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AN ANNOTATED BIBLIOGRAPHY
FOR LIQUID METAL SURFACE
TENSIONS OF GROUPS III-A,
IV-A, AND V-A METALS

MASTER

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Date Transmitted: April 1976

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FOR LIQUID METAL SURFACE TENSIONS
OF GROUPS III-A, IV-A, AND V-A METALS

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ABSTRACT

An annotated bibliography has been prepared which includes summaries of 82 publications dating from 1920 and dealing with the measurement of the surface tensions of Groups III-A, IV-A and V-A metals in the liquid state. The bibliography is organized by key element investigated, and contains a tabulation of correlations for surface tension as a function of temperature. A brief discussion dealing with variables and methods has been included.

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I. INTRODUCTION

The use of lower-melting metals and alloys in their liquid state is being looked to with increasing frequency as new nuclear reactor and industrial processing concepts are proposed. Heat and mass transfer applications are largely involved which, in their design and operation, often require data on physical and chemical properties beyond those now available.

One of these properties which is widely used but for which only limited and scattered data are available is surface tension. This property appears frequently in correlations dealing with corrosion, fluid flow, wetting, bubble nucleation and growth, entrainment, etc. The metals involved most often are the alkali metals, sodium, potassium and lithium, and the metals of Groups III-A, IV-A, and V-A, namely, aluminum, gallium, indium, thallium, germanium, tin, lead, antimony and bismuth. Their melting points are shown in Table I, along with those for the alkali metals.

Nearly all of the surface tension data that are available are for essentially pure metals. As applications develop, information will be needed about the effect of impurities, such as other elements and dissolved gases, on surface tension. Data are also needed in most cases for a wider range of temperature. Most measurements have been made near the melting point so as to minimize the effect of vaporization from the liquid metal surface. Greater precision is also needed; the best data now available probably have confidence limits no better than ± 10 percent.

It is not because of a lack of investigation that the desired data are not available. Scientists have been measuring the surface tensions of pure liquid metals and of alloys by increasingly improved methods from

1900 to the present. The reported results (the best available) for the metals in question are those reported in this annotated bibliography.

In some cases, results from a given investigator fail to agree with results previously published by the same person for the same element. The experimental methods are difficult, but as improvements in equipment and technique occur, better data are appearing and can be expected in the future.

II. VARIABLES WHICH EFFECT SURFACE TENSION

There are reasons for the variance in surface tension data. The surface tension of a material seems to be affected by many different things, and some of these effects are difficult to isolate and control. The basic theories of surface tension are developed in surface chemistry texts such as Adam (1) or Semenchenko (2), and will not be discussed here. But creating the experimental conditions required for use of these theories makes precise measurement of surface tension difficult. Perhaps the most challenging condition to meet is the requirement for complete thermodynamic equilibrium. The metal must be in thermodynamic equilibrium with its own vapor and be free from any chemical, mechanical, thermal, or electrical effects. Electrical, thermal, and mechanical effects present equipment design problems of which mechanical vibration is the only one easily solved. Supplying heat to the metal often causes electrical-field effects, thermal convection, and vaporization.

Chemical effects can be of a random nature. For example, impurities may have different effects in different metals. Semenchenko (2) cites a

method for determining whether an impurity will influence surface tension which is based on the generalized moment of the elements. Essentially an impurity having a smaller moment than the base metal will be surface-active to that metal, i.e., will decrease the surface tension. Impurities with moments larger than that of the base metal will have a negligible effect on surface tension. Table II is a list of generalized moments of elements arranged so that an impurity will be surface active in the metals listed below it.

A comparison of generalized moments can explain why metal purity will not always be a basis for improved surface tension research. For example, six grams of cesium in 10,000 tons of mercury (10^{-10} dilution) has a measurable effect on the surface tension, but the addition of 15 atom percent germanium to pure indium does not change the measured surface tension.

This apparent randomness is also true of the effect of the gaseous atmosphere in which the experiment is run. Many of the researchers made measurements using an atmosphere of hydrogen, helium, or argon which may or may not have had an influence on the results. It has been shown in this laboratory that erroneous data result for some metals when minute amounts of water vapor, oxygen or hydrocarbons are present. The films are not always observable, but the measurements will show a drift with time as the gas is absorbed.

The measurement of the surface tension of liquid metals under even the highest of vacua is not totally satisfactory because of vaporization from the liquid metal surface. Work in this laboratory with liquid tin at 250 to 500°C where the vapor pressure is only 10^{-23} to 10^{-13} torr

demonstrated an effect attributable to surface vaporization. The best arrangement appears to be the use of a totally inert atmosphere at a pressure high enough to suppress vaporization.

III. METHODS FOR MEASUREMENT OF THE SURFACE TENSION OF LIQUID METALS

Methods for the measurement of surface tension can be divided into two general categories: dynamic methods, such as the vibrating jet, and static methods such as the maximum pressure method. The dynamic methods all result in uncontrolled inertial forces which, it is generally agreed, limit their accuracy. Of the static methods, the capillary rise method is the most important and is considered the standard. It is not used with liquid metals because of experimental difficulties, however, and the two methods most often employed are the maximum pressure method and the sessile drop method.

Maximum Bubble or Drop Pressure Method

In the maximum-pressure method either a bubble of gas is formed at the tip of a capillary submerged below the surface of a liquid (maximum-bubble pressure) or a drop of liquid is forced out of the tip of an inverted capillary (maximum-drop pressure). If the metal wets the capillary, the maximum-bubble pressure method should be used; if the capillary is not wetted, the maximum-drop pressure method should be used. Most liquid metals display some wetting tendency.

Proper preparation of the capillaries is important to the success of the experiments. The capillary walls at the tip are sharpened so there will be little difference whether the drop is attached at the inside or

outside radius. Early experiments were with very small capillaries which produced hemispherical bubbles, but many years ago Sudgen (3) and Schroedinger (4) modified the method so that capillaries of reasonable diameter could be used. The theory and various forms of equipment for the maximum pressure method are discussed in Semenchenko (2). This annotated bibliography contains some publications of Russian origin (Pugachevich, Timofeevichova, Pohrovskie and others) which deal with a "gravitational" method that involves measurement of maximum bubble pressure or maximum drop pressure in a single glass apparatus.

Sessile Drop Method

The sessile-drop method is based on the calculation of the surface tension of a liquid using measurements taken from the profile of a drop setting on a plane surface. Bashforth and Adams (5) derived the original equation for the shape of the sessile drop. By using differential approximations they developed tables for rapid calculation of surface tension when the drop maximum diameter, X , and height, Z_{90} , above that maximum diameter were known. The form of the sessile drop equation is

$$\frac{1}{R_1} = \frac{gdZ}{\sigma} - \frac{\sin \phi}{X} + \frac{Z}{b} \quad (1)$$

where R_1 = radius of curvature in the plane at point (X, Z) on the profile

σ = surface tension

d = difference between the density of drop and density of surroundings

g = gravitational constant

ϕ = angle between a normal to the drop at (X, Z) and a vector

opposing the gravitational force

b = radius of curvature at top of drop

For large drops the term Z/b becomes negligible and a simplified equation can be used.

$$\sigma = dg Z_{90}^2 \left(\frac{1.641 X}{1.641 + Z_{90}} \right) \quad (2)$$

The point where Z/b drops out is dependent upon drop density. This modification was developed by Worthington (6).

Because it is extremely difficult to accurately locate a line through the maximum diameter, Dorsey (7) derived an empirical equation for calculating surface tension using a height determined from a geometric construction of the intersection of the polar axis of the drop and a 45° tangent to the profile above the major diameter, X .

Many investigators have adapted Bashforth and Adams' tables with graphs, interpolation computer programs etc., but Maze (8) developed a method based on the original equation (1). A non-linear least squares computer program using data from the entire drop profile calculates the value for σ to best fit the data. If the drop is inverted so that it hangs from a rod or tube, the surface tension can still be calculated by equation (1) with the gravitational direction reversed.

Some other methods of measurement usually used for organic and aqueous liquids have been used with liquid metals. The Wilhelmy plate method has been used in metals which completely wet the plate. In this method the maximum force exerted on the plate as it is withdrawn from the liquid is measured by a torsion balance. Another method which has

been used is the drop weight method. This procedure involves weighing a known number of drops which fall from a rod or tube to obtain W. The surface tension is then calculated as follows:

$$\sigma = \frac{W}{f \ 2\pi r} \quad (3)$$

The term f is the percentage of each drop that falls off the tip in relation to the mass if the entire drop had released completely. To determine this value accurately is difficult and limits the usefulness of the method.

IV. REFERENCES CITED

1. Adam, N. K., The Physics and Chemistry of Surfaces. 3rd ed. Oxford University Press, London, Eng. 1941.
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6. Worthington, A. M., Phil. Mag. 20:51-66. 1885.
7. Dorsey, M. Ernest, J. Wash. Acad. Sci. 18:505-509. 1928.
8. Maze, Craig and George Burnet, Surface Sci. 27:411-418. 1971.

V. ANNOTATED BIBLIOGRAPHY SECTION

Surface tension research of the III-A, IV-A and V-A metals of the periodic table conducted since 1920 has been annotated in the following bibliography. All useful information contained in the original article concerned with surface tension is provided in each annotation.

The Chemical Abstracts were the source of this literature compilation but each reference contained in abstracted articles was also reviewed. Many of the original articles cited are in Russian but when the translation is available both sources are given. When a translation was not available the term "abstracted" follows the citation.

Index of Methods & Systems

The bibliography has been organized by metal in alphabetical order with the citation located with the first metal referred to. Several of the articles refer to more than one metal and information outside the range of the investigation is provided when available. The index lists each citation and the metals referred to in that article. A reference such as In-Bi means that the entire system from 0 to 100 atomic % was studied. A reference Al-(Li,Ca,Mg,Sb) means small amounts of lithium, calcium, magnesium, or antimony were added to pure aluminum to measure surface-activity. The reference is cited under the first alphabetical metal studied, therefore, citations in the antimony section contain data on bismuth, lead, tin, etc.

Table III contains surface tension data as a function of temperature or at a temperature for each metal which has been reported in each

citation. In the author column, Bi-Golubev, means that the data are contained in the paper by N. A. Golubev, E. L. Zhukovskii, and N. L. Pokrovskii that is cited in the bismuth section.

Index of Methods & Systems

Metal	Method of Measurement	Principal Author	Systems Investigated
Aluminum	Sessile drop	Ayushina	Fe-Al
	Sessile drop	Ayushina	Al-Co, Al-Ni
	Maximum pressure	Davies	Al-Si-Na
	Maximum pressure	Engler Eremenko	Al-Cu Cu-Al, Ni-Al, Ni-Be
	Sessile drop	Eustathopoulos	Al-(Ti, Si, Cr, Be, Ca, Li)
	Maximum pressure	Keese	Al-(Be, Ga, Mg)
	Maximum pressure	Koral'kov	Al-(Li, Ca, Mg, Sb, Sn, Pb, Bi)
	Maximum pressure	Koral'kov	Al-(Li, Bi, Pb, Mg, Sb, Sn, Fe, Cu, Ni, Si, Mn, Cr), Zn-(Bi, Pb, Li, Sb, Sn, Fe, Cu, Al)
	Maximum pressure	Lang	Al-(Ce, Co, Zr, V, Sb, Cr, Ca, Ag, Sr, Li, Ti, Ba, Ga, B)
	Sessile drop	Levin	Al
	Sessile drop	Naidich	Cu, Al
	Maximum pressure	Pelzel	Zn, Sn, Al, Mg
	Capillary	Skuchilov	Al-Mg
	Sessile drop	Yatsenko	Sn, In, Al, Ga
Antimony	Maximum pressure	Bircumshaw	Bi, Cd, Zn, Sb
	Maximum pressure	Greenaway	Pb-Sb, Cd-Sb
	Maximum pressure	Lazarev	In-Sb
	Maximum pressure	Lazarev	In-Sb
	Drop weight	Matuyama	Sb, Sn, Zn, Bi, Cd, Pb
	Maximum pressure	Sauerwald	Sn, Pb, Sb, Cu, Sn-Bi, Cu-Sb, Cu-Sn, cast iron

Index continued...

Metal	Method of Measurement	Principal Author	Systems Investigated
Bismuth	Drop weight	Addison	Bi
	Wilhelmy	Bakradze	Pb-Sn, Bi-Pb, Bi-Sn, Bi-Cd
	Maximum pressure	Bohdansky	Ag, Tl, Pb, Bi
	Maximum pressure	Dzhoglev	Bi, Bi-Pb, Bi-Sn
	Maximum pressure	Golubev	In-Bi
	Maximum pressure	Herczynska	Bi-U, Sn-Tl
	Maximum pressure	Hogness	Hg, Cd, Zn, Pb, Sn, Bi
	Maximum pressure	Ibragimov	Sn-Bi
	Sessile drop	Ishiguro	Sn, Bi, Pb
	Sessile drop	Khokonov	Ga-In, Ga-Bi
		Khokonov	Ga-In, Ga-Bi
		Klyachko	Sn-Bi, Pb-Sn, Pb-Bi
	Maximum pressure	Koval'chuk	In-Bi
	Maximum pressure	Koval'chuk	In-Bi
	Sessile drop	Maze	Pb, Bi
	Maximum pressure	Metzger	Cu, Ag-Pb, Ag-Bi, Cu-Pb
	Maximum pressure	Pugachevich	Bi, Bi-Na, Bi-K
	Maximum pressure	Sauerwald	Hg, Bi
	Maximum pressure	Smirnov	Bi-In
		Unezhev	Bi, Cd, Sn, Pb, Ga, In
Gallium	Pendant drop	Abbaschian	Ga
	Sessile drop	Eremenko	Ni-Ga
		Frumkin	Ga
	Maximum pressure	Ibragimov	Ga, Sn-Bi

Index continued...

Metal	Method of Measurement	Principal Author	Systems Investigated
Gallium continued	Sessile drop	Karashaev	Ga
	Sessile drop	Khokonov	Ga-In
	Pendant drop	Mack	Ga
	Maximum pressure	Nal'giev	Ga
	Sessile drop	Nizhenko	Ga-Sn
	Sessile drop	Nizhenko	Ga-Fe
	Maximum pressure	Ofitserov	Sn-Ga
	Sessile drop	Richards	Ga
	Sessile drop	Sukhman	Ga-In-Sn
	Sessile drop	Sukhman	Ga-Pb
	Sessile drop	Sukhman	Ga
	Maximum pressure	Timofeevicheva	Ga, In, Tl, Cd, Ge, Pb, Sn
	Maximum pressure	Timofeevicheva	Ga
Germanium	Drop weight	Keck	Si, Ge
	Sessile drop	Kolesnikova	Ge
	Maximum pressure	Lazarev	Ge-(Sb,Bi,In,Ga,Tl)
	Maximum pressure	Lazarev	Ge-(Sn,Bi,In,Ga,Tl)
	Maximum pressure	Lazarev	Ge
	Maximum pressure	Lazarev	Ge-Sn, Ge-Pb, Ge-Bi, Ge-In, Ge-Tl, Ge-Cu, Ge-Ni, Ge-Co
	Sessile drop	Naidich	Au-Si, Au-Ge
	Sessile drop	Sangster	Ge, Pb, Cd

Index continued...

Metal	Method of Measurement	Principal Author	Systems Investigated
Indium	Sessile drop	Aldrich	In
	Sessile drop	Aldrich	In
	Maximum pressure	Bergh	In-Na
	Maximum pressure	Davies Gratsianskii	In, In-(Ge) In-Pb
	Maximum pressure	Koval'chuk	In-Sn
	Capillary	Melford	Pb, Sn, In
	Maximum pressure	Pokrovskii	In-Pb
	Maximum pressure	Timofeevicheva	In
	Sessile drop	White	In, Cd
Lead	Maximum pressure	Bircumshaw	Sn, Pb
	Maximum pressure	Bircumshaw	Pb-Sn
	Sessile drop	Bradhurst	Pb-(Bi, O ₂ , S, Se, Te)
	Sessile drop	Demeri Gratsianskii	Pb-Sn Pb-Tl
	Sessile drop	Joud	Pb-Ag, Pb-Cu
	Sessile drop	Joud	Ag-Cu-Pu
	Maximum pressure	Koval'chuk	Tl-Pb
	Sessile drop	White	Pb, Sn, Pb-Sn
Thallium	Maximum pressure	Koval'chuk	Tl-Sn
	Maximum pressure	Sauerwald	Fe-C, Hg ₅ Tl ₂ , NaHg ₂ , Tl, slags
	Maximum pressure	Timofeevicheva	Tl

Index continued...

Metal	Method of Measurement	Principal Author	Systems Investigated
Tin	Maximum pressure	Abdel-Aziz	Sn
	Sessile drop	Allen	Fe, Cu, Co, Ni, Sn, Fe-C, Co-C, Ni-C
	Capillary	Atterton	Sn
	Maximum pressure	Cahill	Sn
		Eremenko	Sn-Ti
	Maximum pressure	Foryst	Hg, Sn, Bi, Pb, Pb-(Zn,Sn)
	Sessile drop	Gans	Sn
	Sessile drop	Kaufman	Au, Sn, Au-Sn
	Maximum pressure	Lauermann	Ag, Sn, Ag-Sn
	Sessile drop	Mukai	Sn
	Sessile drop	Naidich	Sn-Ge
	Maximum pressure	Nal'giev	Sn-Hg
	Sessile drop	Nizhenko	Sn-Fe
	Maximum pressure	Pokrovskii	Sn, Sn-Na
	Maximum pressure	Pokrovskii	Sn-(Tl,As)
	Maximum pressure	Pokrovskii	Sn, Sn-(In,Ge)
	Maximum pressure	Pokrovskii	Sn-(Zn,Al,Cd,Mn,Bi)
	Maximum pressure	Pokrovskii	Sn-Au
	Maximum pressure	Sauerwald	Hg, Sn, Tl
	Maximum pressure	Schwaneke	Sn

Table I. Melting Points for the Alkali Metals and the Metals of Groups III-A, IV-A and V-A*

Elements by Periodic Group	Melting Point, °C
Alkali Metals	
Li	186.0
Na	97.5
K	62.3
Group III-A Metals	
Al	659.7
Ga	29.8
In	156.4
Tl	302.0
Group IV-A Metals	
Ge	958.5
Sn	231.9
Pb	327.4
Group V-A Metals	
Sb	630.5
Bi	271.3

* Handbook of Chemistry and Physics, (Chemical Rubber Co., Cleveland, Ohio, 1969) 50th Ed., pp. B83-B176.

Table II. List of Increasing Generalized Moments of Selected Elements

1. Cs	13. Sr
2. Rb	14. Hg
3. Au	15. Ca
4. K	16. Cu
5. Ag	17. Cd
6. Te	18. Sn
7. Na	19. Mn
8. Cu	20. Co
9. Li	21. Zn
10. Ba	22. Mg
11. Bi	23. Al
12. Pb	24. Be

Table III. Summary of Surface Tension Data as a Function of Temperature

Metal	Principal Author	σ , dynes/cm = $f(t)^{\circ}\text{C}$	Temperature Range, $^{\circ}\text{C}$	Temperature $^{\circ}\text{C}$
Aluminum	Ayushina	965 - 0.15 t	900 - 1750	
	Aynshina	965 - 0.15 t	1000 - 1750	
	Davies	825 - 0.05 (t-660)	600 - 900	
	Eremenko	865 - 0.14 (t-660)		
	Eustathopoulos	870 - 0.195 (t-660)	660 - 1050	
	Korel Kov	860 $\pm$ 20	700 - 740	
	Lang	862		700
	Levin	965 - 0.15 t	1000 - 1500	
	Naidick	865 - 0.14 (t-660)	1000 - 1500	
	Pelzel	914 - 0.35 (t-660)	700 - 800	
	Yatsenko	865 - 0.16 (t-660)		
Antimony	Bircumshaw	352 - 0.032 (t-640)	640 - 1000	
	Greenaway	383 - 0.025 (t-635)	635 - 800	
	Lazarev	350 - 0.033 (t-650)	650 - 800	
	Lazarev	350 - 0.033 (t-650)	650 - 800	
	Matuyama	368 - 0.025 (t-640)	640 - 800	
	Sauerwald	368 - 0.063 (t-750)	750 - 1100	
Bismuth	Addison	378 - 0.069 (t-271)	300 - 500	
	Bohdansky	423 - 0.088 (t-273)	1075 - 1275	
	Dzhoglev	400 - 0.33 (t-290)	290 - 350	
	Golubev	370 - 0.05 (t-300)	300 - 500	
	Herczynska	362 - 0.058 (t-350)	350 - 550	
	Hogness	378 - 0.063 (t-269)	320 - 470	
	Ibragimov	370 - 0.065 (t-270)	270 - 500	
	Khokonov	370 - 0.090 (t-271)	270 - 500	
	Klyachko	392 - 0.13 (t-280)	280 - 340	
	Metzger	343 - 0.017 (t-800)	800 - 1000	
	Pugachevich	368 - 0.055 (t-260)		
	Sauerwald	354 - 0.060 (t-583)	580 - 780	

Table III continued...

Metal	Principal Author	σ , dynes/cm = $f(t)^{\circ}\text{C}$	Temperature Range, $^{\circ}\text{C}$	Temperature $^{\circ}\text{C}$
Bismuth continued	Sb - Bircumshaw	391 - 0.055 (t-320)	320 - 1000	
	Sb - Matuyama	400 - 0.165 (t-300)	300 - 600	
	Ge - Lazarev	370		1000
Gallium	Abbaschian	724 - 0.068 (t-30)	4 - 40	
	Eremenko	559		1500
	Frumkin	592		
	Karashaev	718 - 0.101 (t-29.87)	-20 - 360	
	Khokanov	714 - 0.088 (t-28.8)	30 - 550	
	Mack	735 $\pm$ 29		30
	Naligiev	708 - 0.037 (t-29.8)	30 - 450	
	Nizhenko	827 - 0.157 (t-29.8)	800 - 1600	
	Nizhenko	708 - 0.0031 (t-29.8) - 0.000067 (t-29.8) ²		19
	Richards	358		30
	Timofeevicheva	706.6 - 0.000647(t-29.8) - 0.0000965 (t-29.8) ²	30 - 500	
	Al - Yatsenko	712 - 0.0606 (t-30)		
Germanium	Bi - Khokonov	714 - 0.088 (t-29.8)	30 - 500	
	Keck	600		937
	Kolesnikova	650 - 0.6 (t-937)	937 - 1200	
	Lazarev	610 - 0.1 (t-950)	950 - 1150	
	Lazarev	609 - 0.1 (t-950)	950 - 1150	
	Lazarev	621.4 - 0.261 (t-936)		1500
	Lazarev	590		
	Naidich	642 - 0.140 (t-940)	900 - 1200	
	Sangster	632 $\pm$ 5		937
	Ga - Timofeevicheva	610 - 0.22 (t-937)	937 - 1400	

Table III continued...

Metal	Principal Author	σ , dynes/cm = $f(t)^{\circ}\text{C}$	Temperature Range, $^{\circ}\text{C}$	Temperature $^{\circ}\text{C}$
Indium	Aldrich	600 - 670		160
	Aldrich	600		158
	Bergh	514 ± 4		600
	Gratsianskii	592		185
	Koval'chuk	$555 - 0.077 (t-157)$	157 - 457	
	Melford	$559 - 0.10 (t-156)$	156 - 390	
	Pokrovskii	$570 - 0.10 (t-200)$	200 - 500	
	Timofeevicheva	$556 - 0.085 (t-156)$	170 - 500	
	White	$568 - 0.04 t - 7.08(10) - 5t^2$	157 - 557	
	Al - Yatsenko	$565 - 0.09 (t-156)$		
	Sb - Lazarev	$556 - 0.085 (t-200)$	175 - 800	
	Sb - Lazarev	$554 - 0.078 (t-200)$	200 - 800	
	Bi - Golubev	$555 - 0.083 (t-200)$	200 - 500	
	Bi - Khokonov	$556 - 0.081 (t-156)$	156 - 500	
	Bi - Koval'chuk	534		400
	Ga - Khokonov	$556 - 0.081 (t-156)$	200 - 550	
	Ga - Timofeevicheva	$561 - 0.086 (t-200)$	200 - 500	
	Ge - Lazarev	480		1000
				20
Lead	Bircumshaw	$452 - 0.056 (t-327)$	327 - 1000	
	Bircumshaw	$441.5 - 0.063 (t-327)$	327 - 800	
	Bradhurst	430		700
	Gratsianskii	456		390
	Joud	$462 - 0.11 (t-327)$		
	Joud	$462 - 0.11 (t-327)$	550 - 1000	
	Koval'chuk	$447 - 0.080 (t-437)$	437 - 562	
	White	$444.9 - 0.085 (t-327)$	327 - 560	
	Sb - Greenaway	$448 - 0.090 (t-340)$	340 - 440	
	Sb - Matuyama	$470 - 0.166 (t-327)$	327 - 675	
	Sb - Sauerwald	$423 - 0.096 (t-750)$	750 - 1100	
	Bi - Bohdanský	$470 - 0.115 (t-330)$	330 - 495	

Table III continued...

Metal	Principal Author	σ , dynes/cm = $f(t)^{\circ}\text{C}$	Temperature Range $^{\circ}\text{C}$	Temperature $^{\circ}\text{C}$
Lead continued	Bi - Hogness	444 - 0.077 (t-327)	370 - 520	
	Bi - Klyachko	452		360
	Bi - Metzger	420 - 0.12 (t-420)		
	Ga - Timofeevicheva	415 - 0.152 (t-800)	800 - 1030	
	Ge - Lazarev	360		1000
	Ge - Sangster	424 $\pm$ 10		327
	In - Melford	480 - 0.24 (t-324)	340 - 600	
	In - Gratsianskii	455		362
	In - Pokrovskii	440 - 0.10 (t-350)	350 - 500	
Thallium	Sauerwald	440		320
	Timofeevicheva	464.5 - 0.080 (t-303)	310 - 500	
	Bi - Bohdanský	503.5 - 0.119 (t-273)	996 - 1427	21
	Ge - Lazarev	410		1000
	Pb - Gratsianskii	507		390
	Pb - Koval'chuk	447 - 0.064 (t-437)	437 - 562	
Tin	Abdel-Aziz	524 - 0.073 (t-360)	360 - 700	
	Allen	600 - 0.176 (t-273)		
	Atterton	614 - 0.17 (t-232)	400 - 800	
	Cahill	545 - 0.074 (t-232)	475 - 1925	
	Gans	590		290
	Kaufman	550 - 0.133 (t-232)	900 - 1200	
	Lauermann	479.5 - 0.072 (t-1115)	740 - 1115	
	Mukai	580 - 0.053 t	250 - 500	
	Naidich	512 - 0.10 (t-600)	600 - 1000	
	Pokrovskii	537 - 0.078 (t-232)	250 - 450	
	Pokrovskii	540 - 0.072 (t-270)	270 - 450	
	Pokrovskii	545 - 0.092 (t-250)	250 - 500	

Table III continued...

Metal	Principal Author	σ , dynes/cm = $f(t)^{\circ}\text{C}$	Temperature Range $^{\circ}\text{C}$	Temperature $^{\circ}\text{C}$
Tin continued	Pokrovskii	549 - 0.072 (t-250)	250 - 500	
	Pokrovskii	545 - 0.060 (t-250)	250 - 500	
	Sauerwald	508 - 0.089 (t-878)	750 - 1100	
	Schwaneke	555.8 - 0.0476 (t-232)	236 - 583	
	Al - Pelzel	620 - 0.134 (t-230)	230 - 550	
	Al - Yatsenko	540 - 0.064 (t-232)	230 - 548	
	Sb - Matuyama	579 - 0.202 (t-230)	230 - 600	
	Bi - Herczynska	527 - 0.055 (t-300)	300 - 500	
	Bi - Hogness	531 - 0.080 (t-232)	360 - 400	
	Bi - Ibragimov	545 - 0.060 (t-250)	250 - 500	
	Bi - Klyachko	523 - 0.073 (t-280)	280 - 340	
	Ga - Timofeevicheva	490 - 0.105 (t-800)	800 - 1400	
	Ge - Lazarev	480		1000 $\approx$
	In - Koval'chuk	545 - 0.071 (t-237)	237 - 477	
	In - Melford	566 - 0.065 (t-232)	230 - 530	
	Pb - Bircumshaw	528 - 0.014 (t-230)	230 - 1000	
	Pb - Bircumshaw	550 - 0.070 (t-230)	230 - 800	
	Pb - White	550.5 - 0.080 (t-232)	232 - 560	

BIBLIOGRAPHY BY KEY ELEMENT

REFERENCES FOR ALUMINUM

Ayushina, G. D., E. S. Levin, and P. V. Gel'd. Effect of temperature and composition on the densities and surface tensions of iron-aluminum alloys. Zhur. Fiz. Khim. 42:2799-2802. 1968. Russ. transl. Russ. J. Phys. Chem. 42:1489-1492. 1968.

The temperature and concentration dependence of the surface tensions and densities of liquid iron aluminides was studied using the "large drop" method for surface tension measurement. The atmosphere was purified helium and the temperature range covered was 900 to 1750°C. 99.99 wt.% pure aluminum and iron were used. The surface tension data for liquid aluminum as a function of temperature were:

$$\sigma_{Al} = 965 - 0.15t$$

The surface tension isotherm showed a distinct break at about 55 at.% aluminum.

Ayushina, G. D., E. S. Levin, and P. V. Gel'd. The density and surface energy of liquid alloys of aluminum with cobalt and nickel. Zhur. Fiz. Khim. 43:2756-2761. 1969. Russ. transl. Russ. J. Phys. Chem. 43:1548-1551. 1969.

The temperature and concentration variation of the density and surface tension of liquid alloys of aluminum with cobalt and nickel was investigated. The surface tensions and densities of the pure metals and the alloys decreased linearly with increasing temperature. Measurements were made using the "large drop" method over a temperature range from 1000 to 1750°C. The surface tension data for pure aluminum as a function of temperature were:

$$\sigma_{Al} = 965 - 0.15t$$

The isotherms for both Al-Ni and Al-Co exhibited a break at 50 at.% Al, indicating the strong bonding of the intermetallic compounds NiAl and CoAl even in the liquid phase.

Davies, V.de L. and J. M. West. Influence of small additions of sodium on the surface tension of aluminum and aluminum-silicon alloys. J. Inst. Metals, London 92:208-210. 1964.

The maximum bubble pressure method was used to measure the surface tension of aluminum and aluminum-silicon alloys, 1.5 at.% and 12 at.%

silicon. The materials were melted and bottom poured into another vessel to remove the oxide film. The results for pure aluminum and the alloys fit the following equation with respect to temperature:

$$\sigma_{Al} = 825 - 0.05(t-660) \quad 600-900$$

The addition on a sodium salt flux on top of the metal reduced the surface tension to 650 to 600 dynes/cm and increased the effect of temperature on the surface tension sharply. The bubble tube was made of recrystallized alumina and was ground down to a sharp edge.

Engler, Siegfried and Rainer Ellerbrok. Measurement of the surface tension of molten aluminum alloys. *Giessereiforschung* 26(1):43-48. 1974. Ger. abstracted.

The surface tension of Al-Cu alloys was studied by the maximum bubble pressure and capillary depression methods. Al surface tension as measured by the bubble method increases with increasing Cu content when an inert gas, Ar, free of oxygen is used. This behavior is in accordance with the Al:Cu atomic volume ratio. If another inert gas, N, of lower purity is used, the surface tension decreases with increasing Cu. The capillary depression method gave a constant decrease in surface tension with increasing Cu. The surface tension caused by the oxide skin on 99.9% Al was investigated.

Eremenko, V. N., V. I. Nizhenko, and Yu. V. Haidich. Surface tension of the melts of some intermetalloids. *Izvest. Akad. Nauk S.S.S.R., Otdel. Tekh. Nauk. Met. i Toplivo* No. 3, 150-154. 1961. Russ. Abstracted.

The surface tensions and densities of copper-aluminum, nickel-beryllium alloys were determined. The surface tension of pure aluminum at different temperatures was described by the equation

$$\sigma_{Al} = 865 - 0.14(t-660)$$

Eustathopoulos, N., J. C. Joud, P. Desre, and J. M. Hicter. Wetting of carbon by aluminum and aluminum alloys. *J. Matl. Sci.* 9(8): 1233-1242. 1974.

The contact angle of molten Al with vitreous C was measured by the sessile drop method in vacuum at a temperature of about 1100°C. The effect on wetting behavior of the oxide layer on the molten Al was studied with two samples in different states of oxidation. The investigation involved the variation of parameters affecting the stability of the oxide film, e.g. the temperature, additions of Ti, Si, Cr, Be, Ca,

and Li to Al, and the time held at a certain temperature. The state of the molten Al surface under experimental conditions were determined indirectly by surface tension measurements.

$$\sigma_{Al} = 870 - 0.195(t-660) \quad 660-1050$$

Keese, H. J., and H. Cordes. Determination of the surface tension of molten aluminum alloys by the method of maximum bubble pressure. Aluminum (Duesseldorf) 48(10):680-684. 1972. Ger. abstracted.

The thermodynamics of interfaces of single component systems and of binary mixtures is summarized and the surface tension of Al alloys was determined in a specially designed apparatus with an accuracy of $\pm 2\%$. Additions of Be, Ga, and Mg decrease the surface tension of liquid Al; B and Ag do not.

Koral'kov, A. M. Surface tension of aluminum and its alloys. Izvest. Akad. Nauk S.S.S.R., Otdel. Tekh. Nauk No. 2, 35-42. 1956. Russ. abstracted.

The surface tension of molten aluminum was measured by the maximum bubble pressure method. A quartz tube was dipped into molten aluminum at 700° to 740°C. A flux of LiCl and KCl covered the metal to prevent oxidation. The surface tension was measured as 860 ± 20 dynes/cm. Lithium, calcium, magnesium, antimony, tin, lead, and bismuth were found to lower the surface tension greatly, the greater the decrease the larger the difference in atomic volumes between the solute and the solvent.

Korol'kov, A. M. and A. H. Bychkova. Surface tension of metals and alloys. Issledovanie Splavov Tsvet. Metal., Akad Nauk S.S.S.R., Inst. Met. im. A. A. Baikova, No. 2, 122-124. 1960. Russ. abstracted.

The surface tension of metals and alloys was determined at 50 to 80°C above the melting point by the maximum bubble pressure method using argon which was purified by passage through titanium shavings at 700 to 750°C. The molten metals were covered with a flux of KCl + LiCl eutectic. The effect of different impurities on the surface tension of aluminum was in the following order: $Li > Bi > Pb > Mg \approx Sb > Sn$; Fe, Cu, Ni, Si, Mn, and Cr had no effect. The effect on the surface tension of zinc was: $Bi > Pb > Li > Sb > Sn$; Fe, Cu, and Al were inactive. The surface tensions decreased as the concentration of the surface active element increased.

Lang, G. Effect of added elements on the surface tension of liquid pure aluminum. Aluminum (Duesseldorf) 50(11):731-734. 1974. Ger. abstracted.

The effect of less than one wt.% addition of Ce, Co, Zr, V, Sb, Cr, Ca, Ag, Sr, Li, Ti, Ba, Ga, or B on the surface tension of aluminum (862 dynes/cm) was determined at 700°C by the maximum bubble pressure method. Relations were found between the additions and resulting effects. Degree of Al purity was estimated from its surface tension. The results were discussed with reference to the position of the elements in the Periodic Table.

Levin, E. S., G. D. Ayushina, and P. V. Gel'd. Density and surface energy polytherms of liquid (molten) aluminum. Teplofiz. Vys. Temp. 6(3): 432-435. 1968. Russ. transl. High Temp. 6(3):416-418. 1968.

The surface tension and density were measured for three different purity aluminum samples, 99.99 wt.%, 99.99 + wt.%, and a very high purity material. The surface tensions were measured by the sessile drop method. A "large drop" was formed in a hermetic apparatus, held at a constant temperature for at least 10 minutes at each temperature studied, then photographed (8.35 magnification) on high contrast plates. The density data were independent of purity for the three samples, and were non-linear with temperature. A slope of $-2.6(10)^{-4}$ g/cm³ °C fit the data from 660 to 1000°C, and a slope of $-4.0(10)^{-4}$ g/cm³ °C fit the values from 1000 to 1500°C. The surface tension data were quite scattered but a least squares fit of the results gave an equation in agreement with Eremenko (1961).

$$\sigma_{Al} = 965 - 0.15t$$

Naidich, Yu. V. and V. N. Eremenko. The "large drop" method of determining surface tension and the density of melted metals at elevated temperatures. Phys. of Metals and Metallography 11(6):62-66. 1961.

The problem of drop size and drop nonsymmetry when using sessile drops for surface tension measurements was recognized. To provide large, symmetric drops the drop was formed in a cap having a very sharp edge. Calculations were made from a photograph, using the Bashforth and Adams' tables. Pure copper was measured in a beryllium oxide cup. The experiment was performed in a helium atmosphere. The helium was purified by passage over heated magnesium and titanium, passage through a liquid nitrogen trap, and then over sponge titanium again. The data for copper surface tension with respect to temperature were

$$\sigma_{Cu} = 1352 - 0.17(t-1083) \quad 1000 - 1500$$

Copper data were also measured by maximum bubble pressure as:

$$\sigma_{\text{Cu}} = 1358 - 0.20(t-1083)$$

Aluminum data were taken by the "large drop" method using an aluminum oxide cup. These data fit the equation

$$\sigma_{\text{Al}} = 865 - 0.14(t-660)$$

Pelzel, Erich. The surface tension of liquid metals and alloys. Berg-u. hüttenmänn. Monatsh. montan. Hochschule Leoben 93:248-254. 1948. Ger. abstracted.

The surface tension was measured using the maximum bubble pressure method, with nitrogen gas. Data were taken for zinc, tin, aluminum, and magnesium.

Skuchilov, A. I. and N. D. Isaev. Surface tension of oxidized aluminum alloys. Tekhnol. Legk. Splavov, Nauch.-Tekh. Byul., Vses. Inst. Legk. Splavov No. 5:13-15. 1972. Russ. from ref. Zh. Met. 1973, abstract No. 4A68.

Employing the method of capillary depression, the surface tension (σ) of Al alloys was determined. The σ of Al alloys with Mg was 1.5-1.8 times higher in air than in an inert gas. This increase was due to the presence of an oxide film covering the surface of the alloy in air. The addition of Be increased the σ of alloys by 150-200 dynes/cm. Increasing the Mg content decreased the σ of oxidized alloys, whereby the decrease of σ was similar to that in an inert gas.

Yatsenko, S. P., V. I. Kononenko, and A. L. Sukhman. Experimental studies of the temperature dependence of the surface tension and density of tin, indium, aluminum, and gallium. High Temp. 10:55-59. 1972.

A sessile drop of molten metal was photographed while setting on a polycrystalline aluminum oxide plaque in a vacuum of 10^{-6} torr. Measurements were taken from the profile of the photographed drop and used in Dorsey's calculation procedure to yield surface tension data. High purity tin, indium, gallium, and aluminum were used. The gallium was further purified by vacuum filtration and distillation at 1300°K . The surface tension results with respect to temperature were as follows:

$$\sigma_{\text{Sn}} = 540.0 - 0.064(t-232)$$

$$\sigma_{\text{In}} = 565.0 - 0.09(t-156)$$

$$\sigma_{\text{Al}} = 865.0 - 0.16(t-660)$$

$$\sigma_{\text{Ga}} = 712.0 - 0.0606(t-30)$$

REFERENCES FOR ANTIMONY

Bircumshaw, L. L. The surface tension of liquid metals. Part II. Bismuth, cadmium, zinc, and antimony. Phil. Mag. (7)3:1286-1294. 1927.

The maximum bubble pressure method was used to measure the surface tension of the above pure metals. The bismuth used contained traces of copper, iron, and lead; the zinc contained 0.0034 wt.% cadmium, 0.008 wt.% iron, 0.006 wt.% lead, and a trace of copper. The antimony contained 0.030 wt.% lead, 0.001 wt.% iron, 0.016 wt.% copper, and a trace of nickel. The cadmium contained a trace of zinc. Because of volatility, reliable results could not be obtained for zinc above 700°C or for cadmium above 600°C. For zinc it was also not possible to obtain agreement between runs below 600°C. Antimony and bismuth were measured from their melting points to 1000°C. Equations describing the data as a function of temperature are

$$\sigma_{\text{Sb}} = 352 - 0.065(t-640) \quad 640-1000$$

$$\sigma_{\text{Bi}} = 391 - 0.055(t-320) \quad 320-1000$$

Greenaway, H. T. The surface tension and density of lead-antimony and cadmium-antimony alloys. J. Inst. Metals London 74:133-148. 1947.

Surface tension measurements of the pure metals and alloys extending across the entire composition range were made using the maximum bubble pressure method. Both hydrogen and nitrogen were used to form bubbles. Commercial gases were purified by passage through heated copper turnings and dried with calcium chloride and phosphorus pentoxide. The rate of bubble formation was about one bubble per minute. The pure cadmium drossed severely but a thin layer of molten flux (22 wt.% KCl, 78 wt.% CdCl₂) was found to prevent this. Data on the pure metals were:

$$\sigma_{\text{Cd}} = 564 \text{ at } 330^{\circ}\text{C}, 600 \text{ at } 500^{\circ}\text{C}$$

$$\sigma_{\text{Pb}} = 448 \text{ at } 340^{\circ}\text{C}, 439 \text{ at } 440^{\circ}\text{C}$$

$$\sigma_{\text{Sb}} = 383 \text{ at } 635^{\circ}\text{C}, 380 \text{ at } 800^{\circ}\text{C}$$

Lazarev, V. B. Experimental study of surface tension of indium-antimony alloys. Zhur. Fiz. Khim. 38:325-328. 1964. Russ. transl. Russ. J. Phys. Chem. 38:172-175. 1964.

Measurements of the surface tensions of the pure metals and their alloys were made using the maximum bubble pressure method. Sharply pointed

quartz capillaries were used. Purified argon was used for bubble formation. The data collected were as follows:

$$\sigma_{\text{In}} = 556 \text{ at } 200^{\circ}\text{C}, 505 \text{ at } 800^{\circ}\text{C}$$

$$\sigma_{\text{Sb}} = 350 \text{ at } 650^{\circ}\text{C}, 345 \text{ at } 800^{\circ}\text{C}$$

Data with respect to composition were plotted as isotherms and a leveling off or sharp change in the isotherm indicates an intermetallic compound. The compound indium antimonide was shown as a point of inflection on the curve.

Lazarev, V. B. and M. Y. Dashevshii. The surface tension of alloys in the system indium-antimony. Doklady Akad. Nauk S.S.S.R. 146:822-825. 1962. Russ. transl. Proc. Akad. Nauk S.S.S.R., Chem. Sect. 146:856-858. 1962.

Surface tension data for the pure metals and the entire range of alloy compositions were taken by the maximum bubble pressure method. Highly sharpened quartz capillaries were used, and the measurements were made in an argon atmosphere at 100 torr. 99.999 wt.% indium was measured over the temperature range 200 to 800°C, values were linear from 554 dynes/cm at 200°C to 507 dynes/cm at 800°C. This is in good agreement with Melford and Hoar, Pugachevich, and Timofeevicheva. The antimony, 99.99 + wt.% pure, was measured over the temperature range 650 to 800°C and the surface tension data were linear ranging from 350 dynes/cm to 345 dynes/cm. Data for 26 other alloy compositions were taken and the results were linear in both temperature and composition.

Matuyama, Yoshiharu. On the surface tension of molten metals and alloys. Sc. Repts. Tôhoku Imp. Univ. 16:555-562. 1927.

The surface tensions of six molten metals and three binary alloys were studied by the drop-weight method. The measurements were made in a vacuum after carbon dioxide purging. The data obtained for the pure metals antimony, tin, zinc, bismuth, cadmium, and lead with respect to temperature were linear and their slopes almost equal. Calculations of Eötvös constant, K , for these metals were nearly 1.0. Surface tension measurements of tin were also made in air, values were higher than those made in a vacuum environment.

Sauerwald, F. and G. Drath. The surface tension of molten metals and alloys 2. The surface tension of tin, lead, antimony, copper, tin-bismuth, copper-antimony, copper-tin alloys, and of cast iron. Z. Anorgan. Allgem. Chem. 162:301-320. 1927. Ger. abstracted.

The maximum bubble pressure apparatus developed by the authors was used to measure the surface tension of the above metals. The measurements for tin, lead, and antimony were made from about 750°C to 1100°C. The alloys were measured over the entire composition ranges, and to 1100°C. The equations for surface tension with respect to temperature for the pure metals are as follows:

$$\sigma_{\text{Sn}} = 508.0 - 0.089(t-878)$$

$$\sigma_{\text{Pb}} = 423.0 - 0.096(t-750)$$

$$\sigma_{\text{Sb}} = 368.0 - 0.063(t-750)$$

$$\sigma_{\text{Cu}} = 1103.0 + 0.74(t-1131)$$

REFERENCES FOR BISMUTH

Addison, C. C. and J. B. Raynor. Liquid metals. Part XII. The surface tension of liquid bismuth in pure and impure hydrogen, in other gases, and in vacuo. J. Chem. Soc. London A:965-967. 1966.

A drop-weight procedure was used to measure the surface tension of bismuth over the temperature range 300 to 500°C in different atmospheres. The vacuum obtained was 10^{-4} torr and use of different purity gases only increased the scatter in the data, not the mean value. Traces of oxygen and water vapor did not affect the measured result above 400°C, below 400°C the film produced on the molten metal surface was not reduced sufficiently rapidly by hydrogen. Values to 480 dynes/cm were measured on surfaces which showed no visual evidence of contamination. The data measured for liquid bismuth surface tension with respect to temperature were:

$$\sigma_{\text{Bi}} = 378.0 - 0.069(t-271)$$

Bahradze, R. V. and B. Ya. Pines. Surface tension of binary alloys lead-tin, Bismuth-lead, bismuth-tin, and bismuth-cadmium. Zhur. Tekh. Fiz. 23:1548-1558. 1953. Russ. abstracted.

The surface tension of lead-tin alloys was measured by the method of balancing an iron ring which is immersed in the liquid. The liquid was in a vacuum. The wetting angle of the alloy on iron which is needed to calculate the surface tension was determined optically. The surface tension bismuth-cadmium, bismuth-tin, and bismuth-lead alloys were measured by the maximum bubble pressure method using hydrogen gas. The surface tensions of the alloys increased linearly with temperature, but the concentration dependence was not linear.

Bohdansky, J. and H. E. J. Schins. The surface tension of Ag, Tl, Pb, and Bi at high temperature. J. Inorg. and Nucl. Chem. 30:3362-3365. 1968.

The surface tension of these molten metals was measured using the maximum bubble pressure method with the isothermal liquid pool being formed by radio frequency heating of an open heat pipe. The metals used were 99.999 + wt.% bismuth, and spectrographic pure silver. The experimental data are summarized as follows:

$\sigma_{\text{Ag}} = 1136.0 - 0.174 T$	$1800 < T^{\circ}\text{K} < 2330$
$\sigma_{\text{Tl}} = 536.0 - 0.119 T$	$1270 < T^{\circ}\text{K} < 1700$
$\sigma_{\text{Bi}} = 538.0 - 0.114 T$	$1350 < T^{\circ}\text{K} < 1550$

$$\sigma_{\text{Pb}} = 538.0 - 0.114 T$$

$$1440 < T^{\circ}\text{K} < 1970$$

The scatter of the experimental data was less than 3 percent.

Dzhoglev, Dimitur, Kiril Kirilov, Lazar Ilkov, and Todorka Racheva. Surface tension of molten bismuth and some of its alloys. Mashinostroene 18:431-433. 1969. Bulg. abstracted.

The surface tension of molten bismuth, bismuth-lead and bismuth-tin alloys was measured by the maximum bubble pressure method at about 350°C. For pure bismuth the surface tension decreased from 400 dynes/cm at 290°C to 380 dynes/cm at 350°C. For the tin alloys the surface tension increased sharply with increasing tin content and the effect of temperature was negligible. With the lead alloys surface tensions decreased slightly with increasing temperature or with decreasing lead content. In the case of the alloys the surface tension measured in a hydrogen atmosphere was slightly higher than that measured in a nitrogen atmosphere.

Golubev, N. A., E. L. Zhukovskii, and N. L. Pokrovskii. Surface tension of indium-bismuth melts. Abstract only. Zhur. Fiz. Khim. 45:2679. 1971. Russ. transl. Russ. J. Phys. Chem. 45:1521-1522. 1971.

The maximum drop pressure method was used to measure the surface tension of indium-bismuth melts throughout the composition range between 200 and 500°C. The isotherms were smooth showing no indication of the intermetallic compounds In_2Bi and InBi or the eutectic, 22 at.% Bi. The temperature dependence was linear and the data for the pure metals were as follows:

$$\sigma_{\text{Bi}} = 370 \text{ at } 300^{\circ}\text{C}; 360 \text{ at } 500^{\circ}\text{C}$$

$$\sigma_{\text{In}} = 555 \text{ at } 200^{\circ}\text{C}; 530 \text{ at } 500^{\circ}\text{C}$$

Herczynska, E. Surface tension of diluted Bi-U and Sn-Tl alloys. Zeit. Physik. Chem. 214:355-357. 1960.

The method of maximum bubble pressure was used to measure the surface tension of pure bismuth and tin and their alloys with uranium and thallium. Uranium was slightly surface active in respect to bismuth. Thallium showed a change in character of the surface activity with tin as the concentration increased. The experiments were conducted over the temperature range from 300 to 500°C.

Hogness, Thorfin R. The surface tensions and densities of liquid mercury, cadmium, zinc, lead, tin, and bismuth. J. Amer. Chem. Soc. 43:1621-1628. 1921.

The Cantor method, a maximum pressure technique which forms a drop rather than a bubble at the end of a capillary, was used to measure the surface tension of the above pure metals. The apparatus was pyrex with a quartz capillary. Preheating of the apparatus to 500°C for a few hours was found necessary to remove adsorbed water vapor. All the measurements except those for mercury were made in a hydrogen atmosphere at a pressure somewhat greater than the vapor pressure of the metals. The surface tension values measured with respect to temperature are described by the following equations:

$$\sigma_{\text{Hg}} = 467.0 - 0.043(t+39) - 0.000386(t+39)^2 \quad 0 - 350$$

$$\sigma_{\text{Bi}} = 378.0 - 0.063(t-269) \quad 320 - 470$$

$$\sigma_{\text{Cd}} = 630.0 - 0.065(t-320) \quad 340 - 550$$

$$\sigma_{\text{Pb}} = 444.0 - 0.077(t-327) \quad 370 - 520$$

$$\sigma_{\text{Sn}} = 531.0 - 0.080(t-232) \quad 360 - 400$$

$$\sigma_{\text{Zn}} = 758.0 - 0.090(t-419) \quad 480 - 500$$

Bismuth was prepared by fusing twice precipitated bismuth oxychloride with pure potassium cyanide. Electrolytic preparation was used on the other metals except mercury using pure commercial samples of lead, tin, zinc, and cadmium as the anodes. The mercury was washed and triple distilled for purification.

Ibragimov, Kh. I., N. L. Pokrovskii, P. O. Pugachevich, and V. K. Semenchenko. Surface tension in the system tin-bismuth. Doklady Akad. Nauk S.S.S.R. 155:75-78. 1964. Russ. transl. Soviet Physics-Doklady 9:227-229. 1964.

Data have shown that the relation of surface tension to concentration and temperature for the Bi-Sn, Pb-Sn, and Bi-Pb systems has either a maximum or a minimum. The isotherms of Sn-Bi have a minimum near the eutectic composition. It has been supposed that the eutectic structure in the melt shows surface active behavior. This feature lead to the remeasurement of this system with improved facilities, the gravitational apparatus of Pugachevich. Alloys were prepared from metals having total impurity contents less than 10^{-3} wt.% (tin) and 10^{-4} wt.% (bismuth). Fourteen alloys were prepared with six near the eutectic concentration. Measurements were taken from 150°C to 500°C and the isotherms were smooth with no break at the eutectic composition. Data for the pure metals with respect to temperature were:

$$\sigma_{\text{Sn}} = 545 - 0.060(t-250) \quad 250-500$$

$$\sigma_{\text{Bi}} = 370 - 0.065(t-270) \quad 270-500$$

Ishiguro, Masakazu. The absorption of diatomic molecules on surfaces of molten metals. Mem. Inst. Sci. and Ind. Research, Osaka Univ. 8:78-82. 1951. Abstracted.

The silhouette of a molten drop in atmospheres of hydrogen and oxygen was determined from X-ray shadowgraphs. The surface tension was calculated from the shape of the drop. Surface tensions on molten tin, bismuth, and lead were measured in atmospheres of 0 to 30 torr pressure of hydrogen and 0 to 7 torr pressure of oxygen.

Khokonov, Kh. B., S. N. Zadumkin, and B. B. Alchagirov. Electron work function and surface tension of gallium-indium and gallium-bismuth binary systems. Elektrokimiya 10(6):911-916. 1974. Russ. transl. Soviet Electrochemistry 10(6):865-870. 1974.

The electron work function and the surface tension σ were determined of binary liquid systems Ga-In and Ga-Bi from the liquidus temperature of 500°C. In these systems In and Bi behaved like surface-active components. The size of the temperature (T) coefficient $(d\sigma/dT)_x$ changed twice within the scope of the relative concentration change. This is attributed to two counteracting forces: the decrease of σ with an increase of temperature and the desorption of the surface-active components in the liquid volume from the surface which increased the σ .

$$\sigma_{\text{Ga}} = 714 - 0.088(t-29.8) \quad 30-500$$

$$\sigma_{\text{In}} = 556 - 0.081(t-156) \quad 156-500$$

$$\sigma_{\text{Bi}} = 370 - 0.090(t-271) \quad 271-500$$

Khokonov, Kh. B. and S. N. Zadumkin. Work function of an electron of gallium-indium and gallium-bismuth alloys. Izv. Akad. Nauk. S.S.S.R., Met. (2):189-191. 1975. Russ.

A particularly-adjusted cell was used to measure simultaneously the work function ϕ and surface tension σ of liquid Ga, In, Bi, and Ga-In and Ga-Bi alloys, in vacuo. At 200°C the ϕ of Ga and In were approximately 4.35 and 4.08 eV, respectively; and at 300°C ϕ Bi = 4.34 eV. The general shapes of the isotherms of ϕ (%M) of Ga-In and Ga-Bi were identical, with a shallow minimum at approximately 10-20 atomic % M (where M is In or Bi) and a net concentration independence of ϕ at greater than 45 atomic % M. The minimum depths were 0.50 and

0.15 eV for Ga-In and Ga-Bi, respectively. These minimums were not related to the diagrams of state of the alloys. The established ϕ (σ) dependences are consistent with the occurrence of adsorption processes at the surface of the melts.

Klyachko, Yu. A. and L. L. Kunin. Surface tension of eutectic alloys. Doklady Akad. Nauk. S.S.S.R. 64:85-86. 1949. Russ. abstracted.

Data on the surface tensions of liquid binary alloys of tin-bismuth, lead-tin, and lead-bismuth as a function of composition were consistent at temperatures well above their melting points. At temperatures only slightly above the melting point, the alloy surface tensions were much lower than that of the pure metal and the alloy of eutectic composition exhibited the minimum surface tension. Eutectic alloys heated to 100°C above their melting point showed an increase in measured surface tension with increasing temperature. This indicates that for these eutectic alloys there is no adsorption of a surface active component, but that the eutectic itself is a surface-active phase. The often observed increase in surface tension with increasing temperature for pure metals may be due to contamination by eutectic-forming impurities.

Koval'chuk, V. F. and V. A. Kuznetsov. Surface tension of indium-bismuth alloys. Poverkh. Yavleniya Rasplavakh, 173-176. 1968. Russ. abstracted.

Surface tensions of the alloys were determined from their melting points to 723°K. This alloy system has a large difference between the surface tensions of the pure metals. Using the Gibbs equation surface absorptions of indium and bismuth were calculated. The bismuth was surface-active in relation to indium. The isotherm of this alloy system deviates from the ideal isotherm in the negative direction and passes through a minimum at the eutectic composition.

Koval'chuk, V. F., V. A. Kuznetsov, and N. D. Grekova. Surface tension of indium-bismuth alloys. Zhur. Fiz. Khim. 43:184-186. 1969. Russ. transl. Russ. J. Phys. Chem. 43:97-99. 1969.

Surface tension data on alloys of these metals provide information for systems where the components of the alloys differ significantly in surface tension. The measurements were made using the maximum bubble pressure method. Data were presented in the form of isotherms, and they show that bismuth is surface-active to indium. This is expected because the surface tension of the solvent metal is greater than that of the solute. The isotherms are smooth, not affected by the existence of chemical compounds.

Maze, Craig and George Burnet. Estimation of non-equilibrium surface tension. Surface Science 27:411-418. 1971.

A mathematical description of surface tension-temperature behavior of liquid metals under non-equilibrium conditions has been developed based upon entropy production caused by evaporation of liquid. Surface tensions of 99.999 wt.% lead and 99.9999 wt.% bismuth were measured in a 10^{-10} torr vacuum to provide the data. Measurements under these conditions are not linear with respect to temperature and exhibit very little decrease in surface tension as temperature increases.

Metzger, G. Surface tension measurements. VII. Temperature dependence of the surface tension of copper and the surface tension of molten silver-lead, silver-bismuth, and copper-lead alloys. Zeit. Physik. Chem. 211:1-25. 1959. Ger. abstracted.

The surface tensions of these metals were measured by the bubble-pressure method. The temperature dependence for pure copper was found to be negative. The increase in surface tension with temperature reported by other investigators was thought to be due to the vaporization of strongly surface-active surface impurities. Equations for the surface tension of the pure metals are as follows:

$$\sigma_{Pb} = 420.0 - 0.12(t-420)$$

$$\sigma_{Bi} = 343.0 - 0.017(t-800)$$

$$\sigma_{Cu} = 1301.0 - 0.095(t-1100)$$

$$\sigma_{Ag} = 893.0 - 0.14(t-1000)$$

Pugachevich, P. P. and I. P. Altynov. Temperature dependence of the surface tension of bismuth and its alloys with sodium and potassium. Doklady Akad. Nauk. S.S.S.R. 86:117-119. 1952. Russ. abstracted.

The surface tension of pure bismuth and the entire composition range of bismuth-sodium and bismuth-potassium alloys were measured by the maximum bubble pressure method. Both sodium and potassium lowered the surface tension of bismuth but potassium was the more surface-active material.

Sauerwald, F. and G. Drath. The surface tension of molten metals and alloys. 1. The method of measuring the maximum bubble pressure and the surface tension of mercury and bismuth. Z. Anorgan. Allgem. Chem. 154:79-92. 1926. Ger. abstracted.

The maximum bubble pressure method was investigated for effect of capillary size, then the apparatus was used to measure the surface tension of mercury and bismuth. The surface tension of mercury was measured from 20°C to 200°C, and bismuth from 580°C to 780°C. A quartz capillary and hydrogen were used to form the bubble in bismuth. Carbon dioxide was used for mercury. The value of the surface tension of bismuth with respect to temperature was as follows:

$$\sigma_{\text{Bi}} = 354.0 - 0.060(t-583)$$

Smirnov, M. V., V. P. Stepanov, and A. F. Sharov. Electrocapillary phenomena on liquid indium and bismuth in molten sodium chloride-cesium chloride mixtures. *Elektrokhimiya* 9(2):147-151. 1973. Russ. transl. *Soviet Electrochemistry* 9(2):141-144. 1973.

The interfacial tension between liquid In and Bi in molten mixtures of NaCl and CsCl was measured by the method of electrocapillary curves. The surface tension of these mixtures was also measured by the method of maximum bubble pressure of bubbling gas. A symbiotic effect was noted in the occurrence of the isotherm of the interfaces and the surface tension. An excess of Cs^+ was calculated to exist in surface concentrations of NaCl - CsCl mixtures. The zero-charge potential was shown to be displaced to the more electropositive region with the addition of CsCl and NaCl. The obtained experiment results are explained from the point of view of the effect of a surface active component on the interfacial tension and the zero-charge potential.

Unezhev, B. Kh., S. N. Zadumkin, and A. A. Karashaev. Effect of a gaseous medium on the surface tension of liquid metals. *Elektrokhim. Rasplavy* 111-118. 1974. Russ. abstracted.

At temperatures close to their melting point the surface tension σ of molten Sn, Cd, Pb, Ga, In, and Bi was unaffected by Ar or He and that of all metals, with the exception of Bi, decreased in the presence of CO_2 or H. The σ of molten Bi increased in the presence of CO_2 or H. The σ was sensitive to oxygen only at a certain oxygen pressure which was characteristic for the individual metals.

REFERENCES FOR GALLIUM

Abbaschian, G. J. Surface tension liquid gallium. J. Less-Common Met. 40(3):329-333. 1975.

The surface tension of high-purity liquid gallium was determined by the pendant-drop method. The experiments were conducted in N at 4-40°C. The average values were 723.2, 724.6, 723.9, 723.7, 725.0 dynes/cm at 40, 30, 29.6, 25, and 17°C, respectively. The temperature coefficient was -0.068 dynes/cm°C.

$$\sigma_{\text{Ga}} = 724 - 0.068(t-30) \quad 4-40$$

Eremenko, V. N., V. I. Nizhenko, and L. I. Sklyarenko. Surface tension and density of liquid Ni-Ga alloys and the wettability of Al_2O_3 by them. Abridged translation. Russian Metallurgy (Metally), No. 2, 103-104. 1966.

This study was made to compare with the Ni-Al system in which the isotherm indicated the congruent melting intermetallic compound NiAl. Gallium being an analogue of aluminum was chosen. The surface tensions were measured by the "large drop" method and the isotherm showed a slight inflection point at 30 at.% gallium. The data were above the ideal isotherm and the surface tension of pure gallium at 1500°C was measured as 559 dynes/cm.

Frumkin, A. and A. Gorodetskaja. Capillary electrical phenomena and membrane formation on liquid gallium. Zeit. Physik. Chem. A 136:215-227. 1928. Ger. abstracted.

A double U-tube electrometer was used with one capillary in contact with various acidic and basic salt solutions and the other between gallium and a normal calomel electrode. The highest surface tension of 592 dynes/cm was measured when the solution was N KCl + 0.1 N HCl and a voltage of 0.9V was applied across the gallium. The presence of OH^- ions strongly depressed the value of the surface tension measured.

Ibragimov, Kh. I. and N. L. Pokrovskii. Procedure for measuring surface tension of metal melts. Uch. Zap. Checheno-Ingushsk. Gos. Ped. Inst. 22:126-130. 1964. Russ. abstracted

Several problems associated with different methods of measuring surface tension were examined for pure gallium and for tin-bismuth melts. The harmful influence of vapors of greases used in the vacuum system was studied. These vapors are one cause for low values of surface tensions measured for pure metals and for the anomalous shape of the surface tensions as a function of temperature curves. Shortcomings of the ring-tensiometer method and in the design of different maximum bubble pressure apparatuses (gas pressure, gravitational) were examined.

Karashaev, A. A., S. N. Zadumkin, and A. I. Kukhno. Surface tension of gallium and its dependence on temperature. Zhur. Fiz. Khim. 41:654-656. 1967. Russ. transl. Russ. J. Phys. Chem. 41:329-330. 1967.

An apparatus constructed of molybdenum glass was built for large drop surface tension measurements of gallium. From -20° to 360°C the surface tension data collected are described by the equation

$$\sigma_{\text{Ga}} = 718.0 - 0.101(t - 29.87)$$

The gallium used was 99.9999 + wt.% pure. A photograph of the drop was measured and the surface tension was calculated using Dorsey's method. The drop was maintained in an atmosphere of gallium vapor. On initial heating measurements there was an increase in surface tension. This was thought to be due to volatile impurities vaporizing from the drop surface because on subsequent heating and cooling of the drop the surface tension decreased with increasing temperature. Experiments were also conducted with 99.9 wt.% pure material and these results were nonlinear and matched the data of Timofeevicheva and Nizhenko.

Khokonov, Kh. B., S. N. Zadumkin, and B. B. Alchagirov. Electron work function, surface tension, and density of the gallium-indium system. Dokl. Akad. Nauk SSSR 210 (4):899-902. 1973. Russ. translated Doklady Physical Chemistry 210 (4):461-464. 1973.

An apparatus used to measure the electron work function, ϕ , by a photoelectric method, surface tension, σ , by the large drop method, and density, ρ , by the displacement method is described. The apparatus was used to investigate the Ga-In system over the whole concentration range from the liquidus to 500°C . The experimental errors were 1.2, 0.6, and 0.2% for ϕ , σ and ρ , respectively. As measured at 200°C , ϕ was 4.35 ± 0.05 and 4.08 ± 0.04 eV for Ga and In, respectively. The surface tension of Ga was reduced by In.

$$\sigma_{\text{Ga}} = 714 - 0.088(t - 29.8) \quad 30-550$$

$$\sigma_{\text{In}} = 556 - 0.081(t - 156) \quad 200-550$$

Mack, G. L., James K. Davis, and F. E. Bartell. The boundary tension of gallium. J. Phys. Chem. 45:846-851. 1941.

Gallium was purified by solution in hydrochloric acid, extraction with ethyl ether, and electrolytic deposition followed by conversion to the chloride, fractional distillation and again electrolytically deposition. Pendant drops were formed on glass tips turned down in a lathe and hand ground to a sharp inside edge. Temperature was maintained by a constant temperature air bath. Photographs were taken for observation times from a few seconds to 45 min. Calculations were made using Bashforth and Adams' tables. There was considerable variation in the results which was

thought to be due to contamination of the surface. Results were: 735 ± 29 dynes/cm at 30.5°C , 738 ± 20 at 35°C , and 733 ± 7 at 40°C . Measurements were taken in both hydrogen and carbon dioxide atmospheres with no difference.

Nal'giev, A. G. and Kh. I. Ibragimov. Surface tension and density of the tin-gallium system. Zh. Fiz. Khim. 48 (5):1289-91. 1974. Russ. transl. Russ. J. Phys. Chem. 48 (5):754-755. 1974

The surface tension σ and density of pure Sn, Ga, and fourteen Sn-Ga melts of different concentrations were measured at 30 – 450°C by the method of maximum bubble pressure in a drop and pycnometrically. Polytherms of melts rich in Sn (≤ 63 at.% Ga) are straight line. The nonlinearity of polytherms of melts containing more than 73.55 at.% Ga appear in the whole temperature range. A small positive deflection of density from additive values was found.

$$\sigma_{\text{Ga}} = 708 - 0.037(t - 30) \quad 30\text{--}450$$

$$\sigma_{\text{Sn}} = 543 - 0.060(t - 232) \quad 250\text{--}450$$

Nizhenko, V. I. and L. I. Floka. Free surface energy of iron-gallium molten alloys. Zh. Fiz. Khim. 49 (2):431-434. 1975. Russ. transl. Russ. J. Phys. Chem. 49 (2):251-253. 1975.

The free surface energy in the Fe-Ga system was determined by the method of large drop in the whole concentration range and from the liquidus temperature to 1600°C , its temperature dependence was correlated by an empirical equation. Calculated bulk activity coefficients of Ga exhibit negative deviations from ideality at less than 55 atomic % Ga and positive ones at greater than 55 atomic % Ga. The adsorption isotherm at 1550°C was calculated. Deviations from ideality are greater in the surface phase than in the bulk phase.

$$\sigma_{\text{Ga}} = 827 - 0.157(t - 30) \quad 800\text{--}1600$$

Nizhenko, V. I., L. I. Sklyarenko, and V. N. Eremenko. Temperature dependence of free surface energy and density of liquid gallium. Ukrain. Khim. Zhur. 31:559-563. 1965. Russ. abstracted.

The following surface tension relationship was reported for liquid gallium

$$\sigma_{\text{Ga}} = 708 - 0.0031(t - 29.9) - 0.000067(t - 29.9)^2$$

A graph of the contact angle of wetting and the energy of adhesion of gallium on polycrystalline Al_2O_3 is shown.

Ofitserov, A. A., P. O. Pugachevich, G. M. Kuznetsov, and G. N. Kuz'mina. Surface tension of tin-gallium alloys. *Izvest. Vyssh. Ucheb. Zaved., Tsvet. Met.* 11 (2):130-132. 1968. Russ. abstracted.

Surface tensions and densities of tin-gallium alloys were measured. The surface tensions were measured by a gravitation method and densities by a two-capillary pycnometer. Data were collected in a 10^{-4} to 10^{-5} torr vacuum over a temperature range of 250 to 450°C. These data were needed to help confirm Zhukhovskii's equations for theoretical surface tensions of alloys based on addition of pure component surface tensions.

Richards, Theodore W. and Sylvester Boyer. Further studies concerning gallium. Its electrolytic behavior, purification, melting point, density, coefficient of expansion, compressibility, surface tension, and latent heat of fusion. *J. Amer. Chem. Soc.* 43:274-294. 1921.

The above properties of gallium metal were studied with great care taken to determine the effect of different variables on the results. An entire purification technique was developed and materials of different purity were used in all the investigations. The large sessile drop method was used to measure the surface tension at 30°C. A box containing a carbon dioxide atmosphere was submerged in a water constant temperature bath. Both the thermostatic bath and the box had optical glass panes through which drop measurements were taken with a cathetometer. The drop rested on a plane gas carbon block. The result of this study for the purest gallium prepared was

$$\sigma_{\text{Ga}} = 358.2 \text{ at } 30^{\circ}\text{C}$$

Sukhman, A. L., S. P. Yatsenko, and V. I. Kononenko. Change in molar volumes and surface tensions of gallium-indium-tin melts. (Sverdlovsk, USSR). *Izv. Akad. Nauk SSSR, Metal.* 1972, (6), 94-95. Russ. Transl. *Russian Metallurgy (Metally)* 6:70-72. 1972.

The densities and surface tensions of Ga-In-Sn melts at 523°K are presented and discussed. Anomalous properties and nonideality of this system are related to the interaction between the components of the melt. The component interaction decreases with increasing temperature.

Sukhman, A. L. Density and surface tension of the gallium-lead system. *Tr. Inst. Khim., Ural. Natsn. Tsentr, Akad. Nauk SSSR* 29:53-56. 1974. Russ. abstracted.

Sessile drop technique was used to measure the density and surface tension of Ga-Pb melts in He. Addition of Pb substantially decreased surface tension. The molar volume and surface tension were used to calculate the activity of Ga. A positive deviation from the additivity rule was observed.

Sukhman, A. L. Surface tension of low-alloy gallium alloys. Tr. Inst. Khim., Ural. Nanchn. Tsentr., Akad. Nauk. SSSR 29:47-52. 1974. Russ. abstracted.

Sessile drop method was used to determine the surface tension of Ga containing less than 0.06 atomic % Li, Na, K, Mg, Tl, Pb, Cu, Ag, Zn, Bi, Sb, Cd, Sn, In, Al, Ni, Ti, Fe, Co, V, Cr, Pd, and Pt. Measurements were carried out at 303-1073°K under vacuum. Addition of Fe, Cr, Ni, Ti, Co, or V did not affect surface tension, whereas K and Na were active in amounts greater than 0.015 atomic %.

Timofeevicheva, O. A. and V. B. Lazarev. Surface tension and structure of metallic melts. Izvest. Akad. Nauk. SSSR, Otdel. Tekh. Nauk., Met. i Toplivo, No. 3, 147-150. 1961. Russ. abstracted.

The effect of temperature on the surface tensions of gallium, indium, thallium, cadmium, germanium, lead, and tin was determined from data taken using the maximum bubble pressure method. The data showed that there was some regularity in surface tension in elements in the same subgroup, the surface tension decreased with increasing atomic number.

Timofeevicheva, O. A. and P. P. Pugachevich. Temperature dependence of the surface tension of gallium. Doklady Akad. Nauk. SSSR 134:840-843. 1960. Russ. transl. Proc. Akad. Nauk. SSSR, Chem. Sect. 134:1097-1100. 1960.

The surface tension of gallium was measured from 30° to 500°C using a maximum bubble pressure apparatus. The data collected fit the following equation:

$$\sigma_{\text{Ga}} = 706.6 - 0.000647(t-29.8) - 0.0000965(t-29.8)^2$$

The authors felt that non-linear results or increase in surface tension with temperature is caused by small traces of surface-active impurities. Using previously measured indium and thallium data, a graph of surface tension with increasing atomic number of the III-A subgroup of the periodic table is shown.

REFERENCES FOR GERMANIUM

Keck, Paul H. and Wendell Van Horn. The surface tension of liquid silicon and germanium. Phys. Rev. 91:512-513. 1953.

The surface tensions of liquid silicon and germanium were determined at their melting point using the drop-weight method. Rods of high purity material were melted in an argon atmosphere. The results were:

$$\sigma_{\text{Ge}} = 600$$

$$\sigma_{\text{Si}} = 720$$

These values were believed accurate within at least ± 5 percent.

Kolesnikova, T. P. Surface tension of germanium. Izvest. Vysshikh Ucheb. Zavedenii, Chernaya Met. No. 9, 14-17. 1960. Russ. abstracted.

The surface tension of germanium was studied by a sessile drop method. Both graphite and quartz substrates were used. The surface tension of a drop near its melting point setting on a quartz substrate was 650 dynes/cm. This decreased to 530 dynes/cm at 1200°C, a (-) 0.6 dynes/cm °C slope. On graphite the surface tension at 1000°C was 600 dynes/cm and this increased to 720 dynes/cm at 1200°C, a (+) 0.6 dynes/cm °C slope. This difference was thought to be due to impurities in the graphite.

Lazarev, V. B. A study of films absorbed on the surface of molten germanium. Doklady Akad. Nauk SSSR 156:1159-1162. 1964. Russ. transl. Proc. Akad. Nauk SSSR, Phys, Chem. Sect. 156:615-618. 1964.

A case of special interest in semiconductors involves data on surface activity when the surface active substance is an additive introduced to obtain a desired type of conduction. The metals of groups IV and V of the periodic table are frequently alloyed in technical germanium. Alloys of up to 6 at.% antimony, bismuth, indium, gallium, and thallium in germanium were prepared and the surface tensions measured from 950 to 1150°C. The maximum bubble pressure method of measurement was used. All the additives except gallium reduced the surface tension of germanium but their activities differed greatly. Bismuth and antimony showed the highest surface activity with respect to germanium. All the isotherms follow the ideal theoretical isotherm. Data for the surface tension of pure germanium were as follows.

$$\sigma_{\text{Ge}} = 610 \text{ at } 950^{\circ}\text{C}, 604 \text{ at } 1000^{\circ}\text{C}, 600 \text{ at } 1050^{\circ}\text{C}$$

$$595 \text{ at } 1100^{\circ}\text{C}, 590 \text{ at } 1150^{\circ}\text{C}$$

Lazarev, V. B. Surface phenomena in alloyed germanium melts. Zhur. Fiz. Khim. 39:72-75. 1965. Russ. transl. Russ J. Phys. Chem. 39: 36-39. 1965.

The surface tensions of germanium melts containing small amounts of antimony, bismuth, indium, gallium, and thallium were measured to determine the surface activity of the semiconductor germanium. The maximum bubble pressure method of measurement was used, and the germanium purity was such that the resistivity was 40 ohm-cm. The alloys were investigated for the temperature range 950 to 1100°C and in each instance the surface tension of pure germanium varied linearly from 609 dynes/cm at 950°C to 589 dynes/cm at 1150°C. The surface activity was as follows: Bi > Sb > Tl > In, and Ga was surface inactive.

Lazarev, V. B. and P. P. Pugachevich. Surface tension of germanium as dependent on temperature. Doklady Akad. Nauk. SSSR 134:132-133. 1960. Russ. transl. Proc. Akad. Nauk. SSSR, Phys. Chem. Sect. 134:823-825. 1960.

The surface tension of molten germanium was measured by the maximum bubble pressure method. The capillaries were made of spectrographically pure graphite. Purified argon was used as the working gas. Purification was by bubbling the argon through molten lithium at 300°C. The germanium metal used was a single crystal with specific resistance of 20 ohm-cm. The equation describing the surface tension data as a function of temperature is as follows:

$$\sigma_{\text{Ge}} = 621.4 - 0.261(t-936)$$

Lazarev, V. B., V. S. Arahelzan, and A. V. Pershikov. Surface tension of germanium-tin, germanium-lead, germanium-bismuth, germanium-indium, germanium-thallium, germanium-copper, germanium-nickel, and germanium-cobalt melts. Zhur. Fiz. Khim. 42:274-275. 1968. Russ. transl. Russ. J. Phys. Chem. 42:147-148. 1968.

A study of the surface tensions of the above metals was made to determine how the interactions between the melt components are reflected in the surface tension isotherms. The measurements were made by the maximum bubble pressure method using sharply pointed capillaries. The results are presented in the form of isotherms but the following data are available.

$$\sigma_{\text{Ge}} = 610 \text{ at } 1000^{\circ}\text{C}, 600 \text{ at } 1100^{\circ}\text{C}, 590 \text{ at } 1500^{\circ}\text{C}$$

$$\sigma_{\text{Sn}} = 480 \text{ at } 1000^{\circ}\text{C}, \sigma_{\text{Bi}} = 370 \text{ at } 1000^{\circ}\text{C}$$

$$\sigma_{\text{Pb}} = 360 \text{ at } 1000^{\circ}\text{C}, \sigma_{\text{In}} = 480 \text{ at } 1000^{\circ}\text{C}, \sigma_{\text{Tl}} = 410 \text{ at } 1000^{\circ}\text{C}$$

The isotherms for all of the alloys have no maxima, minima, or breaks. However, for the systems which have congruent melting point compounds, Ge-Co, Ge-Ni, Ge-Cu, the isotherms deviate from ideal in a positive direction. The others closely follow the ideal theoretical isotherms.

Naidich, Yu. V., V. M. Perevertailo, and L. P. Obushchak. Density and surface tension of gold-silicon and gold-germanium alloys. Poroshk. Metall. (5):73-75. 1975. Russ. Transl. Soviet Powder Metallurgy and Metal Ceramics 5:403-404. 1975.

The sessile drop method was used to determine the density ρ and the surface tension σ of Au-Si and Au-Ge melts over the whole concentration range at 350-1600°C. The concentration dependences of ρ and σ demonstrated a slight departure from ideal solutions. Unlike rounded off maximums were found in the σ polytherms for alloys containing 22.3, 31.0, 40.0, and 51.0 atomic % Si and 20, 27, and 40 atomic % Ge. The peculiarity was attributed to the temperature-induced desorption of the surface-active component from the alloy surface.

$$\sigma_{\text{Ge}} = 642 - 0.140(t^{\circ}\text{C} - 940^{\circ}\text{C}) \quad 900-1200$$

Sangster, R. C. and J. N. Carman, Jr. Liquid surface tension measurement by analysis of solid-state curvatures; the surface tension of liquid germanium. J. Chem. Phys. 23:1142-1145. 1955.

The authors used the shape measurements from ingots purified in a zone melting unit to calculate the surface tension. By using a bar rather than a drop they eliminated one of the radius of curvature from the sessile drop equation. This allowed direct exact solution of the equation for surface tension. The assumption was made that the shape of the solid was the same as the shape of the liquid. Observation showed that there was no shape change during freezing unless faceting occurred. The values measured at the melting point for several metals were:

$$\sigma_{\text{Ge}} = 632 \pm 5, \sigma_{\text{Pb}} = 424 \pm 10, \sigma_{\text{Cd}} = 525 \pm 30$$

The germanium runs were made in both nitrogen and helium atmospheres, the cadmium runs were made in hydrogen, and the lead runs were made in a vacuum.

REFERENCES FOR INDIUM

Aldrich, R. G. and D. V. Keller, Jr. A sessile drop study of liquid-solid adhesion for the system indium (l)-aluminum using ultrahigh vacuum techniques. J. Phys. Chem. 72:1092-1099. 1968.

A sessile drop study was used to examine the wetting and adhesion behavior for indium-aluminum near the solidification temperature of indium. Ultrapure materials and ultrahigh vacuum techniques were used. With these conditions fixed volumes of highly pure gases were introduced for controlled contamination of the system. Aluminum was vapor deposited on a clean aluminum block immediately before an indium drop was formed on that surface. Contamination gas was added either before or after drop formation. The results were quite qualitative, the surface tension varied from 80 to 500 dynes/cm when contaminated with oxygen to 1 torr, from 80 to 200 dynes/cm in air at 760 torr, and measured 600 to 670 dynes/cm in 10^{-10} torr vacuum and also for hydrogen or nitrogen contamination to 1 torr. The drop was photographed through pyrex flats with a 35 mm camera having a 105 mm lens and a f/5.6 lens setting.

Aldrich, R. G. and D. V. Keller, Jr. Investigation of the contact angle between indium (l) and an aluminum substrate in ultrahigh vacuum. J. Appl. Phys. 36:3546-3548. 1965.

A sessile drop of liquid indium on a vapor deposited layer of aluminum was used to measure contact angle of the system In-Al. Very high vacuum, 10^{-11} torr, was used to prevent oxide formation which would change the system to an In-Al-O system. On annealing, the aluminum layer tended to form quite large grains and this affected the uniformity of the contact angle of the indium drop. Photographs through a pyrex cell were taken with a 35 mm camera with a bellows mounted 105 mm focal length lens. Using Bashforth and Adams' method the surface tension of pure indium at $158 \pm 2^\circ\text{C}$ was calculated to be 600 dynes/cm.

Bergh, A. A. The effect of dissolved germanium on the surface tension of molten indium. J. Electrochem. Soc. 109:1199-1200. 1962.

The surface tensions of pure indium and of alloys containing 5, 10, and 15 at.% germanium were measured using the maximum bubble pressure method. 99.999 wt.% indium was contained in a quartz crucible and a sharply ground quartz capillary was used. Hydrogen gas was used to form the bubbles. Measurements were taken at 600°C . For the pure indium the value was 514 ± 4 dynes/cm. For the alloys the values were 511, 510, and 516, ± 5 dynes/cm which indicated that dissolved germanium did not affect the surface tension of indium.

Davies, H. A. Density and surface tension of dilute liquid sodium-indium alloys and comparison with liquid sodium-cadmium alloys. *Met. Trans.* 3 (11):2917-2921. 1972.

The density and surface tension of five liquid Na-In alloys containing 0.5-7.0 at.% In were measured at 170-400° by using a maximum bubble-pressure technique including an automatic pressure-measuring and recording device. The results are compared with data previously reported for Na-Cd alloys. The gram atomic volumes of the Na-In alloys, calculated from the densities, indicate a substantial contraction on alloying which is, on the average, approximately double that for the Na-Cd alloys and qualitatively consistent with thermodynamic data for the two systems. The surface tension of liquid sodium increased slightly on adding In, indicating a lower In concentration in the surface than in the bulk, in contrast to the marked surface active behavior of Cd. The surface excess concentrations of In and Cd were calculated by using Gibbs' adsorption equation. The excess surface entropy, estimated from the temperature dependence of the surface tension, is compared and discussed for the two systems.

Gratsianskii, N. N. and A. K. Ryabov. Surface phenomena during corrosion of solid metallic solutions. The In-Pb system. *Zhur. Fiz. Khim.* 33:1253-1255. 1959. Russ. abstract transl. *Russ. J. Phys. Chem.* 33:26. 1959.

Measurements were made of the surface tensions of indium, lead, and indium-lead alloys in relation to the concentration of the alloy components. The measurements were made in a vacuum apparatus at 30 to 50°C above the melting temperature of the metals and alloys. The surface tension of indium at 185°C was measured as 592 dynes/cm and of lead at 362°C was 455 dynes/cm. The surface tension of the alloys changed little for lead concentrations from 40 to 100 at.%. A sharp drop in surface tension was observed at the point of solid phase transition from β - to γ - phase for a lead content of about 30 at.%.

Koval'chuk, V. F., V. A. Kuznetsov, and N. P. Kotlovanova. Surface tension of indium-tin alloys. *Zhur. Fiz. Khim.* 42:1754-1757. 1968. Russ. transl. *Russ. J. Phys. Chem.* 42:918-920. 1968.

Alloys of indium and tin were investigated because these are metal elements which have similar surface tensions. The densities and surface tensions for alloys across the entire concentration range were determined at 523°K and 623°K. The surface tensions were measured by the maximum drop pressure method. Measurements were made in a glass apparatus which was evacuated to 5×10^{-7} torr before sealing off. The pure metals and 45 alloy compositions were measured. Surface tensions of the pure metals were linear over the following temperature range.

$$\sigma_{\text{In}} = 555 \text{ at } 430^{\circ}\text{K}, 532 \text{ at } 730^{\circ}\text{K}$$

$$\sigma_{\text{Sn}} = 545 \text{ at } 510^{\circ}\text{K}, 528 \text{ at } 750^{\circ}\text{K}$$

Milford, D. A. and T. P. Hoar. Determination of the surface tensions of molten lead, tin, and indium by an improved capillary method. J. Inst. Metals (London) 85:197-205. 1957.

Two fused silica capillaries having different bores were used to measure the surface tension by measuring the differential gas pressure required to force material to equal levels in the capillaries. A hydrogen gas was used. The assumption was made, and actual observation showed, that the contact angle was near 180° so $\cos \theta = -1$. The hydrogen gas was catalytically purified, dried with magnesium perchlorate, and passed over potassium hydroxide pellets. It then passed through a 400°C furnace containing platinized asbestos, again dried with magnesium perchlorate and bubbled through liquid NaK at room temperature and through a liquid air trap before entering the apparatus. 99.998 wt.% purity lead and tin were used, the indium was 99.95 wt.% pure. The surface tension measurements for lead were higher than the measurements of previous investigators. The authors believe this is due to higher purity materials and precautions to eliminate contamination. The equations for the surface tension of pure metals as a function of temperature are as follows:

$$\sigma_{\text{Pb}} = 480.0 - 0.24(t-324)$$

$$\sigma_{\text{Sn}} = 566.0 - 0.065(t-232)$$

$$\sigma_{\text{In}} = 559.0 - 0.10(t-156)$$

Hydrogen was bubbled through the melt between different temperature settings producing a fresh metal surface for each set of data.

Pokrovskii, N. L., P. P. Pugachevich, and N. A. Golubev. Investigation of surface tension of the indium-lead system. Doklady Akad. Nauk. SSSR 181:80-83. 1968. Russ. transl. Soviet Physics Doklady 13:713-715. 1969.

Interest for this research was based on the fact that the shape of the isotherms of the surface tension of binary metallic solutions sometimes corresponds with the phase diagrams of the binary systems. This system was of interest because it has unlimited solubility in the liquid state and considerable solubility in the solid state. The measurements were made by the maximum drop pressure method using the combined gravitational apparatus developed by Pugachevich with some modifications. Measurements were made over the temperature range 200 to 500°C and from 0 to 100 at.%. The pure metals contained less than 1×10^{-3} wt.% impurities in the indium and less than 1×10^{-4} wt.% impurities in the lead. Twenty-six alloy solutions were studied and the surface tension isotherms had a smooth shape. It was found that for weak solutions, lead lowered the surface tension of indium. Data on the pure metals with respect to temperature are as follows:

$$\sigma_{\text{In}} = 570 - 0.10(t-200) \quad 200-500$$

$$\sigma_{\text{Pb}} = 440 - 0.10(t-350) \quad 350-500$$

Timofeevicheva, O. A. and P. P. Pugachevich. Surface tension of metallic indium. Doklady Akad. Nauk SSSR 124:1093-1094. 1959. Russ. transl. Proc. Akad. Nauk. SSSR, Phys. Chem. Sect. 124:171-172. 1959.

The maximum drop pressure method was used to measure the surface tension of liquid indium over the temperature range from 170 to 500°C. Because the results of this work using 99.99 + wt.% indium compared well with data where higher purity metal was used, it was determined that the impurities, lead, cadmium, zinc, copper, iron, germanium, silver, and tin were either surface-inactive to indium or very weakly active. The data fit the following equation for surface tension as a function of temperature over the range 170 to 500°C.

$$\sigma_{\text{In}} = 569.3 - 0.085 t$$

White, D. W. G. The surface tensions of indium and cadmium. Met. Trans., vol. 3, 1933-1936. 1972.

The surface tensions of 99.9999 wt.% indium and cadmium were measured by the sessile drop method. The data were calculated by Bashforth's method. Indium data were measured under thermal equilibrium conditions from the melting point to about 557°C. These data were slightly nonlinear at low temperatures and can be represented by the equation

$$\sigma_{\text{In}} = 568.0 - 0.04 t - 7.08 \times 10^{-5} t^2$$

The cadmium data over the same range were very nonlinear. No fit to the data was attempted. The drops were formed in a purified hydrogen atmosphere at 760 torr.

REFERENCES FOR LEAD

Bircumshaw, L. L. The surface tension of liquid metals. Part I. Tin and lead. Phil. Mag. [7]2:341-350. 1926.

The maximum bubble pressure method was used to measure the surface tension of the two pure metals. Hydrogen used was generated electrolytically from 5% caustic soda and then passed over 600°C silica chips and dried over calcium chloride. The tin used was at least 99.99 wt. %, and the lead contained only 0.002 wt. % Cu and 0.002 wt. % Fe. The surface tension of each metal was measured from the melting point to 1000°C.

Bircumshaw, L. L. The surface tension of liquid metals. Part V. The surface tension of the lead-tin alloys. Phil. Mag. [7]17:181-191. 1934.

The maximum bubble pressure method was used to measure the surface tension of the lead-tin system across the composition range and for the temperature range from 200°C to 800°C. Additional hydrogen purification consisted of passing the gas over magnesium which was heated to just below the melting point to remove traces of oxygen or water vapor. The data showed that the addition of small quantities of lead caused a marked decrease in the surface tension of tin. Relatively large amounts of tin had very little effect on the surface tension of lead. This showed that lead is surface-active in molten tin.

Bradhurst, D. H. and A. S. Buchanan. The surface properties of liquid lead in contact with uranium dioxide. J. Phys. Chem. 63:1486-1488. 1959.

The sessile drop method was used to measure the surface tension and contact angle of liquid lead on uranium dioxide surfaces. The effects of the metallic solute bismuth and non-metallic solutes oxygen, sulfur, selenium, and tellurium were investigated. A one in. diameter molybdenum tube was enclosed within a water cooled pyrex tube which had optical flats on each end. The gases used were purified by a liquid nitrogen trap, a Na-K trap, and P₂O₅ drying columns. 99.999 wt.% lead was used and the uranium dioxide plaques were prepared by igniting uranyl acetate in air, then reducing, pressing, and sintering. The image was focused on a photographic plate with an 8 in. focal length lens set at F/23 for sharp images. Data were calculated from the drop profiles by the Dorsey method. The surface tensions measured decreased linearly with increasing bismuth concentration at 700°C. Oxygen reduced the surface tension of the molten lead the most rapidly and the order of surface-activity of the non-metallic solutes was

Demeri, M., M. Farag, and J. Heasley. Surface tension of liquid lead-tin alloys. J. Matl. Sci. 9(4):683-685. 1974.

By using the sessile drop technique, the contact angle and surface tension of Pb-Sn alloys on fused SiO_2 substrates were measured at 400-700°C. Surface tension of the entectic alloy is lower than that of either Sn or Pb. The surface tension results for the pure metals were not linear with temperature.

Gratsianskii, N. N., A. K. Ryabov, and V. V. Tobolich. Surface phenomena during the corrosion of solid solutions of metals: the Pb-Tl system. Ukr. Khim. Zhur. 29:408-410. 1963. Russ. abstracted.

The surface tensions of liquid lead-thallium alloys were measured over the temperature range 320 to 410°C. For the 390°C isotherm, minimums occurred at 5 and 50 at.% lead and maximums occurred at 33 and 75 at.% lead. These concentrations correspond to phase transition compositions in the solid lead-thallium system. Lead acts as a surface active agent in thallium. For the pure metals the surface tensions measured at 390°C were 456 dynes/cm for lead and 507 dynes/cm for thallium.

Joud, Jean C., Nicolas Eustathopoulos, Alain Bricard, and Pierre Desre. Determination of the surface tension of silver-lead and copper-lead alloys by the sessile drop method. J. Chim. Phys. Phys-Chim. Biol. 70 (9):1290-1294. 1973. Fr.

The surface tensions of Ag-Pb and Cu-Pb alloys were measured by the sessile drop method on graphite supports. Results were compared to maximum bubble-pressure values and to theoretical estimation. Experimental values, using Gibbs formalism, allow superficial adsorption calculations.

$$\sigma_{\text{Pb}} = 462 - 0.11(t - 327) \quad 550 - 1000$$

Joud, J. C., N. Eustathopoulos, A. Bricard, and P. Desre. Surface tension of ternary liquid alloys. J. Chim. Phys. Phys-Chim. Biol. 71(7-8):1113-1122. 1974. Fr.

Surface tension variation of ternary liquid alloys vs. composition and temperature was studied with a statistical model. Application was made to the Ag-Cu-Pb system which was studied experimentally by the sessile drop method.

$$\sigma_{\text{Pb}} = 462 - 0.11(t - 327)$$

Koval'chuk, V. F., V. A. Kuznetsov, and L. V. Butuzova. Surface tension of thallium-lead alloys. Zhur. Fiz. Khim. 42:2265-2267. 1968. Russ. transl. Russ. J. Phys. Chem. 42:1198-1200. 1968.

A study was made of the density and surface tension of molten thallium-lead alloys at various temperatures. This is another system where the components have similar surface tensions. The maximum bubble pressure method was used with high purity metals. The surface tension-temperature dependence for both pure metals is negative. Values are as follows:

$$\sigma_{\text{Tl}} = 470 \text{ at } 427^{\circ}\text{C}; 460 \text{ at } 552^{\circ}\text{C}$$

$$\sigma_{\text{Pb}} = 447 \text{ at } 437^{\circ}\text{C}; 439 \text{ at } 562^{\circ}\text{C}$$

The surface tension isotherm deviates below the ideal isotherm and has a minimum at 50 at.% lead.

White, D. W. G. The surface tension of Pb, Sn, and Pb-Sn alloys. Met. Trans. 2:3067-3071. 1971.

The surface tensions of 99.9999 wt.% lead and tin and of alloys made from lead and tin of the same purity were measured by the sessile drop method. The surface tension of lead was determined from the melting point, the surface tension of tin from 200°C , and the surface tensions of the alloys from the respective liquidus temperatures, all, up to about 560°C . Data for the pure metals with respect to temperature can be represented by the following equations.

$$\sigma_{\text{Pb}} = 472.7 - 0.085 \text{ } t$$

$$\sigma_{\text{Sn}} = 569.0 - 0.080 \text{ } t$$

The surface tensions of the alloys were not linear with temperature. The drops were formed on a graphite plaque in an atmosphere of purified hydrogen at 760 torr.

REFERENCES FOR THALLIUM

Koval'chuk, V. F. and V. A. Kuznetsov. Free surface energy of molten metallic alloys of the thallium-tin system. Zh. Fiz. Khim. 49 (3):806-807. 1975. Russ. Transl. Russ. J. Phys. Chem. 49 (3):477. 1975.

Additional data considered in abstracting and indexing are available from a source cited in the original document. Tests were made by measuring the maximum pressure in a drop. The surface tension of the alloys depended linearly on the temperature. The temperature coefficients of the surface tension were negative and their abs. magnitude lay within the values of temperature coefficients for pure Tl and Sn. The concentration dependence of the surface tension was characterized by a curve with a minimum in the range of medium concentration. This minimum was not related to eutectics. The concentration dependence did not agree with theory.

Sauerwald, F., B. Schmidt, and F. Pelka. Surface tension of molten metals and alloys. V. Surface tension of Fe-C alloys, Hg_5Tl_2 , $NaHg_2$, its secular variation in thallium and the surface tension of slags. Zeit. Anorgan. Allgem. Chem. 223:84-90. 1935. Ger. abstracted.

The maximum bubble pressure method was used with a 50% H_2 -argon atmosphere. The surface tension of the above materials was measured and an increase in surface tension of thallium with time was confirmed.

Timofeevicheva, O. A. and V. B. Lazarev. The variation of the surface tension of thallium with temperature. Doklady Akad. Nauk SSSR 138:412-427. 1961.

The variation of the surface tension of thallium with temperature was studied to help clarify certain problems connected with the preparation of semiconductors. The maximum pressure method was used. To satisfy the theoretical assumptions, the maximum bubble capillary must have a very sharp edge at the tip. If a maximum bubble pressure is used for drops which wet the walls, and a maximum drop pressure method used for liquids which do not wet the walls, then capillaries with finite wall thickness are permissible. The authors did not know if thallium would wet the glass so they designed a rotating gravitational system which could make either measurement. The data for thallium were linear and over the temperature range 310 to 500°C were represented by the equation.

$$\sigma_{Tl} = 464.5 - 0.080(t - 303)$$

The surface tension data for gallium, indium, and thallium as measured by Timofeevicheva decrease with increasing atomic weight as do the data for the alkali metal subgroup.

REFERENCES FOR TIN

Abdel-Aziz, Abol, H. K., M. B. Kirshah, and A. M. Aref. Surface tension of molten tin and an estimate of its critical temperature. Z. Metallkd. 66(3):183-184. 1975.

The surface tension and density of molten tin were determined by a maximum bubble pressure apparatus. The surface tension changes linearly with temperature from the melting point to 700°C. The temperature coefficient is -0.073 dynes/cm°C. The density of molten tin was 6.83 g/cm³. The critical temperature, estimated from the surface tension polytherm, is approximately 7778°K.

$$\sigma_{\text{Sn}} = 524 - 0.073(t-360) \quad 360-700$$

Allen, B. C. and W. D. Kingery. Surface tension and contact angles in some liquid metal solid ceramic systems at elevated temperatures. Trans. Met. Soc. AIME 215:30-37. 1969.

Surface tension measurements with respect to temperature were made for the pure liquid metals iron, copper, cobalt, nickel, and tin; also for iron-carbon, cobalt-carbon, and nickel-carbon alloys. The sessile drop measurement method was used with the drop setting on a refractory plaque. The liquid metal drop was either in a purified atmosphere (nitrogen, hydrogen, or helium at 0.5 atm pressure) or in a vacuum (10⁻⁶ ton). Photographs of the sessile drop were taken and measurements from the drop profile were used in the Dorsey method for calculation of liquid surface tension from the shape of a sessile drop. The temperature dependence for copper was found to be negative as is normal for metals, and it was felt the positive dependence reported by Sauerwald and Drath was probably caused by small amounts of surface active impurities. The equations for the surface tensions of pure tin and copper as a function of temperature are as follows:

$$\begin{aligned} \sigma_{\text{Sn}} &= 600.0 - 0.176(t-273) \\ \sigma_{\text{Cu}} &= 1270.0 - 0.306(t-1083) \end{aligned}$$

Atterton, D. V. and T. P. Hoar. Simultaneous determination of the surface tension of tin and its contact angle with silica by the use of conical capillaries. J. Inst. Metals (London) 81:541-551. 1953.

The measurement of the differential pressure required to force liquid metal to equal heights in both cylindrical and conical capillaries provided the data for calculation of surface tension. By the use of three capillaries, at least one of which is conical, for each run both

surface tension and contact angle could be determined; i.e., from three equations and three unknowns. The furnace atmosphere and the pressure gas was hydrogen which was purified by passage through saturated potassium hydroxide solution, concentrated sulfuric acid, phosphorus pentoxide, copper, nickel, and iron gauzes (heated to 650°C), and then through a liquid oxygen trap. The equation for the measured surface tension of molten tin as a function of temperature is:

$$\sigma_{\text{Sn}} = 614.0 - 0.17(t-232) \quad 400 - 800$$

Cahill, J. A. and A. D. Kirshenbaum. The surface tension of liquid tin between its melting point and 2100°K. J. Inorg. Nucl. Chem. 26:206-208. 1964.

The surface tension of liquid tin was measured from 850 to 2100°K by the maximum bubble pressure method. Impervious Al_2O_3 capillaries having a wall thickness at the tip of 0.06 mm were used. 99.89 wt % pure tin was contained in an Al_2O_3 crucible. The experimental values for the surface tension of liquid tin over the 1300°C range fit the following linear equation:

$$\sigma_{\text{Sn}} = 581.2 - 0.07424T \quad T^\circ\text{K}$$

with a probable error of ± 4 dynes/cm.

Eremenko, V. N. and V. I. Nizhenko. Wetting power of liquid alloys of tin with titanium and their interfacial tension with aluminum oxide. Ukrain. Khim. Zhur. 26:605-608. 1960. Russ. abstracted.

Data on surface tension and contact angle on Al_2O_3 are reported as the concentration of titanium in the tin increases. For pure tin the surface tension measured was 539 dynes/cm and the contact angle was 140°. The surface tension decreased to 274 dynes/cm and the contact angle increased to 150° for a titanium concentration of $1.5(10)^{-3}$ g. atoms/liter. Since titanium and tin have approximately the same atomic radius this large surface active effect was attributed to a reaction of titanium with oxygen and the formation of a Sn-Ti-O complex surface layer.

Foryst, J. Surface tension of mercury, melted tin, bismuth, lead, and some lead alloys. Prace Glównego Inst. Met., 307-328. 1951. abstracted.

The determination of the surface tension of mercury, melted tin, bismuth, lead, and some lead alloys, using the maximum bubble pressure method lead to the following conclusions: (1) The surface tension of mercury is affected by adsorbed H_2 , N_2 , and CO_2 . (2) For tin and lead these gases had no effect on the surface tension in the range 350 to 650°C. (3) The change in surface tension with temperature was very small for bismuth between 300 and 500°C. (4) Addition of up to 0.5

at. % zinc or tin had no effect on the surface tension of melted lead.

Gans, Wigbert Von and Harry Parthey. Surface tension of liquid tin. Zeit. Metallk. 57:19-21. 1966. Ger. English summary.

The surface tension of sessile drops of liquid tin was determined by the Dorsey method from photographs of the drop profiles. The surface tension of tin drops were measured at 290°C as a function of time. Newly formed drops in a 10^{-4} torr vacuum had surface tensions of 590-600 dynes/cm, within 30 sec this dropped to less than 540 dynes/cm and became constant at 520 dynes/cm. In a hydrogen atmosphere at 760 torr the surface tension of the newly formed drop was about 560 dynes/cm and leveled out at about 525 dynes/cm. It was assumed that the decrease in surface tension was due to the adsorption of hydrogen and oxygen.

Kaufman, S. M. and T. J. Whalen. The surface tension of liquid gold, liquid tin, and liquid-gold tin binary solutions. Acta Metallurgica 13:797-805. 1965.

The sessile drop method was used to measure the surface tension of the pure metals and the alloys across the composition range. The drops were in a vacuum supported on an inert solid such as BeO or graphite. Calculations were made using the tables of Bashforth and Adams. Liquid gold was measured over the range 1100-1400°C. Difficulty was encountered trying to keep the liquid tin oxide free in a 10^{-5} torr vacuum. SnO_2 is metastable in excess of 1200°C. The oxide film was eliminated by adding zirconium chips in the vacuum system as an oxygen "getter." Results without the zirconium were as much as 20% lower than other literature values. Data were taken from 900 to 1200°C but they were combined with the data of others to give a combined equation for tin of:

$$\sigma_{\text{Sn}} = 600.0 - 0.18(t-232)$$

The actual data of the authors were a lower slope than this. Helium was used as an atmosphere for the pure gold runs because liquid gold acted as a catalyst for the cracking of hydrocarbon vapors in the system. This caused uncontrollable pressure rises and carbon deposition on the liquid drop. The equation for the data of liquid gold was:

$$\sigma_{\text{Au}} = 1140.0 - 0.52(t-1060)$$

Lauermann, I., G. Metzger, and F. Sauerwald. Surface tension measurement 8[1]. The surface tension of liquid silver, tin, and silver-tin alloys. Zeit. Physik. Chem. 216:42-49. 1961. Ger. abstracted.

The maximum bubble pressure was used to measure the surface tension of the above metals. The alloys were measured across the entire composition range. The data for tin were taken over the temperature

range from 740 to 1115°C. The data were fit to the following linear equation, but the data were actually somewhat non-linear. The equation representing the surface tension of liquid silver with respect to temperature is as follows:

$$\sigma_{\text{Sn}} = 479.5 - 0.072(t-1115)$$

$$\sigma_{\text{Ag}} = 895.0 - 0.184(t-980)$$

Mukai, Kusuhiro, Ichiro Kashiwagi, and Takanori Hukuda. Determination of surface tension of liquid tin by the sessile drop method. Kyushu Kogyo Daigaku Kenkyu Hokoku, Kogaku 26:155-159. 1973. Jap. Bulletin of the Kyushu Institute of Technology.

The surface tension of liquid tin was determined by the sessile drop method in hydrogen in the range 250-500°C. The surface tension σ (dyne/cm) is given as a function of temperature,

$$\sigma_{\text{Sn}} = 580 - 0.053t$$

The result agrees with results from the differential capillary method. Discrepancy between the present result and that of White (1971) is due to the contamination of Sn through contact with graphite.

Naidich, Yu. V., V. M. Perevertailo, and V. S. Zhuravlev. The surface tensions and densities of tin-germanium melts. Abstract only. Zhur. Fiz. Khim. 45:991. 1971. Russ. transl. Russ. J. Phys. Chem. 45:556. 1971.

The surface tensions and densities of liquid tin-germanium melts were investigated using the "large drop method." The temperature range was 300 to 1200°C. The surface tension data for pure tin were

$$\sigma_{\text{Sn}} = \begin{array}{l} 512 \text{ at } 600^\circ\text{C}, 500 \text{ at } 700^\circ\text{C}, 491 \text{ at } 800^\circ\text{C}, \\ 480 \text{ at } 900^\circ\text{C}, 470 \text{ at } 1000^\circ\text{C} \end{array}$$

The forms of the isotherms were interesting. All the isotherms from 600 through 1000°C passed through a common point at 470 dynes/cm and 10 at. % Ge. Isotherms up to 1000°C showed a sharp minimum at 20 at. % Ge, and the 1000°C isotherm was very smooth increasing monotonically. It was explained that the minimum of the isotherm curve at low temperatures results when the bond energies between different species is lower than the bond energies between similar species, in the temperature range where this difference exceeds kT .

Nal'giev, A. M., Kh. I. Ibragimov, and V. S. Savvin. Surface tension, density, and electron work function of tin-mercury. Zh. Fiz. Khim. 49(7):1857-1858. 1975. Russ. abstracted.

Additional data considered in abstracting and indexing are available from a source cited in the original document. Surface tension σ , density, and electron work function ϕ were determined for liquid Sn-Hg alloy at the whole range of concentrations. The σ exhibits a negative temperature coefficient and an inflection on isotherms at 65 atomic % Hg. Within the whole concentration range the ϕ was constant and corresponded to that of pure Hg. The molar volumes exhibit a negative deviation from additivity with the highest deviation at 65 atomic % Sn.

Nizhenko, V. I. and L. I. Floka. Density and surface properties of iron-tin melts. Izv. Akad. Nauk SSSR, Metal.(4):73-76. 1973. Russ. Transl. Russian Metallurgy (Metally) 4:56-59. 1973.

The density and surface tension in the Fe-Sn system at 1550° in a He atmosphere in Al_2O_3 and ZrO_2 cups were investigated as a function of concentration. Using the large drop method [V. N. Eremenko and V. I. Nizhenko (1960)], the isotherms for the molar volume in both the liquid and solid states showed negative deviations from additive values. The surface free energies for molten Fe-Sn alloys at 1550°C were determined over the entire concentration range. The experimental values were significantly lower than the calculated ones for a system showing ideal behavior. The experimental results were used to evaluate the thermodynamic activity of Sn in Fe and the characteristics of the surface layer.

Pokrovskii, N. L. and N. D. Galanina. Properties of metallic solutions. IV. Surface tension of tin and tin-sodium alloys. Zhur. Fiz. Khim. 23:324-331. 1949. Russ. abstracted.

The surface tension of molten tin was measured with respect to temperature as

$$\sigma_{\text{Sn}} = 537.0 - 0.078(t-232)$$

This was over the temperature range 250 to 450°C, in a vacuum of 10^{-5} torr. The k in Eötvös equation was constant but a very small value (0.266). The parachor increased with temperature.

Pokrovskii, N. L. and D. S. Tissen. A study of absorption layers on liquid metal surfaces. Doklady Akad. Nauk SSSR 128:1228-1231. 1959. Russ. transl. Proc. Akad. Nauk SSSR, Phys. Chem. Sect. 128:879-882. 1959.

The object of this research was to investigate the effect of elements of the 4th and 5th groups of the periodic table on liquid tin. Thallium and arsenic were selected. The maximum bubble pressure method of surface tension measurement was used. Thallium-tin alloy measurements were carried out over the temperature range 270 to 400°C and to 1.96 at. % thallium. Arsenic-tin alloys were measured from 300 to 450°C with a maximum of 5.9 at. % arsenic. The isotherms were smooth and nearly linear which shows both metals are quite surface non-active on tin. The following tin data can be taken from the figures.

$$\sigma_{\text{Sn}} = \begin{matrix} 540 \text{ at } 270^{\circ}\text{C}, & 538 \text{ at } 300^{\circ}\text{C}, & 534 \text{ at } 350^{\circ}\text{C} \\ 530 \text{ at } 400^{\circ}\text{C}, & 527 \text{ at } 450^{\circ}\text{C} \end{matrix}$$

Pokrovskii, N. L. and D. S. Tissen. Properties of metallic solutions VI. Effect of additions of indium and germanium on the surface tension and microstructure of tin. Zhur. Fiz. Khim. 34:1238-1241. 1960. Russ. transl. Russ. J. Phys, Chem. 34:592-594. 1960.

Surface tensions of pure tin and alloys containing small amounts of indium or germanium were measured by the maximum drop pressure method. The surface tension of high purity zone melted tin, total impurities less than 2×10^{-4} wt. %, was measured for comparison with data of less pure tin. The measurements were nearly the same as those for material which was purified by heating at 1000°C in a vacuum; 545 dynes/cm at 250°C and 522 dynes/cm at 500°C. This was explained by the fact that impurities of low vapor pressure (iron, copper) which are removed by zone melting, are inactive at the surface of liquid tin. For impurities which are surface active on tin, lead, bismuth, and antimony, both purification methods remove them. The addition of up to 2.42 at. % indium had only a slight effect on surface tension, indium is probably a neutral additive at the surface of liquid tin. Adding up to 2 at. % germanium had no effect at all on the surface tension of the tin. Although these additives do not affect the surface tension of the tin, they exert a large influence on the microstructure and the kinetics of crystallization.

Pokrovskii, N. L. and M. Saidov. Properties of metallic solutions. V. Effects of Zn, Al, Cd, Mn, and Bi on the properties of liquid and solid tin. Zhur. Fiz. Khim. 29:1601-1609. 1955. Russ. abstracted.

The surface tension and density of the molten alloys were measured in a glass apparatus by the maximum bubble pressure method. The tin was purified by heating in a vacuum to 1000°C. Alloy properties were determined from 250°C to 500°C. Zinc and manganese were found to be surface inactive in the alloy. They raised the surface tension. Manganese was found to inhibit the $\beta\text{-Sn} \rightarrow \alpha\text{-Sn}$ transformation. The equation

for the measured surface tension of pure tin as a function of temperature was

$$\sigma_{\text{Sn}} = 549 - 0.072(t-250)$$

Pokrovskii, N. L., P. P. Pugachevich, and Kh. I. Ibragimov. Surface tension of melts belonging to the tin-gold system. Doklady Akad. Nauk. SSSR 172:829-832. 1967. Russ. transl. Soviet Physics Doklady 12: 170-172. 1967.

The anomalous shape of isotherms of surface tension of alloys corresponding to intermetallic compounds was again investigated. The tin-gold system was picked because there are several Au-Sn compounds and the two components differ greatly in melting point, surface tension, and density. The system also has a strong negative deviation from Raoult's law. Measurements were made using the maximum bubble pressure method and the gravitational apparatus. The pure metals contained total impurities less than 10^{-3} wt % tin and 10^{-4} wt % gold. Sixty-five gold tin melts were measured with concentrations from 0 to 74.54 at. % gold. The isotherms were smooth and did not reflect the compounds of the phase diagram. The data with respect to temperature were linear and for pure tin were:

$$\sigma_{\text{Sn}} = 545 - 0.060(t-250) \quad 250-500$$

Sauerwald, F. and B. Schmidt. Surface tension of molten metals and alloys. IV. Change in surface tension with time and the method of drop measurements at high temperatures. Zeit. Anorgan. Allgem. Chem. 213: 310-318. 1933. Ger. abstracted.

The surface tension of mercury in 10^{-5} torr vacuum was between the initial and final values of the surface tension measured in air. For tin there was no change in surface tension with time at 10^{-5} torr. Thallium showed an increase of surface tension with time. It was thought that for mercury the change was due to the varying effect of the arrangement of the metal atoms and the adsorbed and absorbed gas atoms.

Schwaneke, Alfred E. and Wilbert L. Falke. Surface tension and density of liquid tin. U. S. Bur. of Mines Rept. No. 7372. 1970.

This research on the surface tension of pure molten tin was required because of the considerable differences of existing data. This variance was hindering tin-lead solder research. Pure tin, 99.999 wt. %, was measured by the maximum bubble pressure method from 236 to 583°C. A two-capillary apparatus with silica capillaries was used, and the capillary tips were internally ground to a 60° cone shape. The tip thickness was about 0.04 mm. Purified helium gas was used and the

data indicated an exponential decay with time if oxygen was entering the system. The surface tension data measured were linear with temperature as follows:

$$\sigma_{\text{Sn}} = 555.8 - 0.0476(t-232) \quad 236-583^{\circ}\text{C}$$