were severely attacked, 70-30 brass was pitted, but the Hastelloys A, B, and C, and 10% aluminum bronze were apparently unaffected on exposure for 1300 hours to Bi-Pb alloy at 232°C (450°F). In this test the bath was frozen and reheated twice per week.⁽²⁹⁾ A restrained U-shaped welded specimen of Hastelloy B, however, was cracked adjacent to the weld.

Other Metals with Eutectic Bi-Pb Alloy

Pure manganese is severely attacked, even in the unstressed condition, by molten Bi-Pb alloy.^(143A) See Pages 82 and 86 for its solubility in lead and bismuth, respectively.

Wolfram electrodes used in flow-metering eutectic Bi-Pb alloy became fouled, probably by abstracting oxygen from the melt.⁽¹⁴¹⁾

NON-METALS WITH EUTECTIC Bi-Pb ALLOY (55.5Bi-44.5Pb)

m.p. 125°C (257°F)

Glass tubing had apparently good resistance to attack by Bi-Pb alloy at 219°C (426°F) to 240°C (464°F) under dynamic conditions, but had poor resistance to the impact of the circulating fluid.⁽¹⁴¹⁾

166FERROUS METALS WITH EUTECTIC Bi-Pb-Sn ALLOY (52 Bi-32 Pb-16 Sn)

m.p. 97°C (207°F)

Armco Iron with Eutectic Bi-Pb-Sn Alloy

Armco iron has limited resistance to attack by eutectic Bi-Pb-Sn alloy at 500°C (932°F).

Armco iron specimens vacuum-sealed in a bath of Bi-Pb-Sn eutectic alloy (quartz container) were heated at approximately 500°C (932°F) for 30 days and 80 days, respectively. The surface-volume ratio was 1 sq. cm. of specimen surface to 2.5 cc of liquid alloy. The surrounding of some of the outer grains by a reaction zone was evidence of intergranular attack (such as is characteristic of Bi and Pb), but these grains and other surface grains also appeared to have been attacked transgranularly (presumably by the tin). The rate of penetration over the 80-day period was approximately 2.4 mpy. The liquid alloy decanted at temperature from the specimen still contained less than 0.01% of iron (spectrographic analysis), which indicates no significant solubility of iron.⁽¹⁶⁷⁾

A specimen of Armco iron heated in Bi-Pb-Sn alloy in the presence of air for 16 days at 500°C (932°F) had a reaction zone 5 mils in depth. Calculations taking into consideration increases in dimensions show that an increase in the rate of penetration of the order of ten-fold can therefore be attributed to the presence of air at the surface of the melt. It also is apparent that the rate of alloying attack decreases with time.

Mild-Carbon Steel with Eutectic Bi-Pb-Sn Alloy

Mild carbon steel has limited resistance to attack by Bi-Pb-Sn alloy at 500°C (932°F).

A specimen of SAE 1020 steel vacuum-sealed in a bath of Bi-Pb-Sn eutectic alloy (quartz container) was heated at approximately 500°C (932°F) for 80 days. The surface-volume ratio was 1 sq. cm. of specimen surface to 2.5 cc of liquid alloy. The attack was slightly more intergranular than with Armco iron, but was also transgranular. There was a 1-mil reaction zone, and there was a zone of carbon depletion and grain growth in the solid next to the reaction zone.⁽¹⁶⁷⁾

In another static test a 7/8" ID 4-inch tube of low-carbon steel was three-quarters filled with eutectic Bi-Pb-Sn alloy, plugged, welded around the plug, and heated in the neighborhood of 570°C (1058°F) for seven days. No attempt was made to remove air or to prevent oxidation during welding. The specimen was penetrated transgranularly and unevenly to a depth of

101

one to two mils.⁽¹⁶⁷⁾ The increase in the rate of attack attributable to the presence of air was of the order of ten-fold.

Mention should also be made of a free-machining high-sulphur steel tube in a dynamic heat-transfer system which failed as a result of pitting after 1000 hours of contact with Bi-Pb-Sn alloy at a maximum temperature of 400°C (752°F). As this tube was fabricated from larger diameter bar stock by drilling and machining, and was heated by passing a current through it, the results of this test do not enable one to predict the resistance to attack of drawn (low-carbon) steel tubing heated by some other means in an oxygen-free and sulphur-free system.⁽¹⁶⁷⁾

Cast Iron with Eutectic Bi-Pb-Sn Alloy

Cast iron has limited resistance to attack by eutectic Bi-Pb-Sn alloy at temperatures up to 500°C (932°F).

A specimen of gray cast iron vacuum-sealed in a quartz container with 2 cc of lead per sq. cm of iron surface was heated for one month with eutectic Bi-Pb-Sn alloy at 500°C (932°F), and was found to have been penetrated by a transgranular reaction zone to a depth of one mil.⁽¹⁶⁷⁾ The graphite was not appreciably attacked. Liquid alloy decanted from the specimen at temperature contained 0.0025% of iron as determined by chemical analysis.

A gray iron pump casting, which had been used to circulate Bi-Pb-Sn alloy at 120°C (248°F) to 250°C (482°F) for six days, was broken by expansion of the alloy on attempting to melt it after it had frozen. The presence of dross indicated that there had been leakage of air into the system. Under these oxidizing conditions the reaction zone was some 3 mils (15 times the rate of attack in a relatively oxide-free system), and the graphite near the surface was extensively replaced.

Stainless Steel with Eutectic Bi-Pb-Sn Alloy

Stainless steel has poor resistance to attack by eutectic Bi-Pb-Sn alloy at 500°C (932°F), and limited resistance at 300°C (572°F) to 450°C (842°F).

Austenitic (18-8 Type) stainless steel has been statically tested with eutectic Bi-Pb-Sn alloy for one week (under semi-oxidizing conditions) at about 570°C (1058°F) and for 16 days (under oxidizing conditions) at about 500°C (932°F). Reaction zones 2 mils and 3 mils, respectively, in depth were formed.⁽¹⁶⁷⁾ Some of the eutectic alloy from the first test was sampled after freezing and found by spectrographic analysis to contain less than 0.01% each of nickel, chromium, and iron. The analysis may have been in error because of segregation in the melt.

A niobium-bearing chromium-nickel stainless steel tube of 3/32" wall thickness failed in use with Bi-Pb alloy as part of a dynamic heat-exchange system shortly after it had been used for 1000 hours with Bi-Pb-Sn alloy at a nominal temperature of 300°C (572°F). Although most of the inner surface was unaffected, the tube failed by local penetration at a weld. It is not known whether the attack was initiated at a cold shut, inclusion in the weld, or at the boundary of a large columnar crystal.

103

NON-FERROUS METALS WITH EUTECTIC
Bi-Pb-Sn ALLOY (52 Bi-32 Pb-16 Sn)

m.p. 97°C (207°F)

Wolfram with Eutectic Bi-Pb-Sn Alloy

It can be tentatively assumed that wolfram is resistant to attack by eutectic Bi-Pb-Sn alloy at temperatures up to 550°C (1022°F).

A thin wolfram wire that was immersed in eutectic Bi-Pb-Sn alloy for 20 hours at 550°C (1022°F) to 630°C (1166°F) was removed intact and appeared to be unaffected.⁽¹⁶⁷⁾ This test is not conclusive as there is some evidence that pure lead will attack wolfram at these temperatures. (See Page 82.)

Beryllium with Eutectic Bi-Pb-Sn Alloy

Beryllium has good resistance to attack by eutectic Bi-Pb-Sn alloy at 500°C (932°F).

Beryllium vacuum-sealed with eutectic Bi-Pb-Sn alloy in a quartz container and heated for one month at 500°C (932°F) showed no reaction zone. When the container, which was necked-in at the middle, was inverted at temperature, the liquid alloy ran off the specimen, which was left completely dry (unwetted) in the upper portion. The alloy caught in the lower portion was found by spectrographic analysis to contain less than 0.01% of beryllium.⁽¹⁶⁷⁾

Zirconium with Eutectic Bi-Pb-Sn Alloy

Zirconium has good resistance to attack by eutectic Bi-Pb-Sn alloy at 500°C (932°F).

Two zirconium specimens (Bureau of Mines Magnesium-reduced) vacuum-sealed in a quartz container with eutectic bismuth-lead-tin alloy (about 1 sq. cm. of zirconium per 2 cc of alloy) had reaction zones of approximately 1 mil and 0.5 mils, respectively, after having been heated for one month at 500°C (932°F).

The melt which was poured from the specimen while at temperature, was found by spectrographic analysis to contain less than 0.01% of zirconium.

Since the zirconium was known to contain magnesium and other impurities in substantial amounts, and since the specimen had decreased slightly in volume, the zirconium, itself, obviously was not significantly attacked.⁽¹⁶⁷⁾

Titanium with Eutectic Bi-Pb-Sn Alloy

Titanium has limited resistance to attack by eutectic Bi-Pb-Sn alloy at 500°C (932°F).

Titanium vacuum-sealed in a quartz container with eutectic bismuth-lead-tin alloy (about 1 sq. cm of Ti per 2 cc of alloy) had a reaction zone 2.5 mils in thickness (corresponding to 10 mpy) after having been heated at approximately 500°C (932°F) for 80 days.

The likelihood exists that the attack was due to the presence of manganese and other impurities in the titanium, and that pure titanium would have good resistance at the temperature of test.⁽¹⁶⁷⁾

Aluminum with Eutectic Bi-Pb-Sn Alloy

Aluminum has poor resistance to attack by eutectic Bi-Pb-Sn alloy at temperatures above 300°C (572°F).

It is apparent from the aluminum-tin diagram⁽²⁵⁾ that the solubility of aluminum in eutectic Bi-Pb-Sn alloy in the temperature range of 550 to 630°C (1022 to 1166°F) should be between 3 and 4% if the lead and bismuth in the alloy are inert. This is what was found experimentally on heating a specimen of 2S aluminum welding wire (1/8" diameter) vacuum-sealed with, and immersed about 2 centimeters in 30 grams of eutectic bismuth-lead-tin alloy in a quartz container for 20 hours in the range of 550°C (1022°F) to 630°C (1166°F).⁽¹⁶⁷⁾ The amount of aluminum actually found by analysis in the melt was 3.10%. Extensive diffusion into the aluminum specimen also had taken place.

It is obvious that, except by dilution, lead and bismuth do not affect the tendency of tin to dissolve aluminum. By application of the dilution factor to the phase diagram it is obvious that aluminum has poor resistance to attack by Bi-Pb-Sn alloy at temperatures as low as 300°C (572°F).

It is of interest to the theory of corrosion and of corrosion control that anodized aluminum maintained at a potential of 45 volts with respect to the melt dissolved to the extent of only 0.14% of aluminum (instead of 3.1%) when treated in the same way as the plain aluminum specimen. An anodized specimen of aluminum that was simply immersed in eutectic bismuth-lead-tin alloy under similar temperature conditions (but without maintenance of a potential difference) dissolved to the intermediate extent of 0.94% of aluminum.

105

NON-METALS WITH EUTECTIC Bi-Pb-Sn ALLOY (52 Bi-32 Pb-16 Sn)

m.p. 97°C (207°F)

Clean Pyrex glass is not wet or attacked by clean Bi-Pb-Sn alloy at temperatures up to at least 200°C (392°F).⁽¹⁶⁷⁾

ATTACK BY OTHER LOW-MELTING ALLOYS OF LEAD AND BISMUTH

A number of low-melting binary alloys containing lead or bismuth are known for which little or no data on their reactions with solid metals have been assembled. These include such eutectic alloys as: 35 Mg-65 Bi (m.p. 552°C), 47 Bi-53 Tl (m.p. 186°C), 15 Au-85 Pb (m.p. 215°C), 90 Pb-10 Pd (m.p. 265°C), 2.5 Mg-97.5 Pb (m.p. 250°C) and many others.⁽⁴⁰⁾ Various low-melting polynary alloys containing these metals are also known,⁽⁸⁰⁾ but their reactions with solid metals have not been studied.

Although attack by bismuth-lead alloys containing indium (up to 25% In) has not been studied, experience in handling these alloys indicates that no exceptional difficulty from attack due to the presence of indium need be expected.⁽¹⁴⁷⁾

Under oxidizing conditions, lead containing 8% Sb and lead containing 8% Sn were found to be more aggressive in their attack on Armco iron, 0.13% C steel, and low-chromium steel than is lead.⁽¹⁵⁴⁾ (See Pages 74, 75, and 124)

Lipowitz alloy, which contains Bi, Pb, Sn, and Cd, attacks steel⁽³⁾ at 100°C (212°F).

RESISTANCE OF MATERIALS TO ATTACK BY LIQUID MAGNESIUM

m.p. 651°C (1204°F)

In general, magnesium is less aggressive than either aluminum, antimony, tin or zinc, and can be contained satisfactorily in certain materials and under temperature conditions that would prove unsatisfactory in the case of the latter liquid metals. Information concerning the attack on engineering metals and alloys by liquid magnesium is largely qualitative in nature, and for the most part is the result of experience in the manufacture and casting of this metal and its alloys.

Ferrous Metals with Magnesium

Cast iron and low-carbon steel have good resistance to attack by magnesium at its melting point, 651°C (1204°F), and limited resistance up to 800°C (1472°F).

Cast iron and low-carbon (SAE 1010) steel are most frequently used for handling magnesium, but low-carbon steel in particular is best suited for temperatures up to 900°C (1652°F).^(106,156) Centrifugal pumping units fabricated from cast Meehanite iron, Graphitar, and low-carbon steel are reported to give satisfactory service under erosive conditions up to 760°C (1400°F).^(95,115) Attack occurs by the dissolution of iron which at 651°C (1204°F) corresponds to an apparent solubility of 0.0025% by weight. Both cast iron and low-carbon steel have limited resistance at and above 800°C (1472°F) where the solubility of iron in magnesium increases beyond 0.1% by weight.^(43,113) In the continuous casting of magnesium at temperatures ranging to about 760°C (1400°F) precipitation of iron in the cooler zones of the system has never been observed.⁽¹¹⁵⁾

High-chrome stainless steel is more resistant to attack than cast iron and low-carbon steel. Austenitic stainless steel is attacked by magnesium at its melting point, 651°C (1204°F).

High-chrome stainless steel possesses as good resistance as that exhibited by cast iron and low-carbon steel, and has the added advantage of being oxidation resistant. Under the added condition of erosion the attack is no more severe than it is in the case of cast iron and low-carbon steel.⁽¹⁰⁶⁾

The attack on austenitic stainless steel (18 Cr-8 Ni) at 651°C (1204°F) is attributed to its nickel content and the fact that liquid magnesium can dissolve 23.5% by weight of nickel at 507°C (945°F).^(2,69,106)

Beryllium with Magnesium

Beryllium has good to limited resistance to attack by magnesium at 800°C (1472°F).

There is disagreement in the literature on the solubility of beryllium in magnesium. Oesterheld,⁽¹²³⁾ Kroll and Jess,⁽⁹⁰⁾ and Payne and Haughton⁽¹²⁶⁾ have attempted to alloy the two metals and could find no alloy formation even when both were added together as liquids. The investigations of K. W. Peredelski⁽¹²⁷⁾ place the solid solubility of beryllium in magnesium at approximately 0.05% by weight, whereas W. A. Peresslegin⁽¹²⁸⁾ gives a lower experimentally confirmed value of 0.005 to .01% . If the lower solubility is assumed to be correct and the fact that no magnesium-beryllium compounds are known to exist is considered, then beryllium can be likened to iron in its resistance to attack by magnesium.

Refractory Metals with Magnesium

Titanium has good resistance to attack by magnesium up to 750°C (1382°F), and limited resistance at 850°C (1562°F). Zirconium probably has limited to poor resistance to attack near the melting point of magnesium, 651°C (1204°F). Niobium, wolfram, tantalum, molybdenum, and chromium have been suggested for use with liquid magnesium in the order listed. (See Page 13.)⁽²¹⁾

Titanium appears to have good resistance to attack by magnesium up to 750°C (1382°F) where the reported solubility is approximately 0.01%, and limited resistance up to 850°C (1562°F) where the solubility increases to 0.015%.⁽⁷⁾

Wolfram is reported to be insoluble in both liquid and solid magnesium.⁽⁶⁹⁾

The general belief that chromium cannot be alloyed with magnesium seems to be substantiated by the inactivity of chrome-plate to liquid magnesium at 651°C (1204°F), and its low solubility (0.008% by weight) in magnesium at 734°C (1350°F),^(17,106) (based on chemical analysis). Chromium can therefore be considered to have good resistance to attack by magnesium up to 734°C (1350°F).

The appreciable solubility of zirconium in magnesium^(106,122) indicates that it would have poor resistance to liquid magnesium at any temperature.

Other Metals with Magnesium

Because of their appreciable solubility in liquid magnesium at low temperatures, as indicated by the published phase diagrams, Al, Ag, Au, Ba, Bi, Ca, Cd, Co, Cu, Ga, Li, Mn, Ni, Pb, Pd, Pt, Sb, Si, Sn, Tl, and Zn are excluded from consideration as container materials,^(2,69) or as alloying elements for use in appreciable amounts in container metals.

Practical experience has demonstrated that brass and bronze fittings are dissolved by magnesium at its melting point, 651°C (1204°F); and that Al, Ag, Au, Cu, Ni, Pb, Pd, Pt, Sn, and Zn are dissolved, up to 10% by weight, when added to liquid magnesium at 734°C (1350°F).⁽¹⁰⁶⁾ This is to be expected from a consideration of the respective phase diagrams.

Non-Metals and Oxides with Magnesium

Liquid magnesium does not attack alumina, graphite, magnesia, or silicon carbide at temperatures near its melting point, 651°C (1204°F); although quantitative data is lacking in the case of beryllia, calcium oxide, thoria, and zirconia there is some doubt that these materials would be attacked under similar conditions.⁽¹⁰⁶⁾ Most other oxygen-containing compounds, such as quartz and silicates, are attacked by liquid magnesium at this low temperature.⁽¹⁰⁶⁾

When graphite is used with molten magnesium containing magnesium oxide, attack is not likely to occur below 2000°C (3632°F), however, above this temperature carbon has been reported capable of reducing magnesia⁽¹⁵⁵⁾ and attack can reasonably be expected to occur under these conditions of extreme temperature. The amount of attack on the graphite would depend largely upon the amount of magnesia present.

Experimental results of tests in static magnesium at 900°C (1652°F) have shown that alundum, beryllia, magnesia, porcelain, quartz, and zirconia are strongly attacked in two to three hours.⁽²¹⁾ It is probable that thoria would also show strong attack by magnesium at this temperature in view of the thorium-magnesium compound (Mg_2Th_x) that was formed on heating magnesium powder with thorium oxide.⁽⁶⁹⁾

109RESISTANCE OF MATERIALS TO ATTACK BY LIQUID CADMIUM

m.p. 321°C (610°F)

Information regarding the attack on engineering metals and alloys by cadmium comes largely from experience in the use of such fusible alloys as Woods metal, Lipowitz metal, cadmium solders and lead-tin solders with small cadmium additions.^(3,60,151)

Ferrous Metals with Cadmium

Armco iron, cast iron and mild steel have good resistance to attack by cadmium up to 700°C (1292°F).

Gray cast iron is used most frequently in handling liquid cadmium and fusible alloys containing cadmium, but Armco iron and mild steel can be expected to be just as satisfactory.⁽¹³⁴⁾ There is some evidence that liquid cadmium reacts with iron to form the high melting compound Cd_2Fe which protects the underlying metal from further attack.^(26,77)

The solubility of iron in liquid cadmium is reported as 0.0002% to 0.0003% in the range of 400°C (752°F) to 700°C (1292°F).⁽²⁾

Austenitic and ferritic stainless steels have poor resistance to attack by cadmium at its melting point, 321°C (610°F).

Drastic penetrations (120 to 420 mpy) have been measured for Types 302 (18-8), 410 (12 Cr), and 430 (16 Cr) stainless steels on exposure to cadmium at its melting point, 321°C (610°F). Type 316 (18-8, Mo) has also been reported to be attacked by liquid cadmium.⁽⁸²⁾

Aluminum with Cadmium

Information pertaining to the solubility of aluminum in liquid or solid cadmium is lacking, but the solubilities are believed to be low.^(2,69) Aluminum may have limited suitability as a container material for cadmium near its melting point, 321°C (610°F).

Refractory Metals with Cadmium

Niobium, tantalum, wolfram, molybdenum, and chromium have been suggested for use with liquid cadmium in the order listed. (See Page 13.) There is some evidence that chromium may have good resistance to attack by cadmium up to 650°C (1202°F).⁽⁶⁹⁾

Other Metals with Cadmium

Because of their appreciable solubility in liquid cadmium at low temperatures, as indicated by the published phase diagrams, or other published data, Ag, Au, Co, Cu, Mg, Ni, Pb, Pt, Sb, Sn, and Zn are excluded from consideration as container materials^(2,69), or for use in appreciable proportions as alloying elements in container metals.

RESISTANCE OF MATERIALS TO ATTACK BY LIQUID THALLIUM

m.p. 303°C (577°F)

What little information exists concerning attack by liquid thallium indicates that manganese has good resistance to attack by thallium at temperatures up to about 1000°C (1832°F), austenitic stainless steel (18 Cr-8 Ni) has good resistance up to 649°C (1200°F), aluminum has good resistance to about the same temperature, Armco iron has good resistance at the melting point of thallium, 303°C (577°F),⁽²¹⁾ and nickel and Monel metal are severely attacked at 649°C (1200°F). Iron, wolfram, tantalum, molybdenum, niobium and cobalt have been suggested for use with liquid thallium in the order of preference listed. (See page 13)⁽²¹⁾

Thallium was held at 649°C (1200°F) in stainless steel, Monel metal, and nickel crucibles in contact with the atmosphere. A 19-gauge stainless steel crucible was not completely penetrated after 21 days and only superficial attack was observed. The Monel metal and nickel crucibles (both 22 gauge) were perforated by the thallium in 3 days and 8 days respectively.⁽¹⁴⁵⁾

Aluminum and manganese may be satisfactory container materials since they appear to have no solubility in liquid thallium at temperatures up to 650°C (1202°F) and 1148°C (2098°F), respectively.⁽⁶⁹⁾ (Because of the possible solubility of thallium in gamma manganese, the lower temperature of perhaps 1000°C (1832°F), which is somewhat below the gamma transformation temperature, is suggested.)

Other Metals with Thallium

Because of their appreciable solubility in liquid thallium at low temperatures, as indicated by the published phase diagrams, Ag, Au, Ca, Cd, Cu, In, Mg, Ni, Pb, Sb, and Sn are excluded from consideration as container materials or for use in appreciable concentrations as alloying elements in container metals.⁽⁶⁹⁾

The suitability of cobalt is questionable in view of the fact that less than 3% cobalt has been reported to lower the melting point of thallium approximately 6°C (11°F).⁽⁶⁹⁾

112

RESISTANCE OF MATERIALS TO ATTACK BY LIQUID INDIUM

m.p. 156.4°C (313°F)

The small amount of available information concerning attack by liquid indium indicates that austenitic stainless steel (18-8) has good resistance to attack by indium at 649°C (1200°F) and Type 347 stainless steel (18-8, Nb) has poor resistance at 780°C (1436°F). Armco iron and cold rolled steel (SAE 1020) have poor resistance at 780°C (1436°F), and nickel and Monel metal are severely attacked at 649°C (1200°F). Iron, wolfram, tantalum, molybdenum, niobium and cobalt have been suggested for use with liquid indium in the order listed. (See Page 13)(21)

Indium was held at 649°C (1200°F) in stainless steel, Monel metal, and nickel crucibles in contact with the atmosphere. A 19-gauge stainless steel crucible (18-8) was not completely penetrated after 21 days and only superficial attack was observed. The Monel metal and nickel crucibles (both 22-gauge) were perforated by the indium in one day.⁽¹⁴⁵⁾ The calculated rates of attack, based on the depth of the edge irregularities, were approximately 25 mpy for Armco iron and about 38 mpy for both cold rolled steel and Type 347 stainless steel when exposed separately to 780°C (1436°F) indium for 7 days under vacuum in a quartz container. In addition to being attacked, the cold rolled steel specimen was decarburized to a depth of 10.5 mils.⁽¹⁷²⁾

Armco iron, cast iron, and mild steel may have good resistance to attack by indium near its melting point 156.4°C (313°F).

Other Metals with Indium

Because of their appreciable solubility in liquid indium at low temperatures, as indicated by the published phase diagrams, Ag, Cu, and Pb are excluded from consideration as container materials or as high-concentration alloying elements in container metals.⁽⁶⁹⁾

113

RESISTANCE OF MATERIALS TO ATTACK BY GALLIUM*

*Degree of Resistance: (See text for discussion of these data)

GOOD	-	consider for long-time use
LIMITED	-	for short-time use only
POOR	-	no structural possibilities
UNKNOWN	-	no data for these temperatures

RESISTANCE OF MATERIALS TO ATTACK BY GALLIUM

Gallium is more aggressive in its attack on most solid metals at a given temperature than any other molten metal that has been tested. It has a high affinity for all common engineering metals and can be contained successfully at high temperatures only in some of the refractory oxides, quartz, graphite, and such metals as wolfram, rhenium, beryllium, and tantalum.

The mechanism of attack on solid metals by gallium differs widely from one metal to the next, and from one temperature to the next. With beryllium, for example, the attack occurs chiefly through solution when at 800°C (1472°F), and almost entirely through diffusion into the solid metal at 600°C (1112°F), to form a compound. Molybdenum reacts with gallium at these temperatures to form more than one reaction product, one of which is a solid solution. Wolfram, however, is not attacked at all by gallium at temperatures up to 800°C (1472°F), although it might be expected to behave like molybdenum since compounds of molybdenum and wolfram are isomorphous.

Although gallium does not readily attack most ceramics, it tends to wet magnesia under certain conditions, but does not tend to wet beryllia or alumina. An anodized coating on aluminum, however, offers no barrier to penetration by gallium even at moderate temperatures.

Since there is no rule of thumb to use in charting the resistance of materials to attack by gallium, each substance must be considered individually. It is, of course, futile to calculate "mils per year penetration" on the basis of weight losses unless it is known that uniform solution attack is the only important form of attack that occurs. The bar chart, page 109, for gallium is based entirely on static tests or on tests in which specimens in sealed capsules were rotated end over end in a furnace. It can only indicate what materials are unsuitable for use with gallium at a certain temperature under static or dynamic conditions, but beyond that can only indicate which materials offer reasonable possibilities.

The following is an attempt to outline the considerations used in constructing the bar chart for resistance to attack by gallium. (See Page 109.) The reader is free to interpret in his own way the data on which the chart is based.

115

METALS WITH GALLIUM

m.p. 29.78°C (85.6°F)

Wolfram with Gallium

At temperatures up to 800°C (1472°F) wolfram has good resistance to attack by gallium.

Gallium heated with wolfram rod at 800°C (1472°F) for 360 hours tends to wet some portions of the wolfram specimen, but can be wiped off. The luster of the wolfram surface is slightly dulled from incipient reaction⁽⁷³⁾ in some places, but micro-examination reveals no reaction zone.^(81, 169) The weight of the specimen does not change significantly beyond the precision of measurement. Spectrographic analysis of gallium that had been heated with wolfram at 815°C (1500°F) indicates a solubility in gallium of 0.001 to 0.008% by weight.⁽⁸¹⁾

It is not known whether the oxide film normally present on all wolfram specimens that have been exposed to air is a factor in protecting wolfram against attack or, perhaps, in inducing wetting and promoting attack. Since, however, other oxygen-avid metals, such as aluminum, beryllium, and molybdenum, are not protected by oxide films against attack by gallium, it appears that the protective action of an oxide film on wolfram, if it is actually protective, may be of minor importance.

Rhenium with Gallium

Rhenium has good resistance to attack by gallium at temperatures up to 800°C (1472°F).

Rhenium heated at 800°C (1472°F) in gallium in an argon atmosphere for 360 hours did not change in dimensions. As the only rhenium available was sintered material, the gallium penetrated the surface pores, but a micrograph gave no indication of surface attack.⁽¹⁶⁹⁾

Beryllium with Gallium

The resistance of beryllium to attack by gallium at temperatures up to 500°C (932°F) is good, at 500°C (932°F) to 600°C (1112°F) is limited, and at 600°C (1112°F) to 800°C (1472°F) is poor (unless the gallium is saturated with beryllium in a static system, in which case the resistance is good).

From metallographic observations on beryllium specimens tested statically in gallium at various temperatures, (81,170) and from measurements of changes in weight and dimensions occurring in these specimens as the result of such tests, (170) it has been possible to make the following statements concerning the resistance of beryllium to gallium:

1. Beryllium shows no evidence of attack in gallium at 500°C (932°F) in an argon atmosphere over a period of two weeks.

2. At 600°C (1112°F) beryllium dissolves in gallium to the extent of 4 ppm, but gallium also diffuses very slowly into the beryllium to form a reaction zone. In two days the reaction has progressed so slowly that no attack can be observed, but in about two weeks it is possible to detect on some specimens a reaction layer about 0.3 mil to 1 mil in thickness. This layer is believed to be a protective compound, which retards further diffusion, and which is essentially insoluble in gallium at 600°C (1112°F).

Since rate of attack at this temperature is controlled primarily by rate of diffusion into the solid, the attack is not sensitive to surface-volume relationships. At this temperature the extent of formation of the reaction zone can be rather accurately estimated from the increase in weight or volume of the specimen.

3. At 800°C (1472°F) surface-volume relationships become important, for the reaction layer, which was essentially insoluble at lower temperatures, has an apparent solubility in the gallium of 0.9% by weight of beryllium. As the reaction layer at 800°C (1472°F) is ordinarily of the same order of thickness as at 600°C (1112°F), it is apparent that penetration by transgranular diffusion can progress no more rapidly than the reaction product can dissolve--once the limiting thickness of reaction layer has formed. Under static conditions, therefore, the rate of attack at 800°C (1472°F) is governed by the rate of solution, and this is so slow that a specimen heated in gallium at this temperature for two days showed no evidence of attack.

4. Another factor influencing the rate of attack and the depth of penetration appears to be grain growth, which is often pronounced at elevated temperatures. An explanation for this is that the curvature accompanying growth of surface grains keeps producing virgin surfaces which react readily with gallium until the reaction layer is of rate-limiting thickness. This accounts for the limited intergranular attack that appears at grain boundaries near the surface.

This would explain the fact that fine-grained beryllium is more severely attacked than coarse-grained beryllium or single crystals of beryllium, and why limited intergranular attack becomes more pronounced with increase in temperature.

5. Crystallographic orientation--at least up to 600°C (1112°F)--is of minor importance to the rate and amount of attack of gallium or beryllium.

Tantalum with Gallium

The resistance of tantalum to attack by gallium is good at temperatures up to 450°C (842°F), is limited between 450°C (842°F) and 600°C (1112°F), and is poor at higher temperatures.

The predominant mechanism of attack on tantalum by gallium in the absence of oxygen is simple solution at temperatures up to at least 600°C (1112°F). At 800°C (1472°F) there is evidence of slight transgranular alloying attack, but, even at this temperature, solution is the primary process.

Alloy zones at the tantalum surface have been observed in some polished sections;^(81,169,170) but there is evidence that portions of these zones are due to deposition, perhaps from supersaturated solution on cooling, and therefore that diffusion constants cannot be determined from the total thickness of the zones.

Static tests indicate that the apparent solubility of tantalum in gallium is 0.01% by weight at 450°C (842°F), 0.58% at 600°C (1112°F), and 1.3% at 800°C (1472°F). The rate of attack is, on the basis of these tests, 0.24 mpy at 450°C (842°F) and about 12 mpy at 600°C (1112°F).

Sound welds in tantalum have the same order of resistance as the base metal to attack by gallium; but pits and inclusions in the weld zone are especially susceptible to attack.

The presence of air in a gallium-tantalum system accentuates the attack of gallium on tantalum. Tantalum oxide is then the chief product, even though the tantalum is immersed in the gallium. The oxide film on tantalum is not adherent, and presumably does not protect the base metal against attack by gallium.

Attack on tantalum by Ga-Sn-Zn (82-12-6) eutectic alloy at 815°C (1500°F) is about one-half that by gallium at the same temperature.⁽⁸¹⁾

Niobium with Gallium

The resistance of niobium to attack by gallium is good at temperatures up to 400°C (752°F), limited between 400°C (752°F) and 450°C (842°F), and poor at higher temperatures.

At 450°C (842°F) niobium in gallium sealed in vacuum for 337 hours did not change at all in dimensions, although there was a slight gain in weight. At 600°C (1112°F) and at higher temperatures there was diffusion in both directions, with a tendency for the gallium-rich phase to form a solid. At 400°C (752°F) niobium is not attacked by gallium.⁽¹⁶⁹⁾

Molybdenum with Gallium

Molybdenum is essentially the same as niobium in its resistance to attack by gallium.^(81,169) Siliconized molybdenum is resistant to attack by gallium only to the extent that the brittle silicide coating does not become cracked.⁽⁸¹⁾

Chromium with Gallium

It may be tentatively concluded that the resistance of chromium to attack by gallium is poor.

Chromium in all forms tested (stripped plate with and without hydride, and fused chromium) disintegrated in gallium at 600°C (1112°F) even though neither solution attack nor alloying attack occurs.⁽¹⁶⁹⁾ Since there was no evidence of compound formation or of solution attack, chromium is still thought to offer some promise for use with gallium.⁽³¹⁾

Titanium with Gallium

Titanium is disintegrated by gallium at 450°C (842°F),⁽¹⁶⁹⁾ but is reported to have good resistance at 400°C (752°F).⁽³⁹⁾ The product of reaction between gallium and titanium is reported to be Ga_3Ti .⁽¹⁶¹⁾

Lead with Gallium

Lead has limited resistance to attack by gallium at temperatures up to at least 300°C (572°F). There is conflicting evidence as to the existence of a lead-gallium eutectic,⁽⁶⁸⁾ but any solubility of solid lead in gallium, or of gallium in solid lead, is slight.^(32,69)

Other Metallic Elements with Gallium

Elements such as Cu, Pt, Zr, Ni, V, Mn, Ag, Au, Ce, Pr, Cd, Mg, Fe, Ge, Sn, and In react so readily with gallium to form compounds or solid solutions that none deserves consideration for gallium-resistant uses at high temperatures,^(32,69,168,169,170,174) although copper and platinum do not appear to be attacked by gallium at 100°C (212°F), and zirconium is reported to be resistant to attack by gallium at temperatures of that order.⁽³¹⁾

119Alloys with Gallium

The 18-8 type Cr-Ni stainless steels and the straight-chromium stainless steels are subject to severe alloying attack by gallium at 600°C (1112°F), although they (Type 347 and 430) were not attacked at all by gallium in a month-long static test at 200°C (392°F). They have also been exposed for a two-day period to gallium at about 350°C (662°F) without evidence of attack. Inconel is more severely attacked than is stainless steel. (169)

TaW, a 7-1/2% W tantalum alloy, has excellent resistance to attack by gallium at 400°C (752°F), and moderate resistance at 600°C (1112°F). It is less resistant than pure tantalum, having an apparent solubility in gallium of 0.14% at 500°C (932°F) and 4.2 % at 600°C (1112°F). (169)

The compound FeBe and the following alloys have negligible resistance to attack by gallium at 500°C (932°F) to 600°C (1112°F); Cr-50 Mn, Ni-20W, and 18W-4 Cr-1.25V-0.8 Mo tool steel. (169)

NON-METALS WITH GALLIUM

m.p. 29.78°C (85.6°F)

A beryllia crucible with a 1/16-inch wall has been used successfully as a container for gallium briefly at 1600°C (2912°F), and in two-week tests at 800°C (1472°F). Specimens of sintered beryllia have been unaffected by gallium in 48-hour tests at 1000°C (1832°F).⁽¹⁶⁹⁾

Clean fused silica is unattacked by clean gallium at temperatures up to 1160°C (2120°F), but oxide contamination of either the silica or gallium causes the silica to be attacked, as does contamination of the gallium by some oxygen-avid metals.^(32,169,170)

Alundum crucibles have consistently been used successfully with gallium at 1000°C (1832°F).⁽¹⁶⁹⁾

Graphite is satisfactory as a container for gallium at temperatures up to at least 800°C (1472°F).⁽¹⁶⁹⁾

Stabilized zirconia and dense magnesia are more easily wetted and penetrated by gallium. The zirconia can be used at temperatures up to about 500°C or 600°C (932°F or 1112°F), but magnesia is not recommended as a container for gallium at these temperatures.⁽¹⁶⁹⁾

Pyrex glass is satisfactory for use with gallium at 500°C (932°F), showing no evidence of attack.⁽¹⁶⁹⁾

Organic materials, such as plastics and rubber, are ordinarily resistant to attack by gallium up to the decomposition point of the material.⁽⁸¹⁾

RESISTANCE OF MATERIALS TO ATTACK BY LIQUID ALUMINUM

m.p. 660°C (1220°F)

Experience in handling and experiment have both shown that there are no known metals or alloys totally immune to attack by liquid aluminum. Above 660°C (1220°F) (m.p. of aluminum) almost all solid metals and alloys in contact with aluminum are so severely attacked as to be unsuitable for applications demanding long time contact of the liquid with the solid at elevated temperatures.

Metal equipment (melting pots and handling ladles) has been used successfully in handling the liquid, but in these instances the equipment is usually coated with an inert metallic oxide (Al_2O_3 , MgO , or Kieselguhr). These coats are either painted or sprayed on and must be dried thoroughly before use.⁽³¹⁾

Liquid metal solutions containing 50 weight per cent or more of aluminum will attack materials in the same manner as the pure liquid, but at a somewhat slower rate.

Ferrous Metals with Aluminum

Practically all ferrous alloys tested show poor resistance to attack above 660°C (1220°F). The resistance of a Cr-V steel is limited at this temperature.

Gray cast iron is more resistant to attack by aluminum than the low-carbon steels, Armco iron and all of the ferrous alloys including the stainless steels, and therefore it is recommended as a crucible material.^(15,134) Wrought SAE 1010 is also mentioned for use as a crucible material in the temperature range 690°C-775°C (1274°F-1427°F).⁽¹⁵⁶⁾ The resistance of gray cast iron is attributed to the carbon barrier (in the form of graphite) left behind when the iron is dissolved. Graphite neither reacts with nor is readily dissolved by aluminum below 1200°C (2192°F).⁽³¹⁾ At 750°C (1382°F) iron (presumably Armco) and a chromium steel (analysis not known) showed the same amount of attack ranging between 1800 mpy and 5500 mpy, calculated from weight loss data.⁽¹³⁴⁾

Austenitic and ferritic stainless steels in general are strongly susceptible to embrittlement penetration upon exposure to liquid aluminum at its melting point, 660°C (1220°F). Rates of attack, based on measured penetration, greater than 420 mpy have been reported for Types 302, 410 and 430 stainless steels at this temperature.^(1,82) Type 316,⁽¹⁾ and two Cr-Ni steels (17-25 Cr, 12-37 Ni)⁽¹¹¹⁾ have also been tested with liquid aluminum and found to be attacked much too severely to be useful as container materials.

A Cr-V steel tested in liquid aluminum at 660°C (1220°F) was slightly attacked and possibly would have limited use as a container material.⁽¹³⁴⁾

Other Metals and Alloys with Aluminum

Chrome-plate⁽⁸⁷⁾ is reported to be resistant to attack by aluminum bronze at 1050°C (1922°F), and might also be resistant to attack by liquid aluminum at temperatures near its melting point, 660°C (1220°F).

Copper and nickel and alloys containing either or both of these elements as principal constituents (Monel, Inconel, brasses and bronzes) are severely attacked by aluminum.⁽⁷⁵⁾

Non-Metals and Oxides with Aluminum

Graphite has good resistance up to 1200°C (2192°F) and moderate resistance up to 1700-1800°C (3092-3272°F). Highly sintered alumina (Al_2O_3) and beryllia, (BeO) (free of aluminum-soluble impurities) are inert at temperatures above 1000°C (1832°F). Highly ignited thoria (ThO_2) and zirconia (ZrO_2) can be used with some caution above 1000°C (1832°F).

Graphite can be used with liquid aluminum up to 1700-1800°C (3092-3272°F) without serious attack occurring. At 1200°C (2192°F) the formation of a compound (Al_4C_3) protects the underlying graphite from further attack.⁽³¹⁾

Highly sintered alumina (Al_2O_3) and beryllia (BeO) are inert to aluminum above 1000°C (1832°F) if they are free of soluble impurities. Highly ignited thoria (ThO_2) and zirconia (ZrO_2) are somewhat less resistant under similar conditions of temperature and purity.⁽³¹⁾

Although ceramic materials resist the attack of aluminum satisfactorily they usually find little use as containers for the liquid, particularly in applications demanding ductility and resistance to thermal shock.

123

RESISTANCE OF MATERIALS TO ATTACK BY LIQUID TIN

m.p. 231.9°C (449°F)

Engineering metals and alloys that are attacked by liquid aluminum and zinc will usually also be attacked by liquid tin, though to a slightly lesser degree. The resulting intergranular penetration is reflected in a marked reduction in physical properties, especially those related to ductility.

Metals and alloys that are only slightly affected in the stress-free condition will in some cases show rapid attack when exposed to liquid tin and tin solders while under stress.

Ferrous Metals with Tin

Cast iron and low-carbon steel show a limited resistance to attack by liquid tin at 150°C (302°F) and limited or poor resistance up to 510°C (950°F). When exposed in a stressed condition to liquid tin, low-carbon steels are less susceptible to attack than similar higher carbon steels.

Gray cast iron and low-carbon steel are most frequently used as crucible materials in the handling of liquid tin and its alloys, but the extent of their usefulness is questioned because of the formation of intermediate reaction layers.^(41,61,134,148,156) An iron-tin compound is formed on extensive heating above 150°C (302°F).⁽¹⁴⁷⁾

Stressed Armco iron and carbon steel tested in soft solder (50Sn-50Pb), Lipowitz alloy, and tin respectively, at temperatures up to 400°C (752°F) were attacked at roughly the same rates as similar unstressed specimens. Stressing caused higher carbon steels to be more susceptible to penetration by the liquid metals than similar steels with a lower carbon content.^(8,63)

Austenitic and ferritic stainless steels show limited resistance to attack at the melting point of tin, 231.9°C (449°F), and poor resistance at 400°C (752°F) and above. Stressed stainless steels are more susceptible to attack than the carbon steels.

Austenitic and ferritic stainless steels are intergranularly penetrated at the melting point of tin, 231.9°C (449°F); but there is some disagreement between the reported rates of attack. For Types 302 (18-8), 316 (18-8, Mo)

and 430 (16 Cr) stainless steels rates (measured) of less than 4.2 mpy are reported in one instance, and in another instance the rates vary between 42 and 120 mpy for Types 302 and 430.^(82,158) A series of chromium-nickel stainless steels with various carbon, manganese and molybdenum contents were attacked by liquid tin at rates, calculated from weight loss data, of less than 4.4 mpy at 300°C (572°F) and greater than 440 mpy at 600°C (1112°F).⁽¹³⁴⁾

A stressed piece of nickel-chromium steel tubing (3.0 Ni, 1.0 Cr, .30 C, .30 Si, .55 Mn) exhibited a greater susceptibility than unstressed tubing to attack by liquid tin at 400°C (752°F), but tempering at 700°C (1292°F) decreased its susceptibility to attack.⁽⁴¹⁾

Beryllium with Tin

Beryllium has good resistance to attack by tin up to 500°C (932°F).

Beryllium tested in lead-tin-bismuth eutectic at 500°C (932°F) showed no signs of attack. (See Page 99.)

Refractory Metals with Tin

Titanium shows good resistance to attack by tin at 500°C (932°F). Zirconium shows limited resistance to attack at 500°C (932°F). Wolfram, molybdenum, tantalum, niobium and chromium have been suggested for use with liquid tin in the order listed. (See Page 13.)⁽²¹⁾

Titanium and zirconium have not been tested in pure tin but they both show some attack when exposed to eutectic bismuth-lead-tin. (See Page 99.) It is possible that the impurities in these metals were responsible for their attack, and that pure titanium and zirconium would be more resistant to attack.

Chrome-plate shows no signs of attack by liquid tin at its melting point, 231.9°C (449°F).⁽⁸⁷⁾ The chromium-tin phase diagram indicates that the resistance of chromium may be good at considerably higher temperatures.⁽⁶⁹⁾

Other Metals with Tin

Because of their appreciable solubility in liquid tin at low temperatures, as indicated by the published phase diagrams, Al, Ag, Au, Cd, Co, Cu, In, Mg, Ni, Pb, Pt, S, Se, Sb, and Zn are excluded from consideration for use in high percentages in container materials.

Copper has been exposed to liquid tin and tin solders in the range 250°C (482°F) to 450°C (842°F) and was found to be progressively attacked through the formation and subsequent break-up of a double reaction layer.^(27,71) Copper-base alloys warrant no greater consideration as containers for liquid tin than that accorded to copper.^(30,166) Nickel, Monel, and Inconel have likewise been proven, experimentally, to be unsatisfactory for use with liquid tin.⁽⁷⁵⁾

Stressing of copper and nickel does not increase their susceptibility to attack by liquid tin and tin solders.⁽⁸⁾

RESISTANCE OF MATERIALS TO ATTACK BY LIQUID ZINC

m.p. 419.5°C (787°F)

In general the most common and easiest engineering metals and alloys to fabricate are severely attacked by zinc at 500°C (932°F) and above. Small additions of aluminum, antimony, cadmium, lead, and tin in zinc make the latter more aggressive.

Ferrous Metals with Zinc

With few exceptions the ferrous metals and alloys show poor resistance to attack by zinc at temperatures in the neighborhood of 500°C (932°F), and either limited or poor resistance at the melting point of zinc, 419.5°C (787°F). White malleable cast iron (0.25C) has limited resistance to attack at 470°C (878°F).

Armco iron, technically pure iron, wrought iron, gray cast iron, black malleable cast iron, Niresist, and carbon steels tested in zinc show appreciable attack even at the melting point of zinc, 419.5°C (787°F).^(76,134) At 460°C (860°F) technically pure iron and low-carbon steel (0.06C) show better resistance to attack (9 and 10 mpy respectively) than shown by gray cast iron and the higher carbon steels (0.8C) (35 and 13.5 mpy respectively). In every case the rate of attack increases with temperature and becomes so great at temperatures in the neighborhood of 500°C (932°F) as to preclude good service by any of the ferrous metals tested.^(4,156)

White malleable cast iron has been exposed to zinc at 470°C (878°F) for four days without signs of appreciable attack.⁽⁵⁾

Mild steels (and presumably most ferrous alloys) are attacked by liquid zinc through reaction of the iron and zinc to form the compound layer, FeZn₇. Below 480°C (896°F) this reaction layer acts as a barrier to zinc diffusion, and the rate of attack decreases with time as the reaction layer increases in thickness. In the range 480°C (896°F) to 500°C (932°F) the reaction layer becomes porous and non-protecting, and at 500°C (932°F) it is no longer continuous and the attack proceeds at a constant and rapid rate.⁽²⁶⁾

Electrolytic zinc alone attacks Armco iron at the approximate rate of 13,300 mpy (based on weight loss data) at 500°C (932°F), and a 0.2% aluminum addition is reported to decrease the rate of attack. Additions of 1.0% antimony, 1.0% cadmium, approximately 1 to 2% lead, or 1.0% tin to electrolytic zinc are reported to increase the rate of attack on Armco iron by 1600%, 78%, 23%, and 16% respectively.^(26,134) At 440°C (824°F) the influence exerted by these additions is less pronounced.

Cadmium, if present in zinc in amounts ranging from one to ten per cent, causes the semi-protective reaction layer (FeZn_7) to become granular (porous), and zinc is thereby permitted continual contact with the underlying metal surface. Zinc that is sufficiently diluted with cadmium (more than 60% cadmium) will attack container materials at a slower rate than that of pure zinc.⁽²⁶⁾

Austenitic and ferritic stainless steels are severely attacked by zinc at 500°C (932°F), the attack being chiefly by intergranular penetration and resulting in excessive brittleness.^(107,111) At temperatures as low as the melting point of zinc, 419.5°C (787°F), attack on these steels is sufficient to limit their usefulness. (Rates of attack between 60 and 420 mpy based on weight loss data.)^(1,82,87) Small amounts of nickel and chromium in solution are similar to cadmium in increasing the aggressiveness of zinc.⁽²⁶⁾ Stainless steels stabilized with niobium or titanium appear to be similar to the non-stabilized stainless steels in their resistance to attack by zinc.⁽¹⁵⁷⁾

Refractory Materials with Zinc

Niobium, zirconium, tantalum, wolfram, chromium, titanium, and vanadium have been suggested for use with liquid zinc in the order listed. (See Page 13.)⁽²¹⁾ A molybdenum-iron alloy (more than 80% Mo) showed good resistance to attack by zinc at its melting point, 419.5°C (787°F).⁽¹³⁴⁾

The resistance of chromium electrodeposits to attack by zinc is reported as good at the melting point of zinc, 419.5°C (787°F).⁽¹³⁴⁾ That of chrome-plate is reported as poor at 500°C (932°F).⁽⁸⁷⁾

Since chrome-plate is mentioned as a satisfactory container for brass at 900°C (1652°F)⁽¹³⁴⁾ it may also be resistant to attack by zinc at temperatures near its melting point, 419.5°C (787°F).

Other Metals with Zinc

Because of their appreciable solubility in liquid zinc at low temperatures, as indicated by the published phase diagrams, Al, Ag, Au, Cd, Co, Cu, Mg, Mn, Ni, Pb, Sb, and Sn are excluded from consideration as container materials or for use in appreciable proportions as alloying elements in container metals.^(2,69)

Nickel, Monel, and Inconel have been found, experimentally, to be unsatisfactory for use with liquid zinc at its melting point, 419.5°C (787°F). This is to be expected from a consideration of the Ni-Zn phase diagram.^(75,134)

Non-Metals and Oxides with Zinc

Graphite, Carborundum, and Corundite have shown good resistance to attack by zinc at temperatures below 900°C (1652°F).⁽¹³⁴⁾

RESISTANCE OF MATERIALS TO ATTACK BY LIQUID ANTIMONY

m.p. 630.5°C (1167°F)

Ferrous Metals with Antimony

Armco iron, cast iron, low-carbon steel (0.13C), cast steel, and Sicromal 6 and 12 steels have poor resistance to attack by antimony above its melting point, 630.5°C (1167°F).

Stainless steel has poor resistance to attack by antimony-cadmium alloys containing more than 50% antimony at temperatures in the neighborhood of 100°C (180°F) above their liquidus.⁽⁶⁵⁾

Bar specimens (10 mm diameter and 70 mm long) of Armco iron, DIN Ge 12.91 (German cast iron with a minimum T.S. 12 Kg/cm²) low-carbon steel (0.13 C), DIN ST g 45.81S (German cast steel with a minimum T.S. 45 Kg/cm²), Sicromal 6 and Sicromal 12 were suspended vertically, by means of porcelain holders, in liquid antimony covered with a layer of lithium-potassium-sodium chloride for protection against oxidation. Tests of one hour at 750°C (1382°F) and two hours at 650°C (1202°F) resulted in strong attack on all specimens as shown by a double reaction zone (presumably the compounds FeSb₂ and FeSb) upon etching with an alcohol solution containing 1% of nitric acid. In every case the edge of the outer layer was very irregular and the outer layer itself appeared coarsely crystalline. Attack was slightly stronger at the ends of the specimens nearest the salt-liquid metal interface presumably because of the oxygen content of the bath in this region. Tests run for seven days at 750°C (1382°F) in lead containing 8% antimony showed less attack on these metals because of the dilution with lead. Moreover, dynamic tests show that lead containing 8% antimony is more aggressive than lead itself. All these results seem to indicate that antimony is more aggressive than lead in its attack on ferrous metals. (See Page 75)⁽¹⁵⁴⁾

Other Metals with Antimony

Because of their appreciable solubility in liquid antimony at low temperatures, as indicated by the published phase diagrams, Al, Ag, Au, Cd, Ca, Cr, Cu, Mg, Mn, Ni, Pb, Pt, Se, Si, Sn, and Zn are excluded from consideration as container materials or for use in appreciable proportions as alloying elements in container metals.^(2,69)

Nickel, Monel, and Inconel have been found, experimentally, to be unsatisfactory for use with liquid antimony at its melting point, 630.5°C

129
(1167°F).⁽⁷⁵⁾ This is to be expected from a consideration of the Ni-Sb phase diagram.

Non-Metals with Antimony

The solubility of graphite in antimony is negligible⁽⁶⁹⁾ so that a graphite crucible would probably resist attack by antimony up to 1300°C (2372°F).

130

REFERENCES

1. Allegheny Ludlum Steel Company, Handbook of Special Steels, 1944, erroneously cited in Ref. 114 as Handbook of Special Tools
2. American Society for Metals, Cleveland, Ohio, Metals Handbook, 1948 Edition
3. Anonymous, "Cadmium Solders," Machinery, (London), 42, p. 162, 1933
4. Anonymous, Directory of Materials for Chemical Engineering Equipment," Chem. and Met. Engineering, Sept., 1944 and Nov., 1946
5. Anonymous, Eastern Stainless Steel Sheets, 1945, Cited in Ref. 114
6. van Arkel, A. E., Reine Metalle (Pure Metals), Julius Springer, Berlin, 1939, Cited in Ref. 139
7. Aust, K. and C. Pidgeon, "Solubility of Titanium in Liquid Magnesium," Jour. of Metals (Trans.), 185, p. 585, Sept., 1949
8. Austin, G. W., "The Effect of Molten Solder on Some Stressed Materials," Jour. Inst. Metals, 58, p. 173, 1936
9. B & W, Interim Report on the Investigation of the Corrosive Action of K Na on Metals Under Static Conditions, B & W Rep. No. ES-401-4 (Project Baby) NObs-34222, Feb. 10, 1948
10. B & W, Project "Baby" Bimonthly Progress Reports for Period Nov., 1948 through Oct., 1949, ES-401
11. Bainbridge, D. W. (Univ. of Calif., Berkeley), Private Communication to W. D. Wilkinson (ANL), Feb. 4 and Dec. 14, 1949
12. Bainbridge, D. W. and R. C. Grassi, Progress Report on Metallurgical Investigations, Univ. of Calif., U. S. Navy, G. E. NObs 45468, Oct. 8, 1948, to Jan. 17, 1949
13. Baker, W. A., "Solubility of Oxygen in Lead," Jour. Inst. Metals 65, 345 (1939)
14. Barnes, A. H., F. A. Smith, G. Whitham, Direct Current Electromagnetic Pumps, ANL-4322, Oct. 25, 1949

15. Bastion, P. and S. Daeschner, "Investigation of the Corrosion of Cast Iron by Molten Aluminum," Metallurgia, 34, p. 167, Jan., 1949
16. BMI, "Solubility of Metals in Bi-Pb Eutectic," Progress Reports on Metallurgy of Tuballoy to Univ. of Chicago from BMI, CT-1937 (July 1, 1944), CT-2374 (Nov. 1, 1944), and CT-2483 (Dec. 1, 1944)
17. Beck, A. (Editor), The Technology of Magnesium and Its Alloys, F. A. Hughes and Co., Ltd., Abbey House, N.W.I., London, 1941
18. Bichowsky, F. and F. Rossini, Thermochemistry of Chemical Substances, Reinhold, N. Y., (1936)
19. Bohm, B. and W. Klemm, Zeitschr. anorg. u. allgem. Chem., 249, 69 (1939), cited in Ref. 23
20. Bordfoss, S., "Zur Elektrokemie des Beryllium," Zeitschr. physik. Chem., vol. 124 and 125, 1926-1947, 130 and 131, 1927-1928, Cited in Ref. 139
21. Brewer, L. (Univ. of Calif.), The Thermodynamics of High Vacuum-High Temperature Systems Applied to Refractories, Metallurgical Project, CC-1802, June 8, 1944
22. Bunzel, E. G. and E. J. Kohlmeyer, "On the Thermal Behavior of Sodium Compounds, Especially of Sodium Oxide and Sodium Sulfide, and their Reactions with Metals," Zeitschr. anorg. u. allgem. Chem., 254, 1, (1947), cited in Ref. 163
23. Burton, W. N., S. W. Coffman, and C. L. Randolph, A Compendium of Information Concerning Lithium, Aerojet Engineering Corp., Azusa, Calif., RTM-57, Sept. 16, 1949
24. Collins, J. A., The Resistance of Metals and Alloys to Sodium at 600°C, duPont Eng. Dept., Tech. Div., Wilmington, Del., March 27, 1940
25. Corson, M. G., Aluminum and Its Alloys, D. van Nostrand Co. (1926)
26. Daniels, E. J., "The Attack on Mild Steel in Hot Galvanizing," Jour. Inst. Metals, 46, 1931, p. 81
27. Daniels, E. J., "The Hot-Tinning of Copper: The Attack on the Basis Metal and Its Effects," Jour. Inst. Metals, 58, p. 149, 1936
28. Davis, L., Jr., The Hyperfine Structure of Na²², MIT Research Lab. of Electronics Tech. Rep. No. 88, Dec. 1, 1948

29. DeLong, W. B. (Eng. Dept., Exp. Station, duPont), Private Communication to W. D. Wilkinson, Oct. 17, 1949
30. Dickenson, J. H., "Note on the Failure of Manganese Bronze," Jour. Inst. Metals, 24, p. 315, 1920
31. Edwards, J. D., (Research Laboratory, Aluminum Corporation of America, New Kensington, Pa.), Private Communication to C. B. Jackson (MSA)
32. Einecke, E., Das Gallium, Verlag Leopold Voss, Leipzig, 1937, Reproduced by J. W. Edwards, 1944
33. Emeleus, H. J. and J. S. Anderson, Modern Aspects of Inorganic Chemistry, O. Van Nostrand Co., Inc., New York, 1942, p. 456
34. Ephraim, F., Inorganic Chemistry, Oliver and Boyd, England, or Nordeman, New York, 1943, cited in Ref. 23.
35. Epstein, L. F. (KAPL), Mechanism of Corrosion of Metals by Liquid Sodium and Similar Materials, this paper is a summary of a talk (revised) delivered at the "Symposium on Basic Properties of Liquid Metals" held at ANL on April 5, 1949
36. Epstein, L. F. (KAPL), Private Communication to L. R. Kelman (ANL), compilation of data of S. R. Vandenberg, L. F. Epstein et al. at KAPL. Preliminary data reported in KAPL monthly and weekly progress reports from 1946 to 1950. To be published in AEC Journal of Metallurgy and Ceramics
37. Epstein, L. F. (KAPL), Private Communication to L. R. Kelman (ANL), compilation and discussion of unpublished data of A. J. Nerad and associates at G.E. Also review of literature
38. Epstein, L. F. (KAPL), July 28, 1949, Private Communication to E. K. Falls (ANL)
39. Evans, R. M., S. J. Whalen, and R. I. Jaffee, "Liquid Metals," Progress Report for March, 1949, BMI-P-15.
40. Everhart, J. L., Liquid Metal Heat Transfer Fluid, AS&R Report No. N-1, Nov. 24, 1948 on Navy Contract N8 onr-644 (NRO 31-312) Problem No. 526
41. von Ewijk, L. J. G., "Penetration of Steel by Soft Solders and Other Molten Metals," Jour. Inst. Metals, 56, p. 241, 1935.

42. Ewing, C. T. and R. E. Leed, Literature Survey on Gallium, NRL Al, 3230-161/48 ep., Sept. 20, 1948
43. Fahrenhorst, E. and W. Bulian, "Über das Auftreten von Eisen in Reinmagnesium und in Magnesium-Mangan Legierungen" ("On the Occurrence of Iron in Pure Magnesium and in Magnesium-Manganese Alloys"), Zeitschr. Metallkde., p. 33, Jan. 31, 1941 (cited in Ref. 113)
44. Ferguson, M., Microscopic Examination of Several Metals Subjected to the Action of Molten Potassium-Sodium Alloy, B & W Rep. No. 3198, May 14, 1948
45. Ferguson, M., Examination of Stainless Steels Subjected to the Action of a Potassium-Sodium Bath Containing 3 1/2 to 4 % Carbon, B & W Rep. No. 3216, July 15, 1948
46. Ferguson, M., Examination of Bearing Races After Test in Molten Potassium-Sodium Alloy Contained in an Enclosed Rotor Pump, B & W Rep. No. 3250, Jan. 5, 1949
47. Ferguson, M., Examination of 25Cr-20Ni Corrosion Test Vessels After Operation at 1400°F for 200 and 5400 Hours, Respectively, B & W Rep. No. 3254, Feb. 3, 1949
48. Ferguson, M., Metallurgical Examination of Inconel Corrosion Test Specimens, B & W Rep. No. 3259, Feb. 24, 1949
49. Ferguson, M., Metallurgical Examination of 16-13-3 Cb Alloy Corrosion Test Specimens, B & W Rep. No. 3262, March 24, 1949
50. Ferguson, M., Metallurgical Examination of 25 Cr-20 Ni Alloy Corrosion Test Specimens, B & W Rep. No. 3265, April 11, 1949
51. Ferguson, M., Metallurgical Examination of 16-13-3 Alloy Corrosion Test Specimens, B & W Rep. No. 3269, April 26, 1949
52. Ferguson, M., Metallurgical Examination of 18 Cr-8 Ni Corrosion Test Specimens, B & W Rep. No. 3283, June 14, 1949
53. Ferguson, M., Metallurgical Examination of 18-8 Cb Corrosion Test Specimens, B & W Rep. No. 3284, June 16, 1949
54. Forsyth, P. E. J. and W. R. Smith, "Attack of Platinum Alloy Spark Plug Electrodes by Molten Lead," Metallurgia, 34, 245 (1946)
55. Fredenhagen, K. and G. Cadenbach, "Die Bindung von Kalium durch Kohlenstoff" ("The Bonding of Potassium by Carbon"), Zeitschr. anorg. u. allgem. Chem., 158, p. 249 (1926)

56. Fredenhagen, K. and H. Suck, "Ueber die Bindung der Alkalimetalle durch Kohlenstoff II" ("Over the Bonding of Alkali Metals by Carbon II"), Zeitschr. anorg. u. allgem. Chem., 178, p. 353 (1929)
57. Frandsen, J. P. and R. S. Zeno, Report on Sodium-Resistant Brazing Alloys, KAPL-197, June 30, 1949
58. Frankenburger, W., L. Andrussow and F. Durr, Zeitschr. f. Elektrochem. u. angew. physik. Chem., 34, 632 (1928), cited in Ref. 23
59. Frankenburger, W., Zeitschr. f. Elektrochem. u. angew. physik. Chem., 32, 490 (1926), cited in Ref. 23
60. French, S. J., "Melting Points of Eutectics," Ind. Eng. Chem., 28, p. 111, 1936
61. Genders, R., "Penetration of Mild Steel by Brazing Solder and Other Materials," Jour. Inst. Metals, 37, p. 215, 1927
62. Gilbert, H. N. (Electrochem. Dep. duPont, Niagara Falls, N. Y.), Private Communication to L. R. Kelman (ANL)
63. Goodrich, W. E., "The Penetration of Molten White Metals into Stressed Steels," Jour. Iron and Steel Institute, 132, p. 43, 1935
64. Grassi, R. C. and D. W. Bainbridge, Metallurgical Investigations for Selection of Materials Subjected to an Environment of Liquid Lead-Bismuth Alloy, Final Report, NObs-45468, Univ. of Calif., Dept. of Engineering, Berkeley, Calif., August, 1949
65. Greenaway, H. T., "The Surface Tension and Density of Lead-Antimony and Cadmium-Antimony Alloys," Jour. Inst. Metals, 74, p. 133, Nov., 1947
66. Grube, G., J. Mohr, and W. Bruening, Zeitschr. f. Elektrochem. u. angew. physik. Chem., 41, 880 (1935), cited in Ref. 23
67. Hackett, H. N., "Mercury for the Generation of Light, Heat, and Power," Trans. of the ASME, Oct., 1942, p. 647
68. Hamilton, J. H., J. R. Lewis, J. P. Denny, "Physical Chemistry of Gallium-Indium Alloys," Utah Engineering Experiment Station Technical Report, Oct. 1, 1947-Sept. 30, 1948, Project NR-052 109
69. Hansen, M., Der Aufbau der Zweistofflegierungen (The Structure of Binary Alloys), J. Springer, Berlin, 1936, Reproduced by Edwards Brothers, Inc., Ann Arbor, Mich., 1943

70. Hansen, M., "Note on the Magnesium-Rich Magnesium-Copper Alloys," Jour. Inst. Metals, 37, p. 93, 1927
71. Harrison, C. A., "Damage to Copper Wire by Molten Solder," Metal Progress, 47, p. 282, 1945
72. Hartley, H. J., "Attack of Molten Metals on Non-Ferrous Metals and Alloys," Jour. Inst. Metals, 37, p. 193, 1927
73. Haynes, S. K., The Evaporation of Gallium, MDDC-1604 (Declassified April 2, 1947)
74. Howe, H., Low Melting Alloys of Bismuth, American Smelting and Refining Co. Rep. No. 2490, March 4, 1944
75. International Nickel Company, Corrosion, 1944 and others, cited in Ref. 114
76. International Nickel Company, Engineering Properties of Niresist, Nov., 1946, cited in Ref. 114
77. Isaac, E. and G. Tammann, Zeitschr. anorg. u. allgem. Chem., 60, p. 61, 1907, cited in Ref. 26
78. Jackson, C. B., (MSA), "Chemical Properties and Laboratory Techniques," Chapter in Liquid Metals Handbook now being prepared by the Committee on the Basic Properties of Liquid Metals
79. Jackson, C. B. (MSA), Unpublished Data
80. Jaenecke, E., Kurzgefasstes Handbuch Aller Legierungen (Concise Handbook of All Alloys), O. Spamer, Leipzig, 1937, Reproduced by Edwards Bros., Inc., Ann Arbor, Mich., 1943
81. Jaffee, R. I., R. M. Evans, E. O. Fromm, B. W. Gonser, Gallium in Nuclear Reactors-Considerations for Use as a Primary Coolant, BMI-T-17, Aug. 1, 1949
82. Jessop Steel Co., Washington, Pa., Stainless-clad Steel, cited in Ref. 114
83. Johnson, J. W. and D. S. Jesseman, Preliminary Investigation of Metallic Elements in Bismuth, NEPA 1221-SCR-54, Nov. 17, 1948
84. Johnston, J., Zeitschr. physik. Chem., 62, 330 (1908), cited in Ref. 23

136

85. Kelman, L. R., Effect of Sodium-Potassium Alloy on Various Materials at Elevated Temperatures, ANL Metallurgy Division, CT-3726, Dec. 1, 1946
86. Kelman, L. R., P. G. Drugas, et al., "Resistance of Materials to Attack By NaK," Unpublished data and preliminary data reported in ANL Met. Div. Quart. Progress Reports for period Jan., 1947 through June, 1948, CT-3802, ANL-4003, 4069, 4103, 4150, 4188
87. Kolodney, M., Chrome-Plating Bibliography, Information Release Number 4, July, 1943, Cited in Ref. 114
88. von Kremann, R., "Elektrolyse geschmolzener Legierungen" (Electrolysis of Molten Alloys), Sammlung Chemischer und Chemisch-Technischer Vortraege, 28, 347-408 (1926)
89. Kroll, W. J. and A. W. Schlechten, "Laboratory Preparation of Lithium Metal by Vacuum Metallurgy," Metals Technology, June, 1947, AIME Tech. Paper No. 2179
90. Kroll, W. and E. Jess, Wiss. Veroeff. Siemens-Konzern, 10, 1931, Cited in Ref. 17
91. Kubaschewski, O. and K. Reinartz, "Electrical Transport Measurements for the Investigation of the Heteropolarity of Solid Intermetallic Phases," Zeitschr. f. Elektrochem, u. angew. physik. Chem., 52, pp. 72-75 (1948)
92. Lee, R. E., Corrosion of Certain Metals by Potassium-Sodium, MSA Preliminary Report No. 5 (Appendix to NRL C-3201, Dec. 9, 1947), Oct. 1, 1947
93. Lee, R. E., R. C. Werner, R. A. Tidball, Methods of Handling, Storing, Shipping, and Transferring Liquid KNa Alloys, MSA Preliminary Report No. 3, June 28, 1947, (Appendix to NRL C-3105), April 1947
94. Lichtenberger, H., ANL-4420, March 1, 1949 through Jan. 31, 1950
95. Lindros, E. E. (Byron Jackson Co., Los Angeles, Calif.), Private Communication to W. D. Wilkinson (ANL), May 13, 1949
96. Little, L. F., Corrosion of Certain Metals by Potassium-Sodium, MSA Preliminary Report No. 5, Supplement I. June 24, 1948
97. Little, L. F., Action of NaK and Na at Elevated Temperatures on Protective Materials, MSA Report I, Nov. 10, 1948 and Report I-Appendix I, Dec. 29, 1948

7428 123

98. Lyon, R. N. (ORNL), "Liquid Metal Heat Transfer," Chapter in Liquid Metals Handbook now being prepared by the Committee on the Basic Properties of Liquid Metals
99. Mancherat, N., Compt. Rend., 208, 499 (1939), cited in Ref. 23
100. Markert, W., Jr., Investigation of Galvanic Action Between Dissimilar Metals in a KNa Bath (Electrical Potential Test), B & W Rep. No. ES-401-1 (NObs-34222), April 17, 1947
101. Markert, W., Jr., and E. C. Piottter, Investigation of Thermoelectric Properties of KNa Alloy Versus Various Other Metals (Electrical Potential Test), B & W Rep. No. ES-401-2 (Project "Baby," NObs-34222), June 9, 1947
102. Marshall, Norton and Epstein, In Press, cited in Ref. 37
103. Masing, G., Handbuch der Physik (Handbook of Physics), vol. 2, 1938, Akademische Verlagsgesellschaft BMH, Leipzig, 1937 (Reproduced by Edwards Brothers, Ann Arbor, Mich., 1938), cited in Ref. 139
104. Masing, G. and S. Hircel, Die Korrosionstabellen metallischer Werkstoffe (Corrosion Tables of Metallic Materials), vol. II, P. Bauer and O. Krochnke (Editors), Leipzig, 1948, cited in Ref. 139
105. Masing, G. and G. Tammann, Zeitschr. anorg. u. allgem. Chem., 67, 183 (1910), cited in Ref. 23
106. McDonald, J. C. (Dow Chemical Co., Midland, Mich.), Private Communication to L. R. Kelman (ANL), Nov. 16, 1949
107. McKay, R. J. and R. Worthington, Corrosion Resistance of Metals and Alloys, Reinhold Publishing Co., N. Y., 1936
108. McMahon, K. D. (KAPL), "Large Scale Handling," Chapter in Liquid Metals Handbook now being prepared by the Committee on the Basic Properties of Liquid Metals
109. Mellor, J. W., Comprehensive Treatise on Inorganic and Theoretical Chemistry, Longmans, Green and Co., London, N. Y., Vols. II (Li) and VIII (N)-cited in Ref. 23, Vols. IV and VII (Hg)-cited in Ref. 139
110. Meyer, R. J., Gmelins Handbuch der anorganischen chemie System - Nummer 20: Lithium (1926), (Gmelin's Handbook of Inorganic Chemistry), Verlag Chemie, Berlin, cited in Ref. 23

7428 150

111. Michigan Steel Casting Co., Engineering Data, cited in Ref. 114
112. Miller, H. J., "Penetration of Brass by Tin Solder," Jour. Inst. Metals, 37, p. 183, 1927
113. Mitchell, D. W., "Solubility of Iron in Liquid Magnesium," Metals Technology, 15, T.P. 2309, Jan., 1948
114. Morrell, F. R., "Corrosion of Materials of Construction by Molten Metals," Wire and Wire Products, 23, June-July, 1948
115. Moyle, M. M., "Pumping Molten Magnesium," Metals and Alloys, 22, p. 716, Sept., 1945
116. National Physical Laboratory, Memorandum on the Action of Molten Bismuth, Tin, and Lead on Uranium and Beryllium, AERE-M-1588, Aug. 11, 1948
117. National Research Corp., Report of Lithium Research, OSRD, (1944) cited in Ref. 23
118. Nerad, A. J., Discussion to Paper by H. N. Hackett, Ref. 67, Trans. ASME, Oct., 1942
119. Nerad, A. J., Reported at Fourth Meeting of the Committee on Basic Properties of Liquid Metals, May 13, 1948
120. Neumann, B., C. Kroger and H. Haebler, Zeitschr. anorg. u. allgem. Chem., 204, 81 (1932), cited in Ref. 23
121. Novick, M. and F. D. McGinnis, Report for Period Dec. 1, 1948 through Feb. 28, 1949, ANL-4274
122. Nowotny, H., E. Wormnes and A. Morhnheim, Zeitschr. Metallkde., 32, p. 39, 1940, cited in Ref. 2
123. Oesterheld, G., Zeitschr. anorg. u. allgem. Chem., 97, 1916, cited in Ref. 17
124. Oknoff, M. G. and D. J. Gluskin, "The Dissolution of High Melting Point Metals and Alloys," Metallurgical Abstracts, 7, p. 16 (1940) (From Metallurg. 12, 7, (1938) Russ.)
125. Osborg, H., Lithium, Theoretical Studies and Practical Applications, The Electrochemical Society (1935), cited in Ref. 23

126. Payne, R. J. M. and J. L. Haughton, "Some Attempts at Making Beryllium-Magnesium Alloys," Jour. Inst. Metals, 49, p. 363, 1932
127. Peredelski, K. W., Legkie Metally, 5, 1936, cited in Ref. 17
128. Peresslegin, W. A., Chem. Zentr., 14, 1938, cited in Ref. 17
129. Peters, K., Zeitschr. anorg. u. allgem. Chem., 131, 140 (1923), cited in Ref. 23
130. Pohl, R., and A. Pringsheim, Verh. phys. Ges. 14, 46 (1912), cited in Ref. 23
131. Primak, W. L., et. al., Unpublished data and data reported in ANL Summary Reports from July, 1947 through Dec., 1948, Chemistry Division, Section 2, ANL-4185, 4204, 4258, 4288
132. Rehn, I., Thermoelectric Effect Between NaK and Nickel, ANL-4029, Sept. 2, 1947
133. Rimbach, O., Beryllium: Its Production and Application, Chem. Cat. Co., N. Y., 1932, cited in Ref. 139
134. Ritter, F., Korrosionstabellen metallischer Werkstoffe (Corrosion Tables of Metallic Materials), Julius Springer (Editor), Berlin, 1937-1944 Editions, cited in Ref. 114
135. Roddis, L. H. (Verbal information from Aerojet Engineering Corp.), Private Communication to L. R. Kelman, June 30, 1949
136. Rogers, R. R. and G. E. Viens, "The Production of Lithium Metal," Canadian Mining and Metallurgical Bulletin, 41, 623-628, Nov., 1948
137. Roush, M. S., (Tapco Plant of Thompson Products, Inc.), Private Communication to L. R. Kelman (ANL), Sept., 1949
138. Saitta, V. F. and G. E. Northrup, "Mercury Corrosion Work at ANL," Data reported in Preliminary Feasibility Report on Liquid Control Systems for the Naval Reactor, Westinghouse Electric Corp., Atomic Power Div., WAPD-3, p. 157, Jan. 1, 1950
139. Saitta, V. F. and G. E. Northrup, Private Communication, unpublished review of literature up to 1949
140. Schleede, A. and M. Wellmann, "About the Structure of the Product of the Reaction of Alkali Metals with Graphite," Zeitschr. f. anorg. u. allgem Chem., Series b, 1932, vol. 18, pp. 1-28

190

141. Seban, R. A., W. T. Schrank, and D. Bartz, Flow-Metering of Molten Lead-Bismuth Eutectic at Univ. of Calif., Univ. of Calif., Berkeley, Calif. (NObs 45 468), April 25, 1949
142. Seith, W. and O. Kubaschewski, "Die Elektrolytische Ueberfuehrung von Kohlenstoff in Festen Stahl" ("The Electrolytic Transport of Carbon in Solid Steel"), Zeitschr. f. Elektrochem. u. angew. physik. Chem., 41, 7b, 1935, pp. 551-558
143. Shepard, O. C., Investigation of Materials for use in a Heat-transfer System Containing Molten Lead Alloys, Stanford Univ., School of Mineral Science, Div. of Metallurgy, Contract NObs 45468; (A) Progress Report No. I, July 19 to Aug. 10, 1948; (B) Progress Report No. II, Aug. 10 to Jan. 31, 1949; (C) Progress Report No. III, Feb. 1 to April 30, 1949; (D) Navy Contract N6OR1 21120, Identification No. N-2531M, Status Report No. IV for May 1 to Aug. 31, 1949
144. Simon, F. and R. Swain, Zeitschr. physik. Chem. (B), 28, 189, (1935), cited in Ref. 23
145. Smith, A. A., Jr., (American Smelting and Refining Co.), Private Communication to F. L. Yaggee (ANL), Dec. 20, 1949
146. Smith, A. R. and E. S. Thompson, "The Mercury-Vapor Process," Trans. ASME, p. 625, Oct., 1942
147. Smith, W. C., (Cerro De Pasco Copper Co., N. Y.), Private Communication to W. D. Wilkinson (ANL), May 18, 1949
148. Smith, W. R. and P. E. J. Forsyth, "Grain Boundary Penetration by Liquid Metals," Metallurgia, vol. 34, p. 186, 1946
149. Stanley, J. K., "The Diffusion and Solubility of Carbon in Alpha Iron," Journal of Metals, 1, (10), p. 752, Oct., 1949
150. Suits, C. G. and K. H. Kingdon, Progress Report No. 34 for period May 1-31, 1949, KAPL-199
151. Swartz, C. E., "A Study of Certain Alloys of the Lead-Tin-Cadmium System with Reference to Their Use as Solders," Trans. AIME (Inst. Met. Div.), p. 352, (1928)
152. Tidball, R. A., Corrosion of Certain Materials by Sodium-Potassium Alloy, MSA Preliminary Report No. 9, June 24, 1948
153. Tidball, R. A. (MSA), Final Report on Subcontract NObs 45468 Rep. on Research with Sodium and Sodium-Potassium Alloys From July 1, 1948 to May 31, 1949

154. Timmerhof, W., "Die Loeslichkeit verschiedener Staehle in Bleischmelzen" ("Solubility of Various Steels in Molten Lead and Lead Alloys"), Zeitschr. Metallkde, 34, p. 102 (1942)
155. Treadwell and Hartnagel, Helv. Chim. Acta., 17, 1934, cited in Ref. 17
156. Uhlig, H. H. (Editor), Corrosion Handbook. Electrochemical Society, Inc. (Sponsors), John Wiley and Sons, Inc., N. Y., 1948
157. Union Carbide and Carbon Research Laboratories, Inc., Niagara Falls, N. Y., cited in Ref. 156
158. U. S. Steel Corporation, Stainless and Heat Resisting Steels for Modern Industry, cited in Ref. 114
159. Vandenberg, S. R. (KAPL), Reported at 12th Meeting of the Committee on Basic Properties of Liquid Metals, Nov. 14, 1949
160. Voss, G., "Alloys of Ni and Sn, Pb, Tl, Bi, Cr, Mg, Zn and Cd," Bull. Soc. Chim., 6/1909, 4 Serie, p. 245-246, Abstract of Article that appeared in Zeitschr. anorg. u. allgem. Chem., V. 57-34-71 (1908)
161. Wallbaum, H. Z., "On the Isomorphism of Al_3Ti , Ga_3Zr ," Zeitschr. Metallkde., 1942, 34 (5) 118-119
162. Washburn, E. W. (Editor-in-Chief), International Critical Tables, Published for National Research Council by McGraw-Hill Book Co., 1926
163. Weber, C. E. and L. F. Epstein (KAPL), "Problems in the Use of Molten Sodium as a Heat Transfer Fluid," Jour. of Metallurgy and Ceramics (AEC), Issue No. 3, p. 85, May, 1949
164. Wells, C. and R. F. Mehl, "Rate of Diffusion of Carbon in Austenite in Plain Carbon, in Nickel, and in Manganese Steels," Trans. AIME 140, 1940, p. 279
165. Werner, R. C. (MSA), Private Communication to L. R. Kelman (ANL), Dec. 15, 1949
166. Whitaker, M. E., "Investigations of Attack by Eutectic Tin-Lead Solder at 200°C on Various Brasses," Metallurgia, 39, p. 21, 1948
167. Wilkinson, W. D., et al., "Resistance of Materials to Attack by Lead, Bismuth, and Their Alloys," unpublished data and preliminary data reported in ANL Met. Div. Quarterly Progress Reports for Period July through Dec., 1949, ANL-4364 and 4399

168. Wilkinson, W. D., Properties of Gallium, ANL-4109, Feb. 10, 1948
169. Wilkinson, W. D., Effects of Gallium at Temperatures up to 800°C on Heavy Metals and on Some Refractories, ANL Report submitted for declassification, Aug. 23, 1948
170. Wilkinson, W. D., Effects of Gallium on Materials at Elevated Temperatures, ANL Report
171. Wilkinson, W. D., F. L. Yaggee, et al., "Resistance of Materials to Attack by Lithium," unpublished data and preliminary data reported in ANL Met. Div. Quarterly Progress Reports for period July through Dec., 1949, ANL-4364 and 4399
172. Yaggee, F. L., unpublished work at ANL
173. Young, J. W. and E. C. Piottter, Second Interim Report on the Investigation of the Corrosive Action of KNa Alloy on Metals, B & W Rep. No. ES 401-7, NObs 34222, Feb. 21, 1949
174. Zintl, E., A. Harder, and W. Haucke, "Alloy Phases with a Fluorite Structure," Zeitschr. physik. Chem., 1937, B, 35 (5), 354-362

Abbreviations Used in Bibliography for Names of
Laboratories and Companies

ANL	Argonne National Laboratory
AS & R	American Smelting and Refining Company
B & W	Babcock and Wilcox Company
BMI	Battelle Memorial Institute
GE	General Electric Research Laboratory
KAPL	Knolls Atomic Power Laboratory (GE)
MSA	Mine Safety Appliances Company
NEPA	Nuclear Energy for Propulsion of Aircraft
ORNL	Oak Ridge National Laboratory
WAPD	Westinghouse Atomic Power Division

1- 142