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ZINC AND ITS ALLOYS

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Errata Sheet

Page 32 - Figure 13 - legend; change "stress-stress-strain" to "stress-strain".
" 64 - Figure 30 - "Table 17" change to "Table 18".

" 80 - Optical properties, last sentence; change Figure 39 to Figure 40.
" 105 - Figure 56 - legend; change + to x.

" 127 - Paragraph 2, line 2; change "coated soil" to "coated steel".

" 148 - Figure 79 and page 168 Figure 105, interchange diagrams, legends O.K.
" 148 - Figure 81, legend; change reference "S" to reference "10".

" 159 - Figure 95, legend; change "FeZn" to "$FeZn_7$".

" 186 - Figure 119, legend; change "Table 64" to "Table 65".

" 189 - Figure 66, footnote; change "Figure 121" to "Figure 122".

(See other side)

Page 78 - last line -	30,411 cal/gram atom and 31,569 cal/gram atom at 25°C. or 29,364 cal/gram atom and 30,939 cal/gram atom at the melting point (419.5°C).
Page 116 - line 27,	change °C to °F (150°F).

PREFACE

The bureau is continually in receipt of requests for information concerning the properties, statistics, and manufacture of metals and of alloys, coming from other departments of the Government, technical or purchasing agents of manufacturing firms, or from persons engaged in special investigative work in universities and private technical laboratories. Such information is rarely to be found in systematic form; some sources of such information are difficult of access and their accuracy not always certain. Often quoted information of this sort is valueless, either for the reason that the data upon which it is based are actually incorrrect or that they have not been properly interpreted.

There are, therefore, being issued from time to time, in response to these demands, circulars on individual metals or alloys. The aim is to group in these circulars all of the best information which the bureau has as a result of its tests and investigations, together with that available in records of published tests and investigations of such material.

The circulars deal primarily with the physical properties of the metal or alloy. Except for a few statistics of production, other features such as methods of manufacture, presence of impurities, etc., are discussed primarily in their relation to these physical properties. It must be realized that the physical properties of any metal or alloy are often in great degree dependent upon such factors. Any statement of values for such properties should include accompanying information regarding these factors by which the properties are affected.

The endeavor, therefore, in the circulars is to reproduce only such data as have passed critical scrutiny and to qualify suitably, in the sense outlined above, all statements, numerical or otherwise, made relative to the characteristics of the metal.

The effort has been made to give briefly the most important and fundamental properties of zinc and the alloys in which zinc is the predominating element and to make clear through the bibliography, the sources of more detailed information. As an aid to the latter, the references relating to any phase of the subject have been grouped at the close of the section in which that phase of the subject is discussed. The attempt has been made to include in the bibliography all articles having an important bearing on the subject. Many trade articles, however, especially those of unknown authorship, have been intentionally omitted. In most cases in the bibliography only those articles appearing since 1909 have been included.

Considerable work on various properties of zinc of high purity has been carried out under the supervision of Louis Jordan, senior metallurgist. The results of this work, hitherto unpublished, have been incorporated into the appropriate sections of the circular. In addition, aid has been given by a number of others within the bureau in the discussion of various phases of the subject upon which experience best fitted them to pass.[1] Special mention should be made of the

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[1] Among those who have aided materially in this way are: W. Blum, F. R. Caldwell, E. C. Groesbeck, L. Jordan, G. E. F. Lundell, D. J. McAdam, jr., W. F. Meggers, P. Hidnert, E. L. Peffer, G. W. Quick, H. S. Rawdon, C. M. Saeger, R. L. Sanford, J. A. Scherrer, W. H. Swanger, J. G. Thompson, M. R. Thompson, and F. Wenner.

work of Miss M. G. Lorentz, who has compiled and classified the information from the technical literature which forms the greater part of the text of the circular, and that of Hunter H. Walkup, who has put a great deal of this information into graphical form.

Credit is due to the American Zinc Institute for the aid given in some of the early work in searching the literature. The extensive research work carried out by the New Jersey Zinc Co. constitutes, perhaps, the best single source of information on zinc. The published results of this work have been drawn upon freely in the preparation of this circular.

ZINC AND ITS ALLOYS

ABSTRACT

The physical and mechanical properties of zinc summarized from the technical literature, together with results obtained at the bureau, are given. Special consideration has been paid to the effect of structural condition of the metal resulting from impurities and from such factors as mechanical working, recrystallization, etc., upon the measured physical properties. The corrosion resistance of zinc, especially as related to its usefulness as a protective coating for steel, is discussed. The various alloy systems are summarized from the standpoint of constitution. Particular attention is given to the die-casting alloys and the properties which determine their usefulness industrially. A rather complete bibliography is included in the form of selected references appended to the various sections in which the different properties are discussed.

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I. ZINC

1. INTRODUCTION

Zinc was known to the ancients; zinc bracelets have been found in the ruins of Cameros dating from 500 B. C., and certain passages of the writings of Strabo in which "mock-silver" is mentioned have been interpreted as referring to zinc (13).[2] The German philosopher, Albertus Magnus, who died in 1280, is stated to have been the first of the more modern writers to mention zinc in his writings and Paracelsus (1493–1541) was the first to class it among the metals, the name "zinken" being used. The production of zinc by distillation from calamine was well under way in Europe by the middle of the eighteenth century. The production of the metal on a commercial scale was undertaken in England at Bristol in 1743. There is evidence, however, that zinc was known and produced in the East long before it was in Europe.

Zinc—General

Text reference	Year	Name and title
1	1930	Field, S., Zinc and its compounds, Metal Ind. (London), **36,** pp. 75–76.
2	1929	Finkeldey, W. H., Zinc and its alloys resist atmospheric corrosion, Chem. & Met. Eng. **36,** pp. 556–557.
3	1929	——, Zinc in Canada, Metal Ind. (London), **35,** pp. 204–207, 302–303.
4	1928	——, Bull. American Zinc Institute (Inc.), Zinc and its corrosion resistance.
5	1928	Aston, F. W., The constitution of zinc, Nature, **122,** p. 345; Chem. Abst. **22,** p. 4355.
6	1928	Peirce, W. M., Zinc and its alloys, Trans. Am. Soc. Steel Treating, **13;** p. 530.
7	1928	Zook, J. A., Zinc, Mineral Ind., **37,** pp. 622–650; Chem. Abst., **23,** p. 5136.
8	1927	Richter, K., Zink, zinn und blei, Wien: A. Hartleben.
9	1927	Rowe, R. C., Zinc, basis of bearing metals, Canadian Foundry, May 18, pp. 15–17.
10	1926	Zook, J. A., Zinc, Min. Ind., **35,** pp. 695–726; Chem. Abst., **21,** p. 3586.
11	1925	Henderson, T. B., Spelter prospects, Metal Ind. (London), **27,** p. 233.
12	1925	Lones, T. E., Zinc and its alloys, Pitman & Sons, London.
13	1924	Rawdon, H. S., Protective metallic coatings, Am. Chem. Soc. Monograph No. 40, Chem. Catalog Co., New York, N. Y.
14	1923	Harrington, J. W., Romances of industry—zinc, Am. Industries, **24** (4), pp. 27-31; J. Inst. Metals, **38,** p. 585.
15	1923	Djang, H. D., Origin of zinc in China, Science (China), **8,** pp. 233-243; Chem. Abst., **18,** p. 487.
16	1923	Zook, J. A., Zinc, Mineral Ind., **32,** pp. 697-727; J. Inst. Metals, **33,** p. 503.
17	1921	Haughton, J. L., Zinc and zinc rich alloys, Metal Ind. (London), **18,** pp. 4–7; J. Inst. Metals, **26,** p. 490.
18	1917	——, Symposium on zinc. Met. & Chem. Eng., **16,** pp. 484–490.
19	1916	Smith, E. A., Future of zinc, Iron Age, **98,** p. 1221.
20	1916	Zook, J. A., Zinc. Mineral Ind., **25,** pp. 748–772; Chem. Abst., **11,** p. 2874.
21	1915	Stone, G. C., Spelter—its manufacture and properties, Metal Ind., **13,** pp. 370–373.
22	1912	Hommel, W., History of zinc, Origin of the name zinc. Recognition of zinc as a metal, Chem. Ztg., **36,** pp. 905–906, 918–920; J. Chem. Soc., **102a** (2), p. 942.
23	1912	Hommel, W., Indian and Chinese zinc, Z. Angew. Chem., **25,** pp. 97–100, J. Chem. Soc., **102a** (2), p. 255; Chem. Abst., **6,** p. 729.
24	1911	Bouchonnet, A., Zinc, cadmium, cuivre, mercure, O. Doin, Paris.

2. COMMERCIAL ZINC

(a) SOURCES IN NATURE

Zinc does not occur free in nature, but in combination it is widely diffused. The chief ore is zinc blende or sphalerite, which generally contains, in addition to zinc sulphide, small amounts of the sulphides of iron, silver, and cadmium. It is widely distributed and is particularly abundant in Germany, Austria, Hungary, Belgium, the United States, and England. Second in importance is the carbonate, calamine, or zinc spar, which at one time was the principal ore; it almost

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[2] The numbers in parenthesis appearing throughout the text relate to the reference numbers in the list of references at the end of each section.

invariably contains the carbonates of cadmium, iron, manganese, magnesium, and calcium, and may be contaminated with clay, oxides of iron, galena, and calcite. Calamine occurs chiefly in Spain, Silesia, and the United States. Of less importance is the silicate, $Zn_2SiO_4H_2O$, named electric calamine or hemimorphite; this occurs in quantity in Altenburg near Aix-la-Chapelle, Sardinia, Spain, and the United States. Other zinc minerals are willemite, Zn_2SiO_4, hydro-zincite or zinc bloom, $ZnCO_3.2Zn(OH)_2$, zincite or red zinc ore, ZnO, and franklinite, $3(FeZn)O.(FeMn)_2O_3$.

(b) METALLURGY OF ZINC

The metallurgy of zinc may be considered under two headings—pyrometallurgical and hydrometallurgical. Under pyrometallurgy are included the processes that are commonly generalized as zinc smelting, and the second heading embraces the chemical and electrolytic processes used for precipitating zinc from its solutions.

(1) PYROMETALLURGY .[3]—This characterization is more or less a misnomer inasmuch as there is commonly no such thing in the pyrometallurgy of zinc as smelting. In all processes, zinc oxide is reduced by carbon, metallic zinc is volatilized and distilled, and the only association with smelting as commonly understood is that the metal may be obtained in a molten state.

The art of zinc smelting is simple in principle, but complicated in practice. It depends upon the reducibility of zinc oxide by carbon or carbon monoxide, or both. Consequently zinc sulphide blende must first be roasted to obtain the oxide. Zinc silicate ($ZnOSiO_2$) and zinc ferrite ($ZnOFe_2O_3$) which may be formed during the roasting, are both reducible directly by carbon.

In the distillation of zinc in a retort, whether the original source be zinc oxide to be reduced or crude spelter to be refined, the vapor is condensed essentially as molten zinc if the proper conditions be maintained. If the vapor be quickly led into a large, air-tight vessel of sheet iron and quickly cooled, the zinc is condensed directly to a solid finely divided form which is called blue powder. Instead of being condensed in a manner analogous to rain, as it is in the condenser of the spelter furnace, it comes down in a fashion analogous to that of snow. This is a commercial process for the manufacture of zinc dust, which finds a limited use in the arts as a chemical reagent and for some other purposes.

By limiting the presence of carbon dioxide, combustion of the zinc may be avoided, but the oxidation that results in blue powder can not be avoided. Even so, although it is possible to establish the condition of very low carbon dioxide in the gas issuing from the retort during the period of active distillation, it is seldom possible to attain the minimum theoretically required; and there is always also a certain production of blue powder by physical conditions, especially sudden chilling of the zinc vapor, which causes the metal to drop down in solid form instead of liquid, with the analogy of the condensation of aqueous vapor as snow or hail instead of rain.

On looking into the condenser in place in the furnace in operation, one may see the zinc vapor emerging from the retort as a fog, assuming

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[3] This résumé has been based upon reference No. 19, D. M. Lydell, Handbook of Nonferrous Metallurgy, vol. 2.

a swirling motion and wreathing spirally around the interior surface of the condenser. On cooling by contact with that surface, the droplets run down the sides and fall from the top and collect in the pool in the bottom. If superficial oxidation occurs they fail to coalesce, but this may be brought about to a certain extent by pressure, or, much better, by a rubbing that removes the superficial coating of zinc oxide. The zinc vapor that escapes from the condenser into the "prolong" is precipitated in the latter as powder, as a consequence of the sudden chilling therein, although the powder is but relatively little oxidized. For this reason, the blue powder from the prolong is much higher in zinc than the blue powder from the condenser, and when it is collected as a marketable product the prolong dust rather than the condenser dust is always sought.

Spelter may be refined by redistillation, which may be done either in clay retorts or in an electric furnace. During the war, when refined spelter commanded a very large premium, there was a good deal of refining by redistillation in clay retorts, but under ordinary commercial conditions that is an unprofitable operation. Until recently, the only refining by redistillation normally done was that which is carried out in Scandinavia by means of the electric furnace, which is logically the last step of the Cornelius process of electrothermic smelting.

The best theoretical exemplification of zinc-lead smelting is to be found in work with the electric furnace. This is not a branch of electrometallurgy, but is of pyrometallurgy pure and simple. Electric energy plays no other part than supplying heat. Such generation of heat has the theoretical advantage of ability to develop it inside of the retort rather than outside, and at first sight this is an attractive possibility promising the use of larger and more durable retorts and the best possible utilization of the thermal energy.

The Wetherill process consists essentially in reducing a mixture of oxidized ore and coal in a shallow bed resting upon an iron grate with small apertures, the air for combustion being introduced under pressure beneath the grate. A thin layer of coal is first spread upon the grate and when that has become ignited the mixture of ore and coal to a depth of about 8 inches is thrown upon it. A furnace is charged and worked off and the residues are withdrawn in about 8 hours. Therefore, a normal rate of working is 3 charges per 24 hours.

Another interesting and useful process of zinc burning consists of the use of the reverberatory smelting furnace, which was first developed on a large scale at Florence, Colo. The furnace is of the standard form for smelting copper ore arranged for side charging. Matte and slag are drawn off just as in copper smelting. The ore, mixed with reducing coal, slides down upon the bath of slag, giving up its zinc on the way, while the residual gangue is scorified and flows into the slag.

Another process of zinc burning is found in the extraction of zinc from old brass scrap, this being practiced at Carteret, N. J. The scrap is melted in a cupola furnace, the zinc volatilizing and burning and the fumes escaping through the flue. A large part of this is recovered by cyclone collectors, through which it is made to pass, and the remainder from a bag house, which in this instance is operated mechanically.

The smelting of zinc, the production of liquid zinc and of blue powder and the thermodynamic properties of zinc are discussed fully in a recent publication of the Bureau of Mines (1).

Metallurgy of zinc: General methods

Text reference	Year	Name and title
1	1930	Maier, C. G., Bulletin 324, Zinc smelting from a chemical and thermodynamic viewpoint, Bureau of Mines.
2	1930	Manny, W. R., Adam W., Development of electric zinc melting process, Met. Ind., **28**, pp. 118–120.
3	1930	——, ——, New furnace enables producer of slab zinc to improve product, Am. Metal Metal Market, **37**, Feb. 12, No. 30, p. 5.
4	1929	Greenwood, G. N., Roenfeldt, A. J., Corrosion of rabbles in zinc roasting furnace, Eng. & Mining J., **128**, pp. 851–852.
5	1929	Feiser, Ueber die fluechtigkeit der oxyde von blei, cadmium, zink und zinn, Metall u. Erz, **26**, pp. 269–284.
6	1929	Hanley, H. R., Clayton, C. Y., Walsh, D., Formation of insoluble zinc compounds during roasting, Tech. Pub. 220, Am. Inst. Mining Met. Eng.
7	1929	Morse, P. S., High zinc slags in Australia, Tech. Pub. 222, Am. Inst. Mining Met. Eng.
8	1928	Berthonneau, J., A new process for the manufacture of zinc oxide, Rev. Gen. Caoutchouc No. 38, pp. 7–8; Chem. Abst. **22**, p. 2034.
9	1928	Coley, H. E., Process for the extraction of zinc and other metals from ores, Am. Zinc Inst. Bull.; 11, Mar.–Apr. pp. 30–39, 60; Metal Ind. (London), **32**, pp. 225–227.
10	1928	Fraser, E. H., Drying and roasting of zinc concentrate, Am. Zinc Inst. Bull. 11, Mar.–Apr., pp. 21–23, 60.
11	1928	Hoffmann, R., Waelz process, Tech. Pub. 69, Am Inst. Mining Met. Eng.
12	1928	Millar, R. W., Condenser materials and blue powder in zinc smelting, Mining Met., **9**, p. 395.
13	1928	Roitzheim, A., The physics of charging zinc furnaces, Metallbörse, **18**, pp. 1993–1994, 2049–2050; Chem. Abst., **23**, 1929, p. 2680.
14	1927	Forster, J. A. B., Some possible developments in zinc metallurgy, Chem. Eng. Mining Rev., **19**, pp. 315–320; Chem. Abst., **21**, p. 3034.
15	1927	Frick, A., Ueber die reaktionen zwischen cupro-sulfid und metallischem blei, zinn und insbesondere zink in den schmelztemperaturen, Metall Erz, **24**, pp. 465–472.
16	1927	Holtmann, W., Der zinkdestillationsprozess (published by W. Knapp) Halle: J. Inst. Metals, **39**, 1928, p. 697.
17	1927	Wheeler, E. S., Kuechler, H., The properties of refractories in the metallurgy of zinc. I. Raw materials and body mixtures now in use, J. Am. Ceram. Soc., **10**, pp. 109–131; J. Inst. Metals, **38**, p. 664.
18	1926	Ingalls, W. R., Metallurgy of zinc, Mineral Ind., **35**, pp. 727–734; Chem. Abst., **21**, 1927, p. 3586.
19	1926	Liddell, D. M., Handbook of nonferrous metallurgy, Vol. II, McGraw-Hill Book Co.
20	1926	Maier, C. G., Ralston, O. C., Reduction equilibria of zinc oxide and carbon monoxide, J. Am. Chem. Soc., **48**, pp. 364–374; J. Inst. Metals, **38**, p. 680.
21	1926	Raby, M., Zinc metallurgy in Tonkin (China), Bull. Am. Zinc Inst., **9**, IV, pp. 13–21; J. Inst. Metals, **37**, 1927, p. 751.
22	1926	Siedenthal, C. E., Metallurgical recovery of zinc, Bull. Am. Zinc Inst., **9**, (5–6), pp. 60–62; Chem. Abst., **20**, p. 2808; Metal Ind. (London), **29**, pp. 173–175, 194–195; J. Inst. Metals, **37**, 1927, pp. 670, 751.
23	1925	Jannecke, E., Ueber die theoretischen grundlagen der hüttenmännischen zinkgewinnung, Metal Erz, **22**, pp. 316–321.
24	1924	O'Harra, B. M., Oxidization of zinc vapor by CO_2, Bur. Mines Tech. Paper 336; J. Inst. Metals, **33**, p. 317.
25	1925	Redpath, T., White smoke (zinc loss), Metal Ind. (London), **27**, p. 183.
26	1925	Rigg, G., Possible improvements in zinc metallurgy, Chem. Engng. & Mining Rev., **18**, p. 103.
27	1925	Stock, K., Redistillation of zinc, Amer. Inst. Mining & Met. Eng., **71**, pp.897–918.
28	1924	Meissner, K. L., Advances in the metallurgy of the important metals during and since the war, Z. Angew. Chem., **37**, pp. 1–4; J. Inst. Met., **33**, 1925, p. 478.
29	1920	Lemarchands, M., Reactions of the metallurgy of zinc, Rev. Metal, **17**, pp 803–841; J. Inst. Metals, **25**, 1921, p. 422.
30	1919	Fulton, C. H., Condensation of zinc from the vapor, Am. Inst. Mining & Met. Eng., **60**, pp. 280–302.
31	1918	Fulton, C. H., The condensation of zinc from its vapor, Bull. Am. Inst. Mining & Met. Engrs., pp. 1375–1394; Chem. Abst., **12**, p. 1868.
32	1917	Johnson, E. M., Zinc furnace temperatures, Met. & Chem. Eng., **17**, pp. 300–302.
33	1916	Ingalls, W. R., Metallurgy of zinc, Mineral Ind., **25**, pp. 772–780.
34	1916	Johnson, W. M., Lungwitz zinc-smelting process, Met. & Chem. Eng., **14**, pp. 105–106.
35	1914	Lyon, D. A., Keming, R. M., Smelting of metals in the electric furnace, Bur. Mines Bull. 77, pp. 91–101.
36	1914	Lyon, D. A., Arentz, S. A., Losses of zinc in mining, milling and smelting, Am. Inst. Mining & Met. Engs. Bull. 91, pp. 1411–1423.
37	1913	Clerc, F. L., Condensation of zinc gas to liquid in the presence of inert gases, Met. Chem. Eng., **11**, pp. 637–640.
38	1913	Clerc, F. L., Igneous concentration of zinc ores, Eng. & Mining J., **95**, pp. 222–226.
39	1913	Clerc, F. L., Smelting zinc in an electric furnace, Met. & Chem. Eng., **11**, pp. 428–429.
40	1913	Ingalls, W. R., Metallurgy of zinc, Eng. & Mining J., **95**, pp. 105–107.
41	1913	Mixter, W. G., The heats of formation of the oxides and sulfides of iron, zinc, and cadmium, Z. Anorg, Chem., **83**, pp. 97–112.

(2) HYDROMETALLURGY (Electrowinning).—While most of the zinc is still produced by the retort process, an increasing proportion (over 20 per cent) is now being obtained electrolytically. In this process (5, 54), often called "electrowinning," the ores are extracted with a suitable solvent, and the resultant solution of zinc salts is purified and electrolyzed with insoluble anodes. The metal deposited on the cathode is usually of very high purity.

Sulphuric acid is the principal solvent used for extracting zinc ores. The latter are usually sulphide ores, which have been roasted to convert the zinc sulphide to a mixture of oxide and sulphate. The sulphur dioxide formed in the roasting may be recovered and used for the manufacture of sulphuric acid, though in localities remote from industrial centers it is still wasted.

The roasted ore is sometimes passed through magnetic separators to remove iron oxide and zinc ferrite. The latter compounds, which are difficultly soluble, are first treated with the strongly acid electrolyte from the cells, after which the nonmagnetic portion of the calcine is added to the acid solution. Before filtering, the solution is sometimes treated with manganese dioxide to oxidize the ferrous salts (5). It is then neutralized by agitation with a slight excess of the oxidized zinc ore or with limestone. This precipitates ferric hydroxide which is filtered out, together with the other insoluble residues. These contain the gangue, lead, gold, and silver.

The resultant solution is treated with zinc dust, which precipitates copper, cadmium, cobalt, and nickel. This is the principal commercial source of cadmium. The cobalt and nickel must be very completely removed from the solution because even small traces greatly reduce the cathode efficiency in the zinc deposition. It has recently been shown (6) that very small traces of hitherto unsuspected impurities, such as germanium in amounts of 1 mg/L, may have a marked effect in lowering the general efficiency of the process, expecially the "high-acid high-density" process.

It may or may not be necessary to add sulphuric acid to the purified solution of zinc sulphate before electrolysis, according to the current density to be used. It is possible to deposit zinc with a high cathode efficiency from a strongly acid solution by using a relatively high current density. This deposition is rendered possible by the high overvoltage of hydrogen on zinc.

In the electrolytic cells, lead anodes in sheet or grid form and aluminum cathodes as thin plates are used. Cathode current densities range from 2 to 11 amp/dm^2 (20 to 100 amp/sq. ft.) according to the acidity maintained in the process. The solution is circulated through the cells and is cooled when necessary. Electrolysis is continued until the major portion of the zinc has been deposited and the sulphuric acid has been regenerated. If manganese is present, this is converted to manganese dioxide at the anodes and recovered. The depleted solution is finally used to leach more roasted ore and the cycle is repeated.

The deposit is periodically stripped from the aluminum cathodes and melted into slabs for market. The purity is high, being always above 99.9 per cent and in some processes above 99.99 per cent.

Hydrometallurgy (*Electrowinning*)

Text reference	Year	Name and title
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2	1930	Elfred, F. S., A new electrolytic zinc, Metal Ind. (London), **37**, pp. 325–326.
3	1930	Hanley, H. R., Clayton, C. Y., Walsh, D. F., Investigation of anodes for production of electrolytic zinc, Tech. Pub. 321, Am. Inst. Mining Met. Eng.
4	1930	Sanson, A., L'etat actuel de la metallurgie electrolytique du zinc d'apres des recentes publications. Rev. Metal, **27**, p. 125.
5	1930	Tainton, U. S., Bosqui, D., The electrolytic zinc plant of the Evans-Wallower Zinc Co. at East St. Louis, Ill., Trans. Am. Electrochem. Soc., **57**, pp. 241–250.
6	1930	Tainton, U. S., Clayton, E. T., Germanium in relation to electrolytic zinc production. Trans. Am. Electrochem. Soc., **57**, pp. 279–286; Metal. Ind (London) **37**, p. 229.
7	1929	Henault, O. D., The thermal and electrothermal reduction of zinc oxide, Trans. Am. Electrochem. Soc.
8	1929	Tainton, U. S., Taylor, A. G., Ehrlinger, H. P., Lead alloys for anodes in electrolytic production of zinc of high purity, Tech. Pub. 221, Am. Inst. Mining Met. Eng.
9	1929	Zentner, A., World developments in electrolytic zinc, Mining & Met., **10**, pp. 526–531.
10	1928	Deutsch, W. H. B., Electrical precipitation of metal-containing dusts from industrial gases. Z. Metallkunde **20**, pp. 25–27; Chem. Abst., **22**, 1928, p. 1284.
11	1928	Fosdick, E. R., The electrolytic zinc plant of the Sullivan Mining Co., J. Am. Inst. Elec. Eng., **47**, pp. 808–811.
12	1928	Hanley, H. R., Review of conditions leading up to electrolytic practice, Metal. Ind. (London), **33**, pp. 135–136, 152; Chem. Abst. **22**, p. 4068.
13	1928	Marcus, A., The future significance of electrolysis in zinc production, Metall. Erz, **25**, pp. 133–134; Chem. Abst., **22**, p. 2515.
14	1928	Rontgen, P., Hogel, H., Fundamental principles of commercial zinc electrolysis, current requirements and composition of electrolyte, Metall. Erz, **25**, pp. 12, 291–298, 319–327; Chem. Abst., **23**, 1929, p. 566.
15	1928	Seto, H., Electrolytic zinc refining. II. The influence of foreign elements upon the hydrogen overvoltage, Hokko, **24**, pp. 122; Chem. Abst. **23**, 1929, p. 2107.
16	1928	Tainton, U. S., Sullivan electrolytic zinc plant, Eng. Mining J., **126**, pp. 856–860; Chem. Abst., **23**, 1929, p. 774.
17	1927	Harris, W. E., Electrolytic zinc, Ind. Chemist, **3**, pp. 27–31; Chem. Abst., **21**, p. 860.
18	1927	Ralston, O. C., Twenty-five years progress of electrolytic zinc, Trans. Am. Electrochem. Soc., **51**, pp. 129–133.
19	1927	Stanley, G. H., Preparation and some properties of pure electrolytic zinc, African J. Sci., **24**, pp. 173–177; Chem. Abst., **22**, 1928, p. 1282.
20	1927	Zentner, A. A., Electrolytic zinc plant practice: a review, Eng. Mining J., **24**, pp. 925–928; Chem. Abst., **22**, 1928, p. 358.
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Hydrometallurgy (*Electrowinning*)—Continued

Text reference	Year	Name and title
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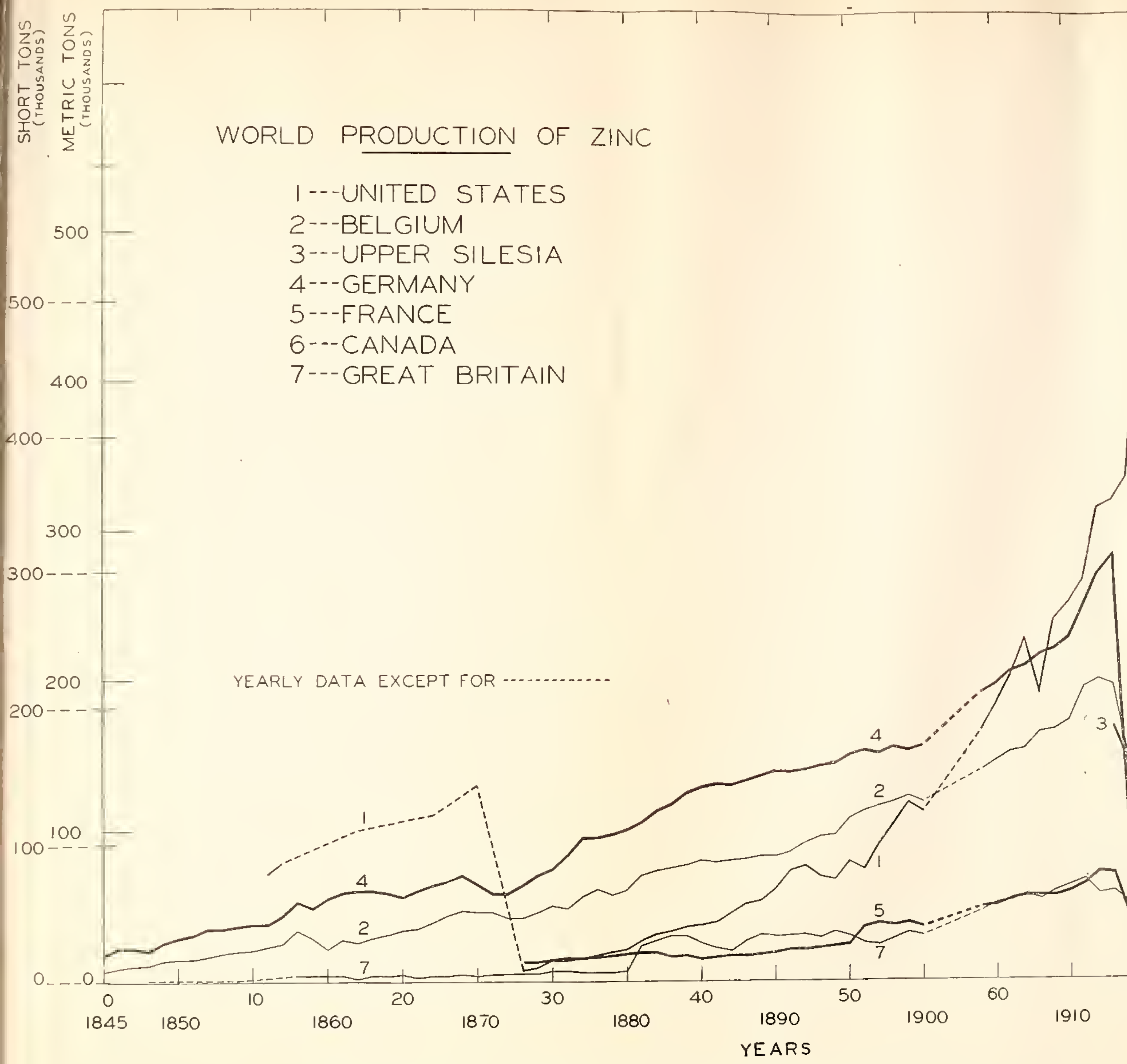

FIGURE 1.—*World production of zinc, 1845–1930*

Based on statistics from W. R. Ingalls, Production and Properties of Zinc; E. A. Smith, The Zinc Industry; Bureau of Foreign and Domestic Commerce Trade Information Bulletin No. 246; Mineral R
Survey and later by the Bureau of Mines; Yearbook of American Bureau of Metal Statistics 1927 and 1929; Commerce Yearbook, II, 1929.

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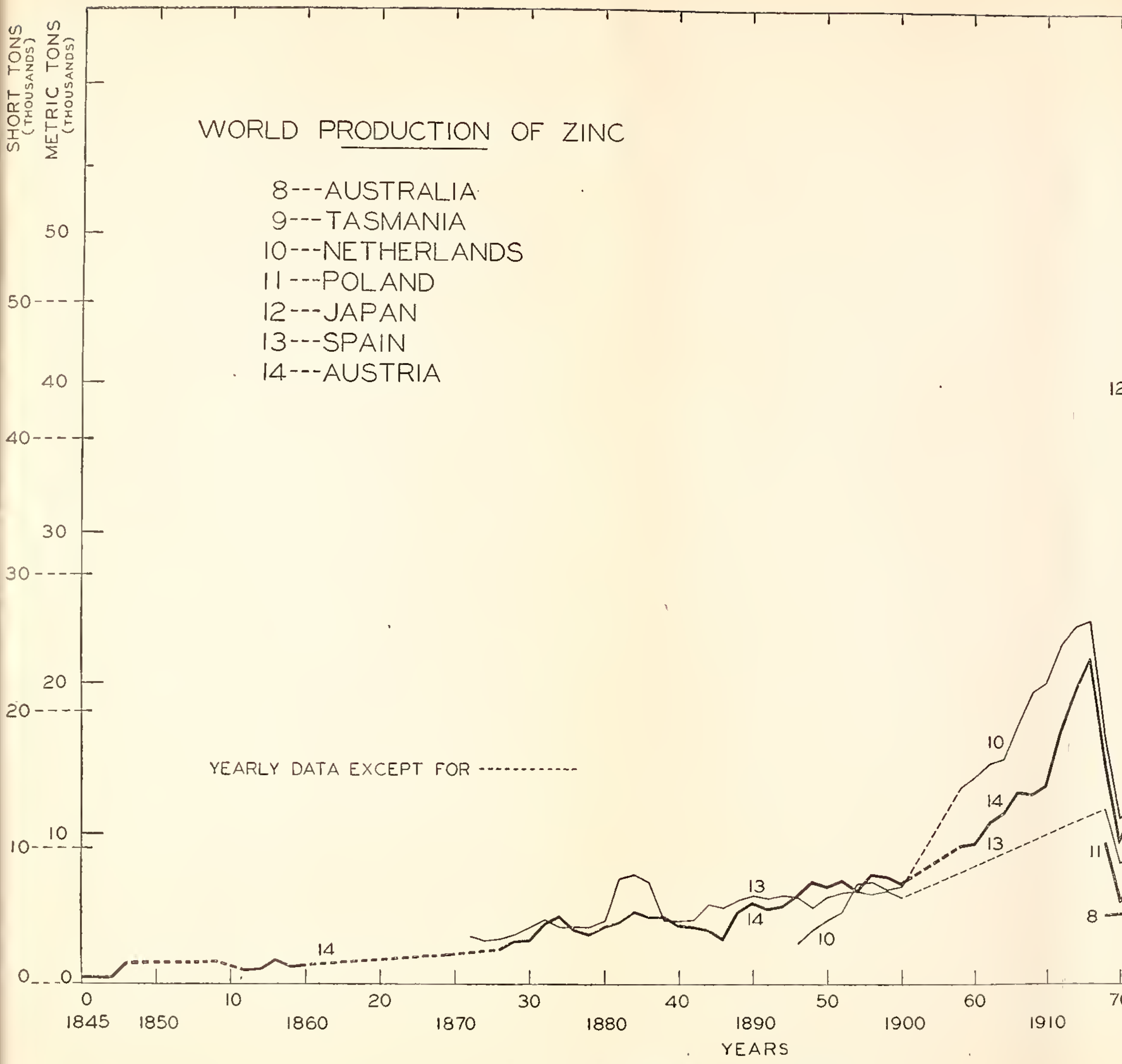

Figure 2.—*World production of zinc, 1845–1930* (continued)

(c) PRODUCTION, PRICES

(1) Primary sources.—In Figures 1 and 2 are given curves showing the world's production of zinc by countries. As these curves have been based on data from several different sources, they should be understood to represent tendencies and trends rather than exact values. Countries producing quantities less than 10,000 tons per year throughout the entire period for which figures are available have not been included.

The total mine production in short tons of recoverable zinc in the United States is given in Figure 3 based on data presented before the American Zinc Institute (1) and the percentage of this production for the various States is given in Figure 4. Similar diagrams in Figures 5 and 6 show the change in the relative importance of the sources of supply within the United States in the two decades, 1908 to 1928.

Figure 3.—*Mine production of zinc in the United States, 1908–1928*

The relative commercial importance of the various methods used in the production of zinc is indicated by Figure 7 which gives information on the production during the period 1920 to 1929.

Data on the world consumption of zinc are given in Figures 8 and 9.

In Tables 1 and 2 are given data on the imports of zinc ore and metallic zinc, and in Tables 3 and 4 similar data on exports of zinc in various forms. Information on the amount of zinc exported relative to the total production within the United States is given in Figure 10.

Table 5 shows statistics on rolled zinc in the United States and Table 6 gives the yearly average price of zinc since 1875.

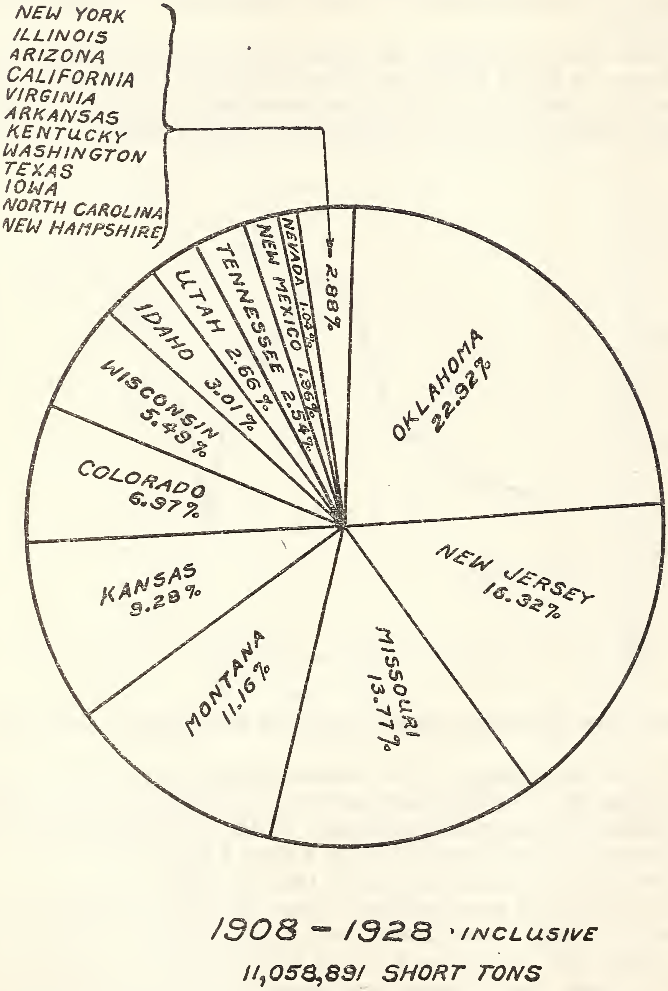

FIGURE 4.—*Mine production of zinc in the United States, by States, 1908–1928*

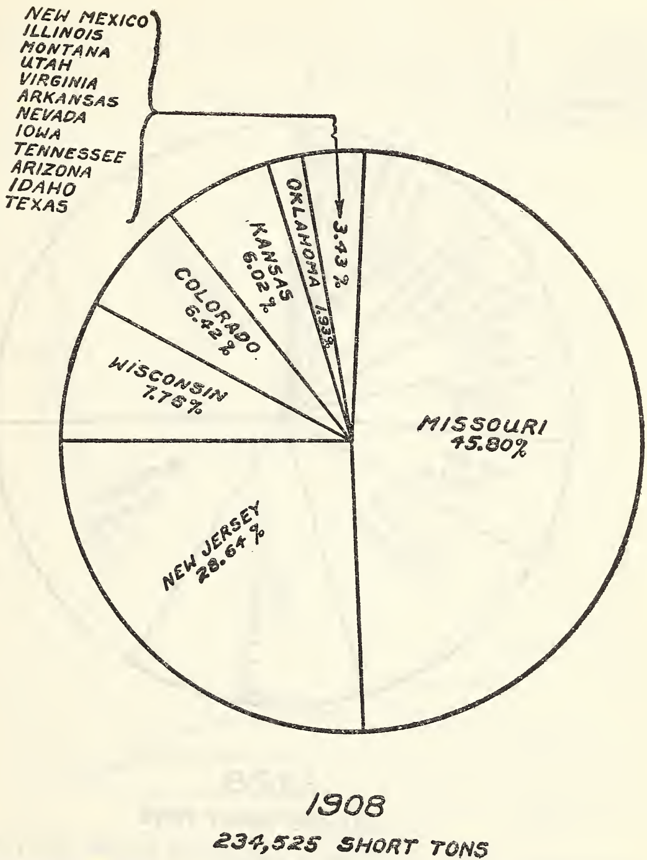

FIGURE 5.—*Mine production of zinc in the United States, by States, in 1908*

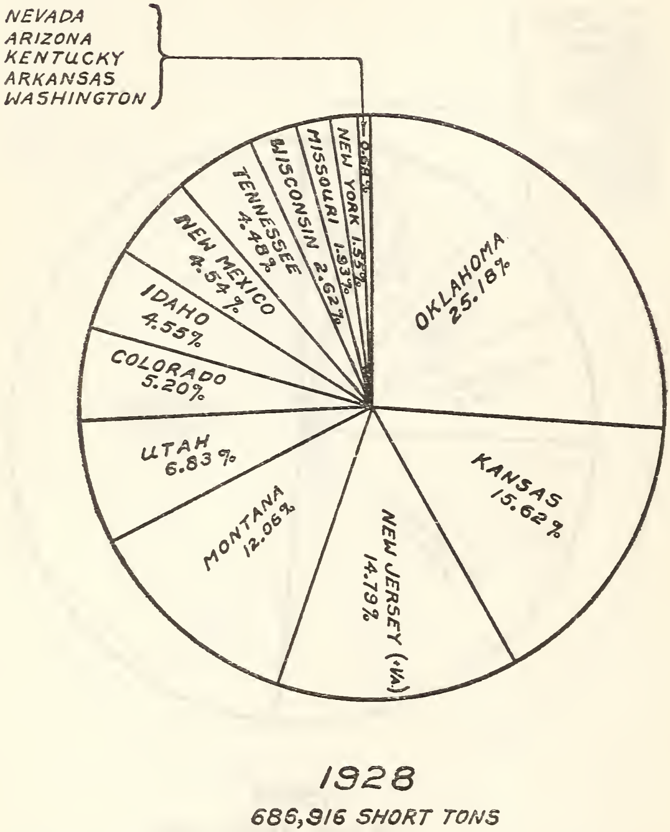

Figure 6.—*Mine production of zinc in the United States, by States, in 1928*

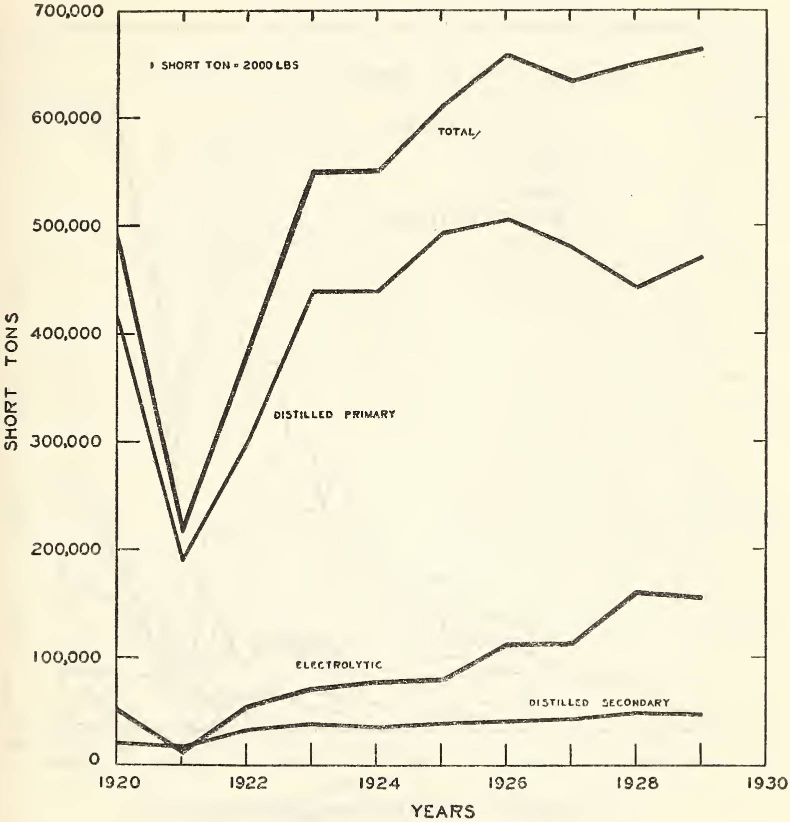

FIGURE 7.—*Amount of zinc produced in the United States, 1920 to 1929, by different methods*

(Based on data given by American Bureau of Metal Statistics, Yearbook, 1929.)

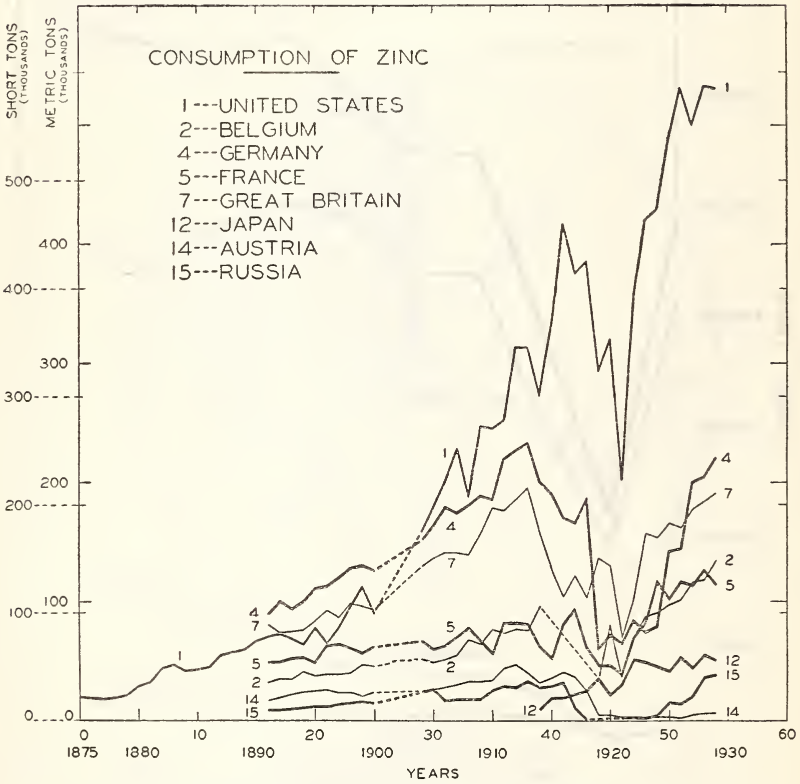

FIGURE 8.—*World consumption of zinc*

(Sources of information as in Fig. 1.)

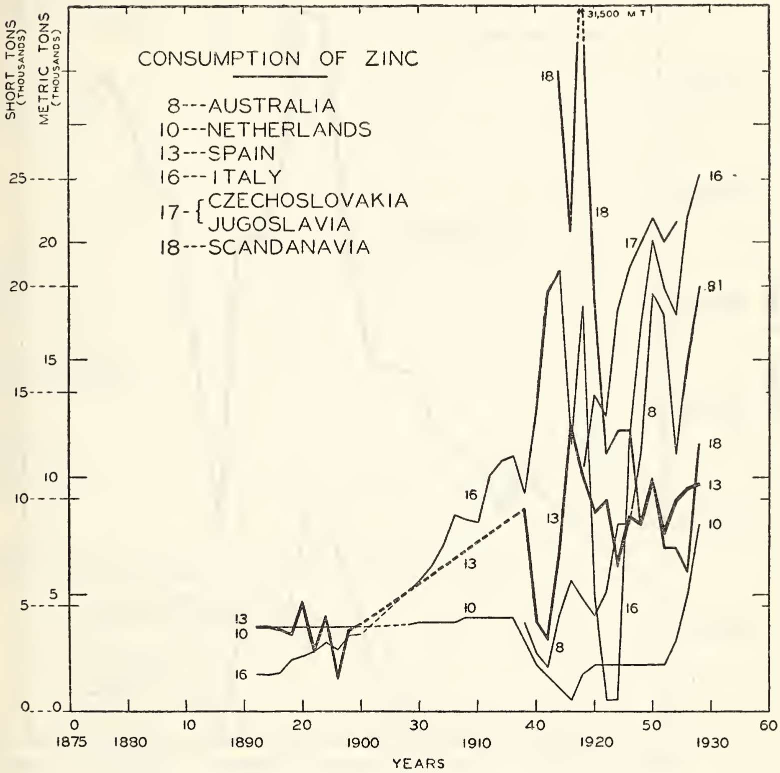

Figure 9.—*World consumption of zinc* (continued)

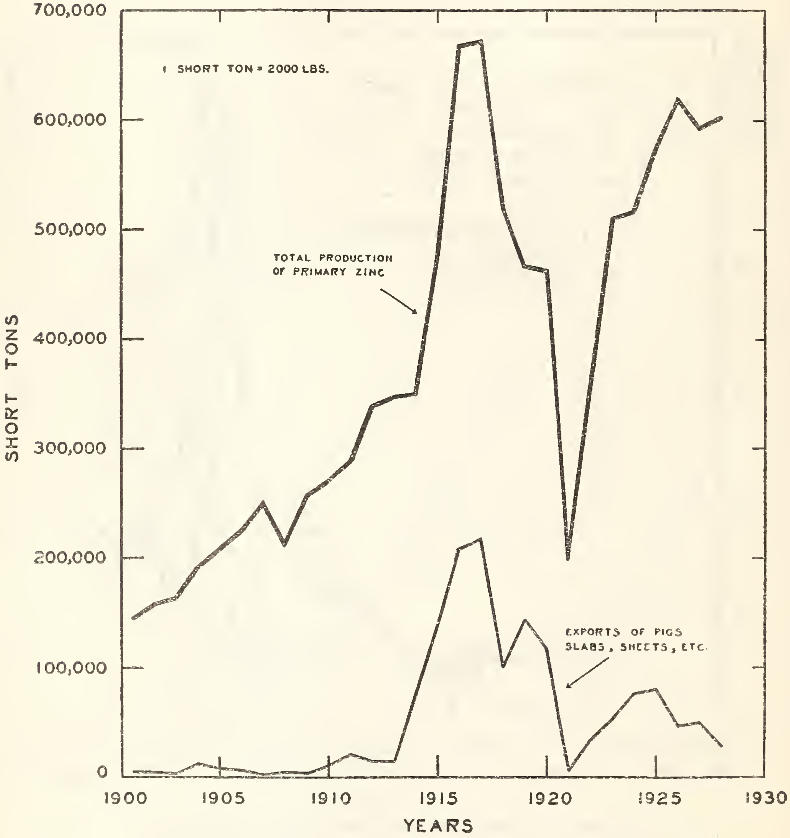

FIGURE 10.—*Exports of zinc as compared with the total production in the United States*

(Commerce Yearbook, 1929.)

TABLE 1.—*Imports of zinc ore (concentrates) into the United States, 1915–1929, by countries*

(In tons of 2,000 pounds)

Country	1915 [1]	1916 [1]	1917 [1]	1918 [1]	1919 [1]	1920 [1]	1921 [1]
Canada	4, 710	8, 790	5, 155	5, 173	3, 878	1, 794	554
Mexico	17, 804	51, 028	45, 697	18, 426	11, 225	14, 975	2, 147
France	---------	1, 422	---------	---------	---------	---------	---------
Spain	---------	23, 081	6, 083	---------	---------	---------	---------
Italy	2, 125	5, 783	2, 411	---------	---------	---------	---------
French Africa	---------	1, 857	623	---------	---------	1, 224	---------
French East Indies	---------	746	---------	---------	---------	---------	---------
China and Hong Kong	2, 738	4, 568	---------	---------	---------	---------	---------
Japan	499	---------	---------	---------	---------	---------	---------
Australia	29, 724	49, 657	12, 503	---------	---------	3, 852	---------
New Zealand	---------	944	---------	---------	---------	---------	---------
Chile	---------	---------	---------	1, 149	1, 902	632	---------
Other countries	69	271	2	61	4	---------	4
Total	57, 669	148, 147	72, 474	24, 809	17, 009	22, 487	2, 705

Country	1922 [1]	1923 [1]	1924 [1]	1925 [1]	1926 [1]	1927 [2]	1928 [2]	1929 [2]
Canada	235	204	97	3, 894	2, 340	--------	--------	--------
Mexico	1, 665	3, 201	4, 649	9, 607	12, 265	--------	--------	--------
France	--------	--------	--------	--------	--------	--------	--------	--------
Spain	--------	--------	--------	--------	--------	--------	--------	--------
Italy	--------	--------	--------	--------	--------	--------	--------	--------
French Africa	--------	--------	--------	--------	--------	--------	--------	--------
French East Indies	--------	--------	--------	--------	--------	--------	--------	--------
China and Hong Kong	--------	--------	--------	--------	--------	--------	--------	--------
Japan	--------	--------	--------	--------	--------	--------	--------	--------
Australia	--------	--------	--------	--------	--------	--------	--------	--------
New Zealand	--------	--------	--------	--------	--------	--------	--------	--------
Chile	--------	--------	--------	--------	3	--------	--------	--------
Other countries	30	21	--------	35	18	--------	--------	--------
Total	1, 930	3, 426	4, 746	13, 536	14, 626	154	344	2, 631

[1] As reported by the Bureau of Foreign and Domestic Commerce.
[2] Bureau of Mines, Mineral Resources of the United States, 1928 and 1929.

TABLE 2.—*Zinc imported for consumption in the United States*

Year	Blocks or pigs		Sheets		Old		Zinc dust		Manufactures	Total value
	Short tons	Value	Short tons	Value	Short tons	Value	Short tons	Value		
1912	10, 719	---------	728	---------	147	---------	2, 736	---------	---------	---------
1913	5, 165	---------	223	---------	275	---------	2, 368	---------	---------	---------
1914	195	---------	277	---------	388	---------	2, 004	---------	---------	---------
1915	63	---------	95	---------	729	---------	707	---------	---------	---------
1916	21	---------	2	---------	642	---------	522	---------	---------	---------
1917	18	$2, 279	73	$16, 570	259	$25, 974	233	$48, 604	$250	$93, 677
1918	11	2, 897	(1)	29	24	2, 056	16	3, 522	331	8, 865
1919	32	2 284	1	249	37	2, 216	52	5, 753	1, 258	11, 760
1920	(1)	17	4	614	14	1, 065	17	6, 207	1, 746	9, 649
1921	6, 598	559, 870	6, 688	496, 445	6	341	42	1, 121	8, 290	1, 066, 067
1922	40	3, 327	416	59, 037	46	2, 403	79	5, 614	9, 517	79, 898
1923	1	375	(1)	41	20	1, 624	4	891	16, 331	19, 262
1924	11	1, 973	(1)	88	14	1, 493	59	9, 241	20, 089	32, 884
1925	(1)	303	(1)	55	24	2, 495	116	20, 936	18, 979	42, 768
1926	(1)	195	(1)	46	21	1, 315	2	451	44, 574	46, 581
1927	39	---------	1	271	19	1, 443	---------	114	91, 519	98, 436
1928	(1)	66	3	2, 556	3	260	146	14, 147	115, 784	132, 813
1929	226	21, 502	3	52	(1)	20	159	19, 543	128, 395	169, 512

[1] Less than 1 ton.

1913–1916 from Tech. Bull. 246, Tr. Inf. Bull., Bureau Foreign and Domestic Commerce.
1917–1926 from Min. Res. of U. S. 1926.
1912 and 1927, Bureau Foreign and Domestic Commerce in Yearbook of Am. Bureau of Metal Statistics, 1927.
1927–28 from Min. Res. U. S. 1928, Bureau of Mines.

TABLE 3.—*Exports of zinc from the United States, by classes*

(In tons of 2,000 pounds)

Year [1]	Domestic					Foreign			In manufactures exported with benefit of drawback
	Zinc ore	Zinc pigs, slabs, etc.	Zinc sheets, strips, etc.	Zinc dust	Zinc dross	Ores and calamine zinc content	Zinc pigs, slabs, etc.	Zinc dust	
1912	23,349	[2] 6,634	--------	--------	205	6,778	48	--------	1,219
1913	17,713	[2] 7,783	--------	--------	28	5,406	620	--------	7,459
1914	11,110	[2] 64,802	--------	--------	2,536	140	5,580	178	4,128
1915	832	[3] 106,220	[4] 12,383	--------	4,167	--------	12,775	216	32
1916	78	150,621	12,512	--------	48	--------	43,230	195	--------
1917	1,320	137,272	16,524	--------	13,302	--------	64,680	79	1,588
1918	62	66,368	13,875	--------	15,816	--------	20,069	40	6,337
1919	--------	109,746	19,761	--------	5,123	--------	12,256	109	4,533
1920	--------	74,046	11,852	--------	2,445	--------	28,131	--------	237
1921	--------	1,753	1,816	--------	510	--------	1,256	--------	130
1922	1,695	26,815	3,217	1,998	8,412	--------	3,471	--------	1,298
1923	(5)	42,131	3,732	3,679	14,745	--------	7,080	--------	--------
1924	(5)	[6] 72,583	3,657	2,270	10,845	--------	(6)	--------	--------
1925	68,951	[6] 76,340	4,196	2,242	15,968	--------	(6)	--------	--------
1926	95,249	[6] 42,920	4,641	1,091	10,461	--------	(6)	--------	--------
1927	46,716	[6] 45,706	3,922	1,357	4,451	--------	(6)	--------	--------
1928	4,518	35,270	4,325	1,008	3,148	--------	(6)	--------	--------
1929	71	14,411	5,265	1,255	3,490	--------	(6)	--------	--------

[1] 1912–1927 as reported by the Bureau of Foreign and Domestic Commerce. 1928–29, Bureau of Mines, Mineral Resources of the United States.

[2] Includes sheets.

[3] Includes sheets up to July 1, 1915.

[4] Figure covers period beginning July 1, 1915.

[5] Exports of zinc ore are included with "zinc dross" in 1923 and 1924.

[6] Beginning 1924 zinc in pigs, slabs, etc., produced in the United States from foreign ore was not reported separately. Domestic exports since that date also include small quantities of foreign slab zinc.

TABLE 4.—*Exports of zinc slabs and sheets from the United States, by countries* [1]

(In tons of 2,000 pounds)

Country	1923			1924			1925			
	Ore, concentrates, and dross	Slabs, blocks, etc.	Sheets, strips, etc.	Ore, concentrates, and dross	Slabs, blocks, etc.	Sheets, strips, etc.	Ore and concentrates	Dross	Slabs, blocks, etc.	Sheets, strips, etc.
Canada	2,622	327	908	98	547	1,007	42	49	695	1,535
Mexico	--------	193	480	--------	376	265	--------	22	491	270
Argentina	--------	55	89	28	381	280	--------	--------	1,653	134
Belgium	89	1,008	--------	917	2,647	--------	61,544	4,828	3,402	--------
France	--------	6,181	136	--------	10,835	59	3,976	57	10,292	85
Germany	33	1,730	--------	552	3,715	12	3,297	2,832	7,512	122
Great Britain	10,884	37,587	709	8,628	44,541	858	84	7,585	35,548	1,244
Italy	--------	1,283	113	382	5,589	--------	--------	129	9,046	7
Netherlands	--------	90	--------	166	1,412	--------	--------	419	3,913	--------
Russia	--------	168	--------	--------	112	--------	--------	--------	112	--------
Japan	1,079	1	131	--------	1,223	186	--------	2	420	92
China	--------	6	73	--------	--------	23	--------	--------	1	22
British India	--------	--------	6	--------	454	8	--------	--------	1,464	8
Other countries	38	582	1,087	74	751	959	8	45	1,801	677
Total	14,745	49,211	3,732	10,845	72,583	3,657	68,951	15,968	76,350	4,196

[1] Yearbook, American Bureau of Metal Statistics, seventh annual edition, 1926, and tenth annual edition, 1929, 115 Broadway, New York, N. Y.

Table 4.—*Exports of zinc slabs and sheets from the United States, by countries* [1]—Continued

(In tons of 2,000 pounds)

Country	1926				1927			
	Ore and concentrates	Dross	Slabs, blocks, etc.	Sheets, strips, etc.	Ore and concentrates	Dross	Slabs, blocks, etc.	Sheets, strips, etc.
Canada	85	25	508	1,430	118	64	634	1,616
Mexico	--------	--------	73	204	--------	--------	394	68
Argentina	--------	--------	1,468	198	--------	--------	4,173	132
Belgium	63,169	1,405	1,207	--------	28,525	1,535	813	--------
France	9,920	--------	4,575	74	14,128	51	3,190	--------
Germany	18,326	1,801	3,639	--------	1,215	909	1,939	110
Great Britain	52	6,314	15,912	1,798	--------	1,157	20,462	1,230
Italy	2,531	312	1,921	7	--------	182	2,257	--------
Netherlands	--------	414	896	--------	1,207	466	555	10
Russia	--------	--------	678	--------	--------	--------	890	--------
Japan	--------	--------	9,699	147	1,523	30	8,724	130
China	--------	--------	--------	--------	--------	--------	2	24
British India	--------	--------	829	--------	--------	--------	56	9
Other countries	1,166	40	1,430	783	--------	49	1,550	593
Total	95,249	10,311	[2] 42,835	4,641	46,716	4,443	[2] 45,639	3,922

Country	1928				1929			
	Ore and concentrates	Dross	Slabs, blocks, etc.	Sheets, strips, etc.	Ore and concentrates	Dross	Slabs, blocks, etc.	Sheets, strips, etc.
Canada	--------	32	--------	1,877	61	20	974	2,124
Mexico	--------	--------	--------	53	--------	--------	22	149
Argentina	--------	--------	--------	212	--------	--------	3	193
Belgium	532	674	--------	--------	--------	959	420	--------
France	1,892	151	--------	7	--------	56	2,299	13
Germany	1,644	478	--------	6	8	462	1,894	35
Great Britain	13	958	--------	1,385	--------	562	4,716	1,592
Italy	--------	--------	--------	1	--------	--------	56	1
Netherlands	--------	8	--------	32	--------	36	554	58
Russia	--------	--------	--------	--------	--------	--------	8	2
Japan	130	843	--------	219	--------	1,357	587	270
China	--------	--------	--------	38	--------	1	--------	63
British India	--------	--------	--------	5	--------	36	1,681	340
Other countries	307	4	--------	490	2	1	1,130	425
Total	4,518	3,148	[3] 35,270	4,325	71	3,490	14,344	5,265

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[2] Does not include exports of foreign slab zinc amounting to 102 tons in 1926 and 28 tons in 1927.

[3] American Zinc Institute.

TABLE 5.—*Statistics of rolled zinc, United States*

(In tons of 2,000 pounds)

Year [1]	Production				Exports of rolled zinc	Available for domestic consumption
	Zinc sheets	Boiler plates and special sheets	Zinc strips	Total rolled zinc		
1917	37, 865	3, 450	18, 127	59, 442	16, 514	42, 928
1918	29, 873	7, 112	22, 902	68, 887	13, 875	56, 012
1919	28, 257	2, 542	23, 498	54, 297	19, 762	34, 535
1920	28, 406	1, 975	22, 852	53, 233	11, 852	41, 381
1921	14, 290	1, 273	14, 837	30, 400	1, 816	[2] 35, 272
1922	25, 102	1, 115	27, 293	53, 509	3, 215	[2] 50, 708
1923	24, 590	1, 147	30, 096	55, 833	3, 732	52, 101
1924	29, 517	991	30, 525	61, 032	3, 658	57, 375
1925	30, 085	1, 101	39, 946	71, 132	4, 196	66, 936
1926	29, 933	1, 235	55, 166	86, 334	4, 641	81, 693
1927	24, 686	2, 090	47, 354	74, 130	3, 922	70, 208
1928	26, 041	1, 917	45, 573	73, 531	4, 325	69, 209
1929	24, 358	1, 131	42, 845	68, 334	5, 265	63, 069

[1] 1917–1927 inclusive, from data collected by U. S. Geological Survey or Bureau of Mines, 1928 and 1929 from American Bureau of Metal Statistics.

[2] In figuring deliveries for consumption in 1921 and 1922 imports for consumption amounting to 6,688 tons and 415 tons, respectively, have been taken into consideration.

TABLE 6.—*Yearly average price of zinc (New York)*

(Cents per pound)

Year [1]	Price	Year	Price	Year	Price
1875	7. 00	1895	3. 63	1915	13. 23
1876	7. 25	1896	3. 94	1916	12. 80
1877	6. 03	1897	4. 12	1917	8. 90
1878	4. 88	1898	4. 57	1918	8. 16
1879	5. 036	1899	5. 75	1919	7. 34
1880	5. 51	1900	4. 39	1920	8. 1
1881	5. 243	1901	4. 07	1921	5. 0
1882	5. 325	1902	4. 84	1922	5. 7
1883	4. 495	1903	5. 40	1923	6. 8
1884	4. 443	1904	5. 10	1924	6. 344
1885	4. 345	1905	5. 88	1925	7. 622
1886	4. 40	1906	6. 20	1926	7. 337
1887	4. 625	1907	5. 96	1927	6. 242
1888	4. 91	1908	4. 73	1928	6. 1
1889	5. 023	1909	5. 50	1929	6. 6
1890	5. 55	1910	5. 52		
1891	5. 02	1911	5. 76		
1892	4. 63	1912	6. 94		
1893	4. 075	1913	5. 65		
1894	3. 52	1914	5. 12		

[1] 1875–1900 from Ingall's "Production and Properties of Zinc."

1901–1919 from "Yearly Average Prices of Principal Metals, 1895–1923; Eng. Min. J. Press, **17,** 1924, p. 140
1920–1923 from Min. Res. U. S. 1923 (I), p. 98.
1924–1926 World Zinc Production Breaks All Records, E. N.Hickman. Eng. & Min. J., **123,** 1927, pp. 80–81.
1927 from Yearbook Am. Bureau of Metal Statistics, 1927.
1928 from Min. Res. U. S., 1928, Bureau of Mines.
1929 from Min. Res. U. S., 1929, Bureau of Mines.

TABLE 7.—*By-products from galvanizing* [1]

(In tons of 2,000 pounds)

Year	Zinc used	Dross	Skimmings	Ashes	Year	Zinc used	Dross	Skimmings	Ashes
1924	240, 000	40, 000	19, 000	12, 000	1927	275, 000	44, 000	29, 000	9, 000
1925	283, 000	47, 000	27, 000	10, 000	1928	286, 000	45, 000	30, 000	9, 000
1926	288, 000	46, 000	28, 000	10, 000	1929	285, 500	45, 000	31, 000	9, 000

[1] From Yearbook, American Bureau of Metal Statistics, 1929.

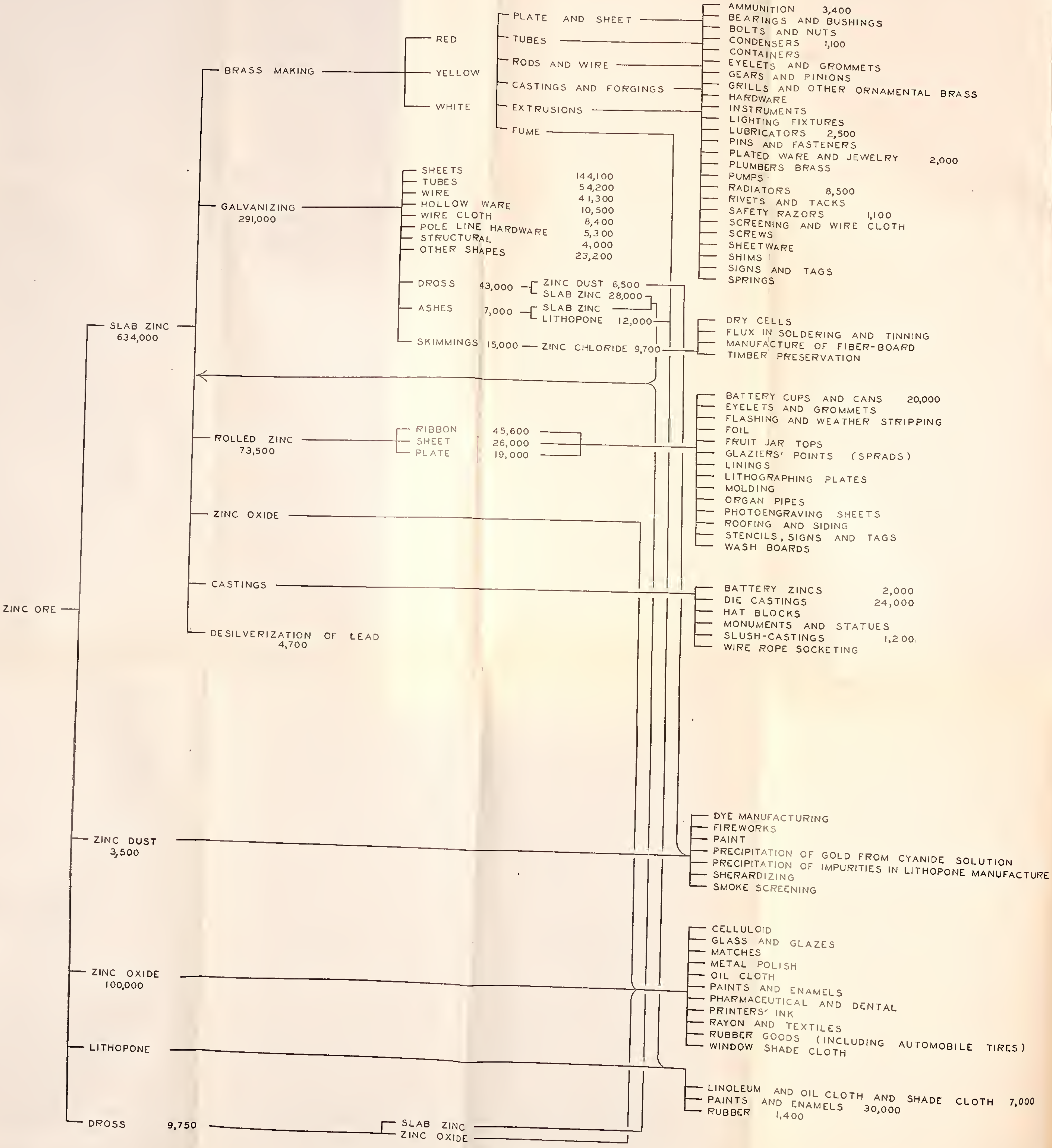

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FIGURE 11.—*Uses of zinc*

The numbers express the amount of zinc used, in tons, in 1928 according to American Bureau of Metal Statistics.

(2) Secondary Zinc.—Secondary zinc may be recovered from zinc scrap and dust and from galvanizing wastes. These galvanizing wastes consist of skimmings, zinc dross (iron-zinc alloy), ashes, zinc-lead alloy and zinc oxide. (See fig. 11.) Statistics on galvanizing wastes are given in Table 7. The dross may be partially recovered as zinc dust or slab zinc, and the ashes as slab zinc and lithopone.

Ingalls (12) has estimated that the skimmings contain about 20 per cent zinc, 30 per cent ammonium and zinc chlorides, 35 per cent zinc oxide, and 15 per cent iron scale and dirt. Zinc skimmings are usually sold to refiners who mix the skimmings with ore, reduce the mixture and obtain pure zinc by distillation. About 11 per cent of the zinc used in galvanizing is converted to sal-ammoniac skimmings, which are leached with hot water and steam, whereby the chlorides are dissolved. The remaining residues of zinc and zinc oxide are dried and ground in a mill to remove the oxides, the zinc shot staying in the mill. This is sold as such or is melted and cast for galvanizing purposes (2, 3).

About 10 per cent of the total amount of zinc used in galvanizing is converted to dross. This is essentially an iron-zinc alloy containing 4 to 5 per cent iron. Zinc is recovered from the dross by melting it in a large iron pot at about 500° C., carbonaceous material being forced in below the surface. A little aluminum in the form of an aluminum-zinc alloy, containing approximately 5 per cent aluminum, is then added to break up the oxides. Zinc, usually containing 1 to 2 per cent lead and 0.12 to 0.25 per cent iron, is ladled off. It may be further purified by repeating the process or by distillation; a second treatment with carbonaceous material gives zinc of about 99.5 per cent purity (2).

The zinc-lead waste formed in galvanizing is melted in an iron pot at about 450° C., just above the melting point of zinc. Liquation occurs and a layer of zinc floats on the surface of the lead, where it can be skimmed off. At this temperature zinc retains only about 1 per cent lead in solution. The solubility of lead in zinc increases with the temperature. The lead that settles contains about 6 per cent zinc. Some zinc-iron alloy dross also collects on the lead. The lead "bottoms" produced in this process are used for the Parkes process for desilvering lead, or the lead is refined by burning off the zinc (2, 3).

The zinc content of galvanized iron scrap varies from 1 to 15 per cent according to the galvanizing process and character of the scrap. Electro-plated material has less zinc than corresponding hot-galvanized material. Galvanized scrap may be assumed to contain 8 per cent zinc on the average.

During the World War, numerous processes were developed for the recovery of zinc from the immense amount of scrap which accumulated. The processes developed by Paweck (10) may be mentioned as typical. These consisted in dissolving the scrap, such as dry-cell electrodes, etc., or the dust, which was formed when brass scrap was blown in a converter to separate the copper and the zinc, and recovering the zinc from the solution by chemical and electrolytic methods.

Statistics on the amount of secondary zinc recovered in the United States are given in Table 8.

TABLE 8.—*Statistics of secondary zinc in the United States*[1]

(In tons of 2,000 pounds)

	1916	1917	1918	1919	1920	1921	1922
Zinc recovered by redistillation:							
By primary smelters	16,196	8,519	7,931	10,767	[2] 16,395	[2] 13,114	[2] 19,401
By secondary smelters	13,467	8,316	1,987	8,981	[2] 4,976	[2] 4,459	[2] 13,587
Total	29,663	16,835	9,918	19,748	21,371	17,573	32,988
Zinc recovered by sweating, remelting, etc	21,037	14,565	17,190	20,162	21,479	16,260	36,326
Total zinc recovered unalloyed	50,700	31,400	27,108	39,910	42,850	33,833	69,314
Zinc dust made from dross	(3)	(3)	(3)	(3)	1,179	839	3,783
Lithopone made from skimmings and ashes	51,291	64,260	62,403	53,000	57,849	19,306	29,928
Zinc content of lithopone made from skimmings and ashes	(3)	(3)	(3)	10,600	(3)	(3)	6,095
Zinc chloride made from skimmings, ashes, etc	15,000	15,000	24,000	26,250	(3)	44,535	37,885
Zinc content of zinc chloride made from skimmings, etc	(3)	(3)	(3)	6,500	(3)	9,798	8,334
Zinc content of sulphate made from zinc skimmings, ashes, etc	(3)	(3)	(3)	(3)	(3)	427	682

	1923	1924	1925	1926	1927	1928
Zinc recovered by redistillation:						
By primary smelters	[2] 20,768	[2] 18,507	[2] 17,982	[2] 20,100	[2] 21,032	[2] 14,627
By secondary smelters	[2] 18,666	[2] 16,979	[2] 21,199	[2] 20,699	[2] 21,752	[2] 34,039
Total	39,434	35,486	39,181	40,799	42,784	48,666
Zinc recovered by sweating, remelting, etc	25,776	23,400	22,249	23,771	22,016	22,034
Total zinc recovered unalloyed	65,210	58,886	61,430	64,570	64,800	70,700
Zinc dust made from dross	4,402	5,659	5,813	4,889	4,850	6,208
Lithopone made from skimmings and ashes	43,902	37,564	48,705	45,356	54,214	61,665
Zinc content of lithopone made from skimmings and ashes	8,723	7,492	9,741	9,204	10,873	12,186
Zinc chloride made from skimmings, ashes, etc	43,089	42,574	45,772	43,106	40,107	44,057
Zinc content of zinc chloride made from skimmings, etc	9,478	9,367	10,070	9,481	8,824	9,692
Zinc content of sulphate made from zinc skimmings, ashes, etc	1,241	858	858	603	720	771

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[1] American Bureau of Metal Statistics, 1929; data compiled by the U. S. Geological Survey through 1923; subsequently by U. S. Bureau of Mines.

[2] Distribution estimated by American Bureau of Metal Statistics.

[3] Not reported.

Production of zinc

Text reference	Year	Name and title
1	1930	Mine production of zinc in United States J. Am. Zinc Inst., **13**, Annual Meeting, June, 1930.
2	1930	Pehrson, E. W., Zinc in 1928. Mineral resources of the United States, 1928, I., U. S. Bur. Mines, 1930, pp. 363–421. (Previous annual numbers of this publication are not listed in this bibliography.)
3	1929	——, Summarized data of zinc production, Bur. Mines Econ. Paper 2; Chem. Abst., **23**, p. 4914.
4	1929	Production of slab zinc and rolled zinc in 1926, Bureau of Mines; Metal Ind. (London), **34**, p. 593.
5	1928	Jones, W. R. D., Spelter and nickel in South Wales, Metal Ind. (London), **32**, pp. 85–86.
6	1927	Field, S., The zinc industry, Metal Ind. (London), **30**, pp. 19–20, 29, J. Inst. Metals **38**, p. 561.
7	1927	Holtmann, Die entwicklungsmoeglichkeiten in der zink industrie, Metall Erz, **24**, pp. 25–29.
8	1927	Schneider, W. H., The electrolytic zinc industry of Tasmania, World Power, **7**, pp. 34–38; J. Inst. Metals **38**, p. 561.
9	1927	Sharpe, A. J. M., Review of the zinc markets, Eng. & Min. J., **123**, pp. 35, 547, 708.
10	1927	Sidney, L. P., The British zinc industry. Metal Ind. (London), **30**, pp. 479–80.
11	1927	——, Lead and zinc production in 1926, Min. Cong. J., **13**, p. 118; Iron Age, **119**, p. 259.
12	1926	Reimer, G., Die Oberschlesische zink industrie, Metall Erz, **23**, pp. 57–64.
13	1926	Boscheron, L., The zinc industry of the Liege district, J. Inst. Metals, **36**, pp. 21–26.
14	1925	Palmaer, W., The electrochemical industry in Sweden, Tek. Tids., Kemi, pp. 20–24; J. Inst. Metals, **33**, 1925, p. 462.

Production of zinc—Continued

Text reference	Year	Name and title
15	1924	Budgen, N. I., Zinc Industry in Belgium, Metal Ind. (London), **25,** pp. 31–34, 53–58.
16	1924	——, Fifty-fifth annual review and year book number, Eng. Mining J. Press, **117,** No. 3; Chem. Abst., **18,** p. 651.
17	1924	——, Market outlets of zinc, a diagram showing the many industries which now consume zinc and its derivatives, Eng. & Mining J., **117,** p.1071; Ind. & Eng. Chem., **16,** p. 710.
18	1924	——, World survey of the zinc industry. U. S. Bur. For. & Dom. Com. Trade Info. Bull. **246,** pp. 1–60.
19	1923	Redmayne, R., A review of the base metal industry, with special reference to the resources of the British empire. J. Roy. Soc. Arts, **71,** pp. 548–563; J. Inst. Met., **31,** p. 578; S. African Eng., **34,** pp. 97–99.
20	1922	Scott, A. L., The nonferrous metal industry, aluminum, zinc, Brass World, **18,** pp. 121–124; Chem. Abst., **16,** p. 2297.
21	1921	Ingalls, W. R., Zinc—market and metallurgy, Eng. & Mining J., **111,** pp. 139–140; Chem. Abst.,**15,** p. 1004.
22	1921	Tuthill, S. S., Industrial development of zinc. Eng. Mining J., **111,** pp. 426–427; Chem. Abst., **15,** p. 1121.
23	1921	——, World's production of zinc 1911–1920; Min. & Sci., pp. 122, 886.
24	1920	Hendricks, W. H., The zinc industry. Brass World, **16,** pp. 128–129, 171–172; Chem. Abst. **14,** p. 2152.
25	1918	Kellaway, F., Some developments in industry during the war, Electrician, **81,** pp. 669–670; Chem. Abst., **13,** 1919, p. 248.
26	1918	Siebenthal, C. E., The production of rolled zinc in the United States. Metal Ind., **16,** p. 556; Chem. Abst., **13,** 1919, p. 218.
27	1918	Smith, E. A., The zinc industry, Longmans, Green & Co.
28	1916	Cook, W. A., Facts about zinc and the supply. Metal Work, **85,** pp. 821–822, 848–849.
29	1916	Smith, E. A., Development of the spelter industry. J. Inst. Metals, **16,** pp. 118–174.
30	1915	Ingalls, W. R., Nonferrous metals and the war, Iron Age, **96,** pp. 420–421.
31	1914	——, Spelter statistics for 1913. Eng. & Mining J., **97,** pp. 671–672.
32	1905	Scholl, G. P., The Silesian zinc industry. Mining Mag., **12,** pp. 206–212.
33	1902	Ingalls, W. R., Production and properties of zinc, Publ. by Eng. & Mining J.

Secondary zinc

Text reference	Year	Name and title
1	1929	Ingalls, W. R., Rueckgewinnung von zinkverluesten in verzinkereien und zinkschmelzen, Das Metall, **50,** p. 34.
2	1928	Bannard, W., Money in Zinc wastes, Brass World., **24,** pp. 37–39.
3	1928	Kershaw, J. B. C., The recovery and utilization of nonferrous metallurgical and foundry wastes. Metal Ind. (London), **32,** pp. 137–139.
4	1927	Thews, E. R., Production and refining of remelted zinc, Metal Ind., **25,** pp. 60–62, 107–108; C. A., **21,** p. 2637; J. Inst. Metals, **38,** p. 639.
5	1925	Brandt, O., Recovery of zinc dust and cement dust, together with utilization of waste heat, Warme, **48,** p. 450.
6	1925	Thews, R., The removal of iron from old zinc, Metallbörse, **15,** pp. 1183, 1407–1408; J. Inst. Metals, **36,** p. 565; Chem. Abst. **22,** p. 2535.
7	1944	Muller, R. W., Zinc recovery from galvanized iron. Metall Erz, **21,** pp. 404–405.
8	1924	Muller, D. R. W., Zinkverlueste beim messingschmelzen und ihre zurueckgewinnung, Chem. Ztg. **48,** pp. 943–944.
9	1921	Reinboth, F., Smelting of scrap metal. Metall. Technik., **47,** pp. 21–23.
10	1921	Paweck, H., Electrometallurgical procedure for the working up of zink dust and scrap metal. Z. Elektrochem., **27,** pp. 16–21.
11	1915	Krom, L. J., Refining of zinc waste. Metal Ind., **13,** pp. 281–283.
12	1903	Ingalls, W. R., Metallurgy of zinc and cadmium, Eng. & Mining J.

(d) GRADES, SPECIFICATIONS

(1) Pure Zinc.—"Spectroscopically pure" zinc containing less than 0.0001 per cent of metallic impurities is now available in small amounts (2). It is prepared by a series of fractional distillations of "chemically pure" zinc under vacuum until the product shows no impurity lines when examined spectrographically. This extremely pure zinc exhibits unusual resistance to tarnishing and to the action of certain acids. In its physical properties, this exceptionally pure zinc is marked by unusual softness, a low recrystallization temperature

which prevents strain hardening in cold rolling, and a tensile strength of 14,000 lbs./sq. in. (1,000 kg/sq. cm.). This grade of zinc is, at the present time, being produced in small quantities in the laboratory and is used in scientific investigations requiring zinc of the highest purity.

Pure zinc

Text reference	Year	Name and title
1	1927	Cyr, H. M., Pure zinc, Trans. Am. Electrochem. Soc., **52,** pp. 349–351; Chem. Abst. **21,** p. 1570; Met. & Ind., (London), **30,** pp. 455–456; J. Inst. Medals **38,** p. 385.
2	1923	Drescher, A., Preparation of chemically pure zinc, Bull. Soc. Chim. Romania, **5,** pp. 80–81; J. Inst. Metals, **31,** p. 383.

TABLE 9.—*Specifications for slab zinc (spelter)*

Specifications	Designation	Grade	Lead maximum	Iron maximum	Cadmium maximum	Aluminum maximum	Total lead, iron, and cadmium maximum	Antimony maximum	Arsenic maximum	Tin maximum	Arsenic and antimony maximum	Remarks
			Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	
A. S. T. M.[1]	B6-18, adopted 1911; revised 1914, 1918.	1, high grade	0.07	0.03	0.07	None.	0.10					Virgin metal required in all 5 grades.
		2, intermediate	.20	.03	.50	None.	.50					
		3, brass special	.60	.03	.50	None.	1.00					
		4, selected	.80	.04	.75	None.	1.25					
		5, prime western	1.60	.08								
F. S. B.[2]	91a current designation QQ-Z-351.	A to E inclusive	(3)	(3)	(3)	(3)	(3)	(3)	(3)	(3)	(3)	Only virgin metal to be used for grade A.
B. E. S. A.[4]	220-1926	Fine Zn, A	.02	.01	.02	Nil.		Nil.	Nil.	Nil.		
		Fine Zn, B	.08	.01	.03	Nil.		Nil.	Nil.	Nil.		
	221-1926	Special Zn	.20	.05	.25	Nil.				Nil.	0.02	
	222-1926	Foundry Zn	1.25	.07	.25	Nil.				0.02	.02	

[1] American Society for Testing Materials, Standards, 1930, p. 582.
[2] Federal Specifications Board, Washington, D. C.
[3] Chemical requirements same as A. S. T. M. B6-18. Aluminum as determined on a 25-gram sample.
[4] British Engineering Standards Association.

(2) Commercial Grades and Specifications.—The American Society for Testing Materials has designated five classifications under which zinc ("spelter") shall be identified (1). These grades are very generally recognized and accepted in the United States. They are listed in Table 9, together with the grades covered by various other specifications.

With the improvement of electrolytic methods for refining zinc and also the recent development of a special distillation method there has been made available commercially, a grade of zinc of exceptionally high purity. It is especially desirable for high-grade zinc-base alloys for die casting (p. 182). The following composition can be secured in this grade:

	Per cent
Lead + cadmium, maximum	0. 01
Tin	Nil.
Zinc, minimum	99. 99

Commercial grades of zinc

Text reference	Year	Name and title
1	1930	Standard specification for spelter, serial designation B6-18. American Society for Testing Materials, Am. Soc. Testing Materials Standards, Pt. I, Metals, p. 524.
2	1929	N. J. Zinc Co. (research department), Research Bulletin, Rolled zinc.
3		Proc. Am. Soc. Testing Materials, Report of Committee B-2, Subcom. XV, on Die-cast metals and alloys, **29**, Pt. I, pp. 192-199.

Table 10.—*Estimated industrial uses of zinc in the United States*[1]

(In tons of 2,000 pounds)

Purpose	1917	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929
Galvanizing (total)	190, 000	163, 000	192, 000	138, 100	205, 400	235, 200	240, 000	283, 000	290, 000	280, 000	291, 000	290, 000
Sheets	(2)	81, 500	99, 800	72, 500	110, 800	121, 300	122, 900	138, 000	142, 500	138, 500	144, 100	142, 800
Tubes		27, 900	34, 000	28, 200	44, 100	49, 000	50, 300	61, 100	62, 100	54, 000	54, 200	52, 200
Wire		33, 900	35. 900	19, 500	25, 000	32, 700	29, 000	35, 700	34, 200	38, 500	41, 300	39, 000
Wire cloth		4, 300	4, 800	3, 800	6, 100	6, 100	7, 100	6, 800	6, 800	6, 500	8, 400	10, 800
Shapes [3]		15, 400	17, 500	14, 100	19, 400	26, 100	30, 700	41, 400	44, 400	42, 500	43, 000	45, 200
Brass making	170, 000	155, 000	144, 000	75, 000	145, 000	175, 000	155, 000	165, 000	180, 000	160, 000	174, 000	180, 000
Rolled zinc	57, 000	55, 000	53, 200	30, 400	53, 500	55, 800	61, 000	71, 100	86, 300	74, 100	73, 500	68, 300
Die castings	(4)	(4)	(4)	(4)	(4)	(4)	(4)	(4)	13, 500	18, 000	30, 000	36, 000
Other purposes [5]	28, 000	29, 000	35, 000	19, 000	36, 000	49, 000	56, 000	60, 000	52, 500	51, 000	58, 000	54, 000
Total	445, 000	402, 000	424, 200	262, 500	439, 900	515, 000	512, 000	579, 100	622, 300	582, 100	626, 500	628, 300

[1] From Yearbook of American Bureau of Metal Statistics, 1927, 1929.

[2] Not separately reported.

[3] Includes full line hardware, hollow ware, chains, and all articles not elsewhere mentioned. The estimates for the use of slab zinc under this head, and for also wire cloth, are probably incomplete. The enumeration for 1924 includes figures from consumers not previously accounted for.

[4] Included in "Other purposes."

[5] Includes slab zinc used for the manufacture of French oxide, lithopone, atomized zinc dust, die castings, steel castings, and for the desilverization of lead.

(c) USES

Figure 11 based on data from the 1929 Yearbook of the American Bureau of Metal Statistics summarizes the various uses of zinc as a metal and as an alloy, as well as the other important products of which zinc is a constituent. In Table 10 are listed the amounts of zinc used in different industries since 1917. It will be seen that the galvanizing industry is, by far, the greatest single user of zinc, 46 per cent of the zinc recovered in the metallic forms being used for this purpose in 1929, of which 22 per cent was used in galvanizing sheet steel and iron. Over 28.5 per cent was used in the same year for making brass, and about 11 per cent of the zinc was rolled and used for manufacturing articles of wrought zinc. The die-casting industry, a rapidly increasing outlet for zinc, used somewhat less than 6 per cent and the remainder, used for other purposes, was about 8.5 per cent. The largest single use for rolled zinc is in the manufacture of dry cells. An important growing use is for weather strip.

Table 11.—*Uses of rolled zinc*

Grade of zinc	Type of rolling	Temper	Uses
High or intermediate	Strip	Dead soft and soft	Drawn dry cells, automobile hardware, standing seam roofing, miscellaneous drawn-formed articles.
Brass special	do	Dead soft	Miscellaneous drawn and formed articles,[1] soldered dry cells, weather strip and other uses requiring some stiffness.
Brass special or prime western.	do	Medium	
	Pack		Soldered dry cells, weatherstrip, batten type roofing, corrugated roofing and siding, organ pipes, photo-engraver's plates, lithographer's sheets, etc.

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[1] The uses of soft-rolled brass special and prime western zincs overlap those of high-grade and intermediate to a certain extent. In general, the deepest draws and hardest bends are made with high-grade zinc.

In the field of wrought zinc, a distinction may be made as to the usefulness of the different grades. (Table 9.) Information on this point as given by Peirce and his associates (5) is given in Table 11.

In addition to the older and better known uses for zinc dust, such as in pyrotechnics, dyeing, and in coating iron and steel (sherardizing), mention may be made of its increasing use in paints. This usage is not to be confused with the similar one of some of the zinc compounds.

Brief mention may be made of the uses of the important zinc compounds. The oxide is used in paints, pharmaceutical preparations, in the manufacture of rubber articles, in pasteboards, and enamels. The sulphides are used in paints, rubber, and linoleum; the chlorides in the preservation of wood and leather, as a flux in soldering and galvanizing, as a mordant in printing fabrics as well as various pharmaceutical uses. The sulphate is used in the manufacture of cotton goods and the carbonate in paints (19).

Uses

Text reference	Year	Name and title
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3. METALLOGRAPHY

(a) CRYSTAL STRUCTURE

The results of X-ray diffraction analyses made at the National Bureau of Standards (15) on powdered pure zinc confirmed Hull's finding (25) that zinc crystallizes in the hexagonal (triangular) close-packed system. Three determinations gave the value for a_o (the shortest distance between atoms in the basal plane) as 2.649, 2.649, and 2.650, the average value, 2.65 A, being somewhat at variance with the value of 2.670 A, based on Hull's work, generally quoted in the literature. Hull, in a private communication has confirmed the value of 2.65 A as being more correct. The shortest distance between atoms in the pyramid plane, according to Hull, is 2.920 A. Pierce, Anderson, and Van Dyck (18) obtained the corresponding values

2.657 and 2.903 A, for the shortest distance between atoms in the basal and pyramid planes.

Since the zinc lattice is of the hexagonal close-packed type, the fundamental crystal unit may be considered as a hexagonal prism with the atoms shown in Figure 12(*b*) as black dots. The length of a side of the base of a unit cell, a_o is 2.65 A (as already mentioned above), the altitude of this cell, c_o, 4.93 A, and the axial ratio, c_o/a_o, 1.86.

Information on the crystal structure of the different constituents in the various alloy systems of zinc is given in Part II under the appropriate alloy system.

(b) MECHANISM OF CRYSTAL DEFORMATION

When a stress exceeding the elastic limit is applied to a crystal unit of zinc, consideration must be given essentially to the resultant stresses along the planes designated in Figure 12 (*b*) and (*c*), the basal plane (0001) and the pyramid face $(10\bar{1}2)$, there being six of the latter which are all crystallographically equivalent.

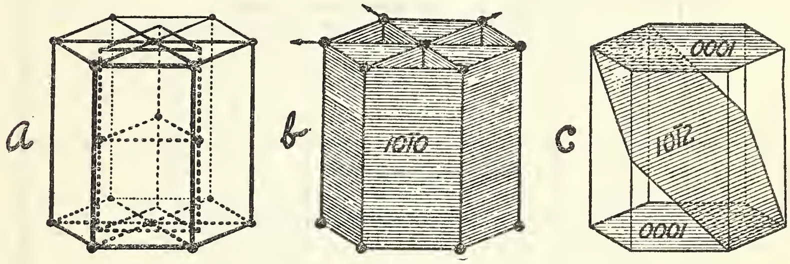

Figure 12.—*Characteristics of the crystal system of zinc*

Slip on the basal plane occurs easily, and if continued on a number of parallel planes results in an extensive deformation of the crystal. Mathewson and Phillips (12) have shown that twinning can occur along the pyramid face with a maximum deformation of 6.75 per cent, measured as a reduction in thickness perpendicular to a basal plane. A higher stress is probably necessary to produce, at room temperature, this change than to cause a basal slip. Although twinning, in itself, does not result in much deformation, it has the very important effect of producing a reoriented space lattice (in the twinned layers), in which the basal plane is 94° 5′ removed from the preexisting basal plane, but lies approximately in some one of the six prism face positions according to the pyramid face on which twinning has occurred. Additional deformation in the direction of the applied stress may then occur by slip on the new basal plane. Obviously the direction of the stress with respect to the orientation of the crystal will determine whether basal slip or twinning occurs first.

(c) SINGLE CRYSTALS

The single crystal is the simplest form of metallic structure known, and it is therefore one of the most commonly used materials in studies of plastic deformation. Since there are no grain boundaries and random crystal orientations, the changes resulting from the application of a tensile or compressive force may be definitely correlated to the direction of applied stress and to each other. As pointed out by Mathewson and Phillips (12), the behavior of a single crystal under stress is, however, very different from that of a crystal in a polycrystalline aggregate. In the latter case the crystal is hemmed in on all sides so that the usual deformational effects observed in single crystals are altered. Thus, in a polycrystalline zinc wire, fragmentation and straining of the lattice cause hardening after deformation as much as slip in the single crystal does along basal planes. The stress-strain diagrams shown in Figure 13 for brittle and ductile zinc

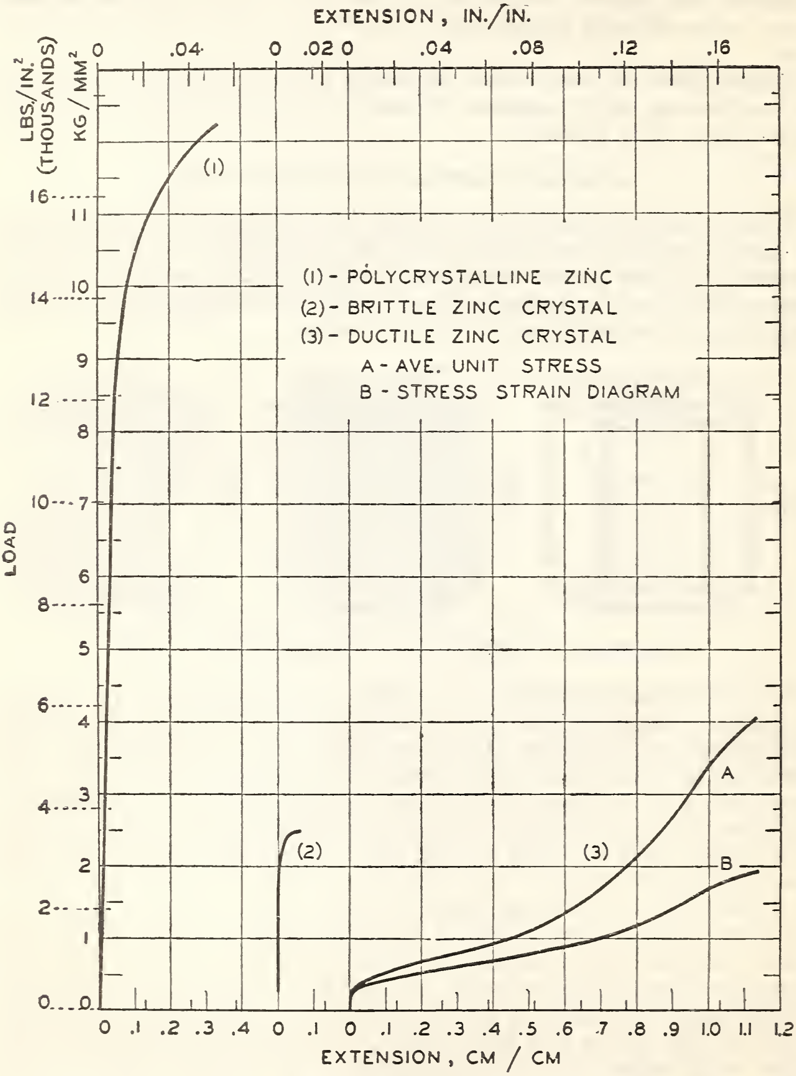

FIGURE 13.—*Stress-stress-strain diagrams of brittle and ductile zinc single crystals and also of polycrystalline zinc*

single crystals and also for polycrystalline zinc clearly illustrate the marked differences in the strength of these types of zinc as developed by tensile stress (11).

The preparation of single crystals of metals may be carried out by any one of the following methods: (*a*) By annealing at a rather high temperature to promote grain growth, usually with a slight straining before the annealing to facilitate the grain growth; (*b*) by drawing polycrystalline wires at a determined speed through a heated zone having a rapid decrease in temperature; (*c*) by starting solidification at the capillary end of a glass tube filled with the molten metal either by passing the tube, the capillary end forward, through a furnace, the temperature of which is precisely controlled, or by directing a carefully regulated blast of air on the capillary end of the tube (the capillary must be small enough that a single nucleus from the overlying metal solidifies as a single crystal) (13); and (*d*) by drawing the molten metal through a temperature zone having a sharp gradient which freezes the metal quickly. Method (*d*) is known as the Czochralski-Gomperz method (3, 8, 11, 13) and (*c*) as the Bridgman method. Hoyem and Tyndall (3) determined experimentally the various conditions required to grow by method (*d*) zinc single crystals of 2.7 mm (0.10 inch) diameter, 10 cm (4 inches) or more in length, and of any desired orientation. They found that the orientation of the crystal obtained is a function of the temperature gradient used, and showed graphically (fig. 14) the upper and lower limits of a region, within which single crystals may be grown at the rate of 1.2 cm/min.

Many investigators agree with Mark, Polanyi, and Schmid (24) in that plastic deformation of zinc single crystal wires produces mainly a slip along the basal planes (0001) as indicated in Figure 15. This block movement along the basal plane is accompanied by a small amount of rotation or tilting of the basal planes as they attempt to align themselves parallel to the direction of stress. This basal slip is the most predominant effect when a zinc single crystal is subjected to tensile deformation. The parallel elliptical-shaped slip bands that are formed on the surface of a zinc single crystal by stretching (fig. 16 (*a*)) indicate the orientation of the basal planes. A ductile single crystal of zinc stretches under plastic deformation, into a thin ribbon of an elliptical cross section, with the major axis essentially the same as the initial diameter of the crystal and the narrowing of the crystal occurring in the direction of the minor axis. The area of the slip plane, however, remains constant.

The slip plane in zinc, as in other metals, is the plane of greatest atomic density, wherein the atoms are united with the greatest cohesive force. Planes of this type are separated from each other by the greatest interatomic distance. As would be expected from the atomic arrangement of zinc, the slip plane is the basal plane, and the slip along the basal plane is in the direction of one of the three hexagonal axes which lie in the basal plane. The direction of the slip will, therefore, be along that hexagonal axis which most nearly coincides with the direction of maximum shear (that is, the most highly stressed primitive direction contained by the basal plane) in the slip plane or with the major axis of the elliptical cross section of the basal plane. (Fig. 15.) All these movements (tilting, translation, and rotation) progress in an orderly and continuous manner throughout the course of the plastic (static) deformation and are governed by the simple geometrical arrangement of the atoms of the zinc crystal, which has been found not to be greatly disturbed by even severe plastic deformation.

Mark, Polanyi, and Schmid (24) found that the most ductile wires have the basal plane at approximately 45°, whereas that in brittle wires was nearly parallel to the wire axis. Brittle crystals have been observed to be less pure than ductile crystals, the principal impurity being zinc oxide, and often are obtained by the use of impure zinc.

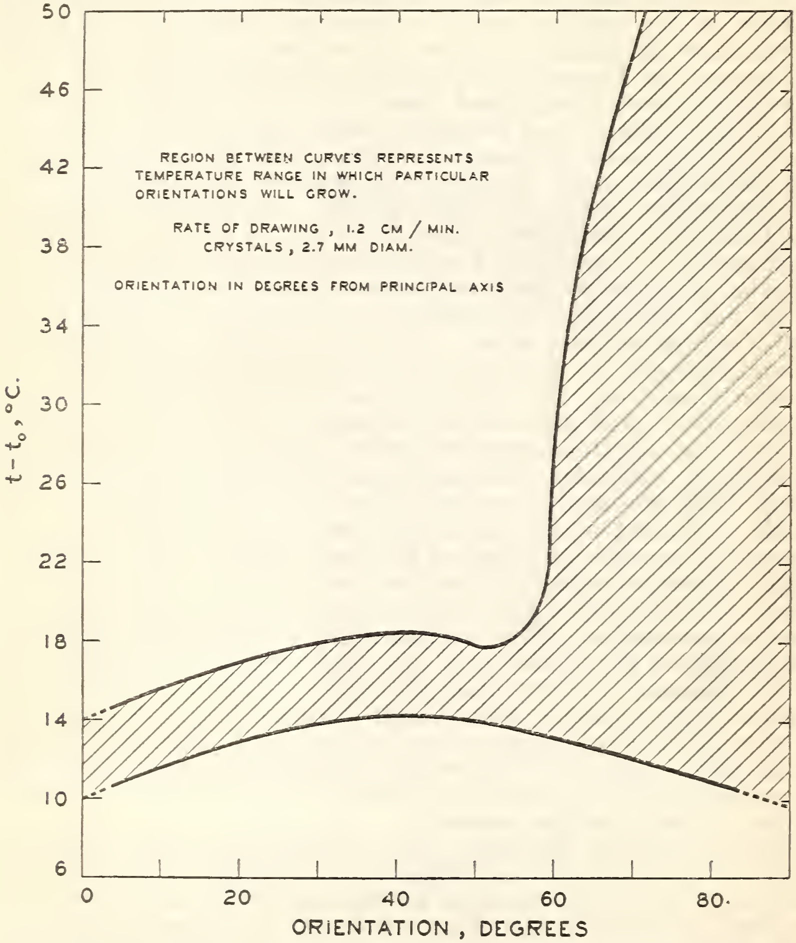

Figure 14.—*Temperature gradient-crystal orientation relationship for the growth of zinc single crystals*

When the deformation of the zinc single crystal has extended sufficiently, the elliptical-shaped ribbon may change suddenly at some point into a thin thread of circular cross section having a diameter equal to the minor axis of the ribbon. (Fig. 16 (*d*), (*e*), and (*f*).) According to Schmid (6, 7) the change at this point consists essentially of the formation of a mechanical twinning, whereby the translation plane is shifted from the already unfavorable position, with

Figure 15.—*Representation of the block movement along basal planes in a zinc single crystal*

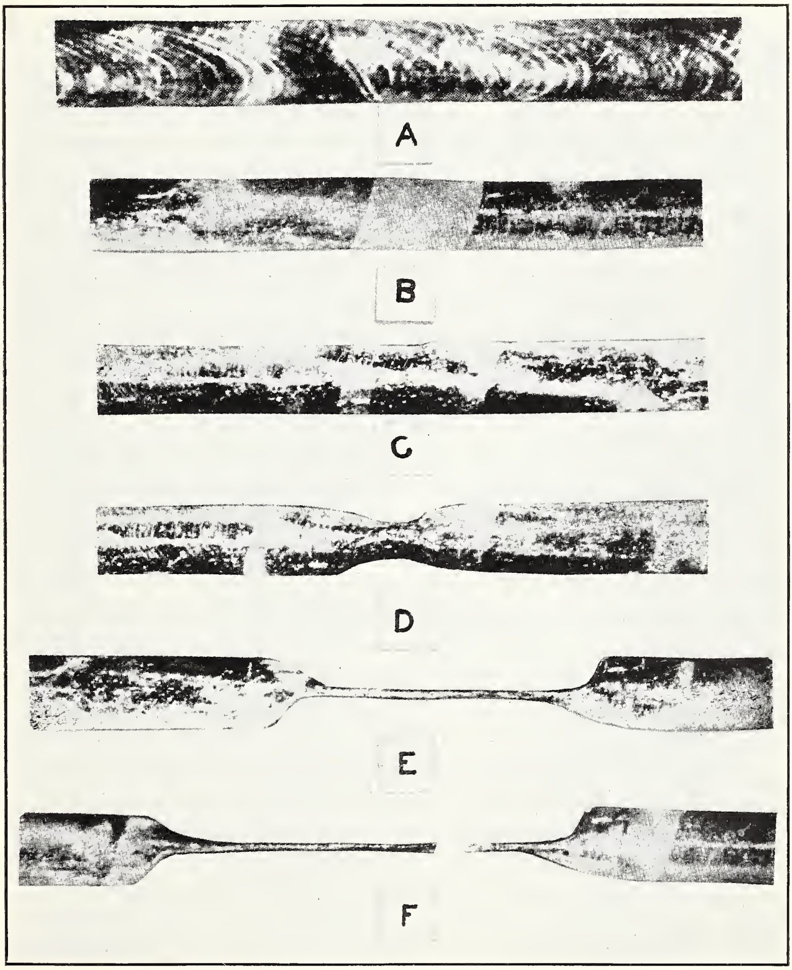

Figure 16.—*Appearance of a zinc single crystal in wire form after different successive stages of plastic (static) deformation in tension,* × *14*

A, Elliptical edges of basal slip planes showing after considerable deformation; *B,* formation of mechanical twins, shown by light band near center; *C,* broadening of twinned zone and beginning of "after elongation"; *D* and *E,* progressive and pronounced "after elongation" within the twinned zone; *F,* after fracture of the crystals. (*A* from reference 24, *B* to *F* from reference 7.)

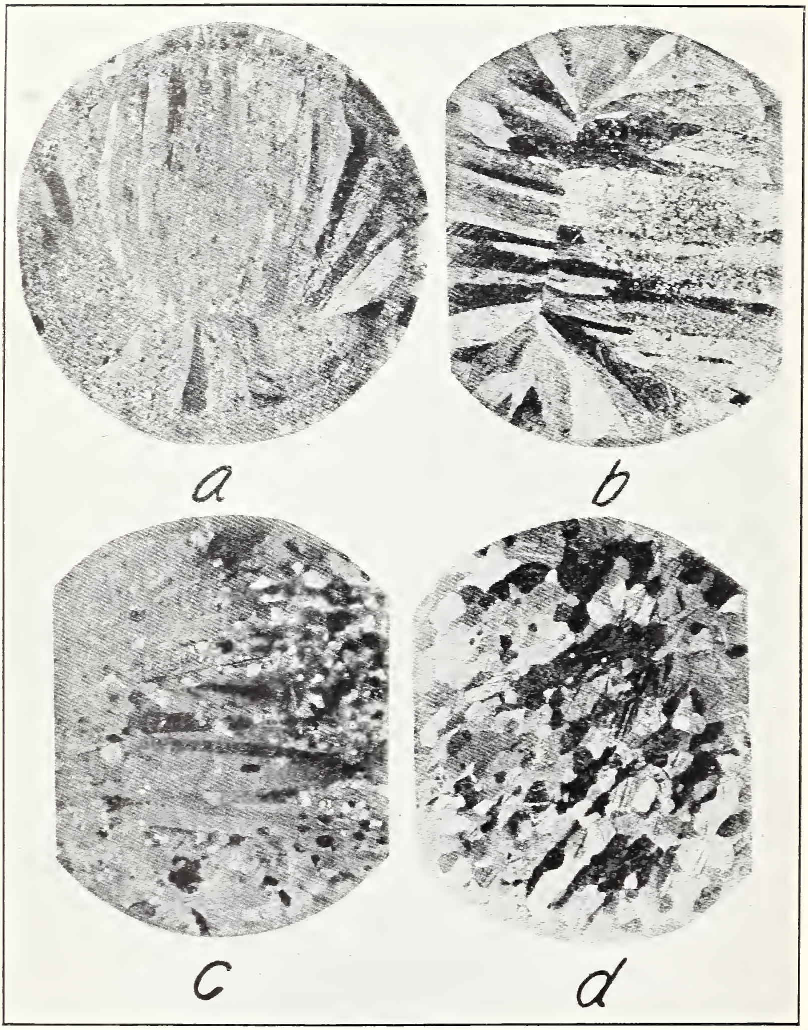

FIGURE 17.—*Macrostructure of cast zinc of high purity, × 3*

a, Annealed at 150° C.; *b*, quenched from 154° C.; *c*, quenched from 267° C.; *d*, quenched from 342° C. Etched with 5 per cent alcoholic solution of hydrochloric acid.

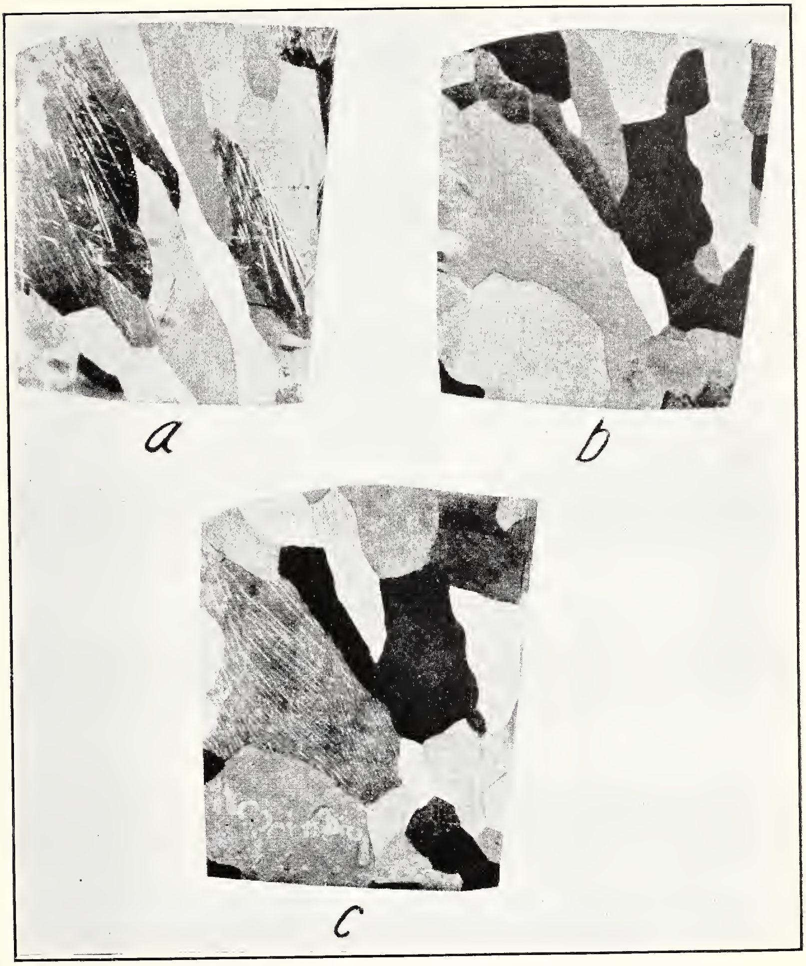

FIGURE 18.—*Macrostructure of cast zinc of high purity, × 3*

The metal was free from casting strains. *a*, The molten metal was allowed to cool very slowly in the crucible to room temperature, and was subsequently annealed at 125°, 150°, and 220° C., respectively, for one hour; *b*, same specimen after being annealed for one hour at 390° followed by slight polishing; *c*, same specimen after being annealed for one hour at 390° C. in hydrogen followed by very slight polishing and etching. Etched as in Figure 17.

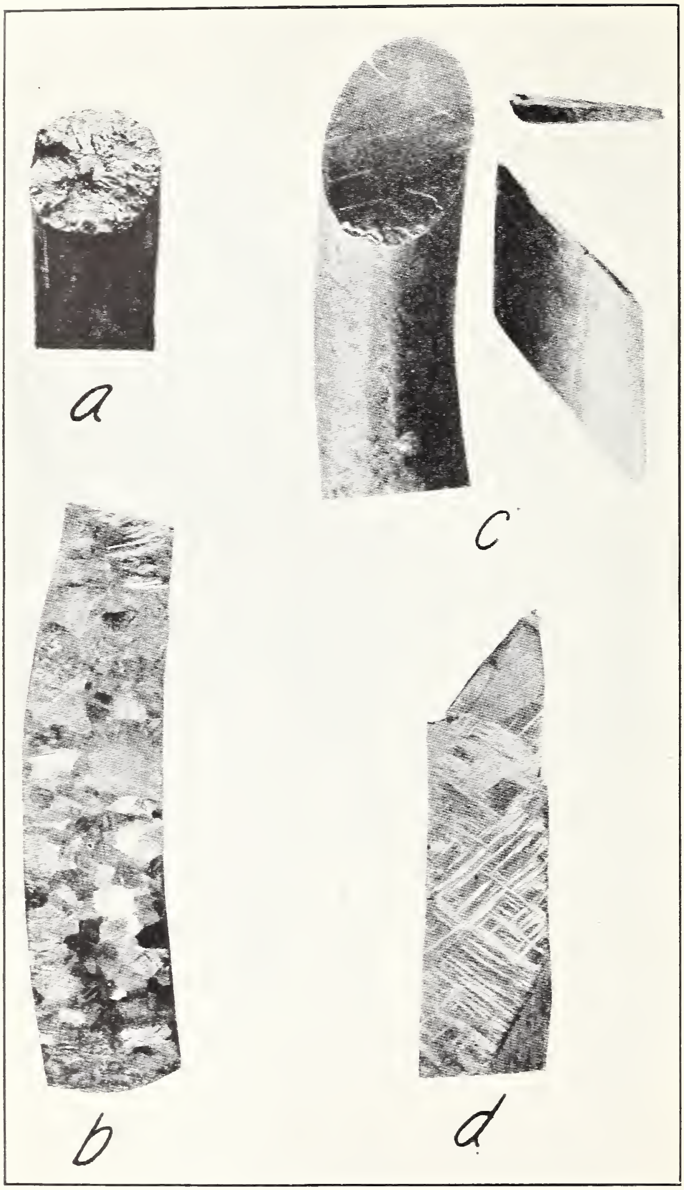

FIGURE 19.—*Conversion of polycrystalline zinc into a single crystal by annealing,* × 2½

The specimen was used in the determination of thermal expansivity. *a*, Fractured end of specimen showing initial condition; *b*, polished and etched section of sample similar to *a*; *c*, fractured portions of specimen after annealing; *d*, polished and etched section of sample similar to *c*. Etched as in Figure 17.

respect to the direction of stretching and consequently for further extension in this direction, into another in which further translation of an appreciable extent may be obtained to the point of fracture. This phenomenon is known as "after elongation" or "after extension." In other words, the after elongation is due to secondary slip produced on basal planes which had been reorientated by twinning during the plastic deformation. Mathewson and Phillips (12) have concluded that this twinning is essentially a rotation of some of the basal planes into positions 94° removed from their original position, that fracture occurs along these same basal planes in their altered positions, and, therefore, that fractures previously regarded as prismatic are really basal. They determined that the twinning plane occurs along the pyramidal plane $\{10\bar{1}2\}$, and that twinning about this plane would produce a twinned basal plane whose position would make a small angle, 4°, with prismatic planes of the parent crystal.

Gough and Cox (2) subjected specimens of zinc single crystals to alternating torsional stresses, and found that the facts established for statically stressed zinc single crystals held similarly for the torsionally stressed specimens. They stated that fracture in their specimens followed three general directions: (*a*) Parallel to the traces of the original basal plane, (*b*) parallel to the traces of the twinned basal plane within the twinned structure, and (*c*) along the edges of the twins. They determined that neither slip or cleavage planes occurred along prismatic planes.

(d) PREPARATION AND ETCHING OF SPECIMENS FOR MICROSCOPIC EXAMINATION

A recommended procedure (4) for the polishing and etching of zinc is as follows: The face of the specimen to be examined is first ground, after having been leveled off to a flat surface if necessary, on a belt sanding machine, by using successively a coarse and a fine grade of belt. This is followed by a grinding on two or three grades of emery papers of increasing fineness, such as Nos. 0 and 00 (American or French manufacture). In all these steps of dry grinding, care should be exercised to prevent undue heating of the zinc specimens. Wet grinding on two canvas-covered disks and wet polishing on a broadcloth-covered disk are next undertaken in this order, with the disks rotating at a moderate rate of speed. The three abrasive powders used successively are a coarse grade of emery, a fine grade of emery, and a polishing powder. Grades SFX, SF3X, and SF10S (one American manufacturer's designation), or their equivalent are satisfactory. A thin suspension in water, which is kept stirred during the grinding and polishing operations, is used. The disks should be kept moist, but not flooded. Hand polishing with alumina has also been found satisfactory.

After washing and drying, the specimen is etched. An etching reagent, recommended by the New Jersey Zinc Co. (4) and described by Mathewson, Trewin, and Finkeldey (26), is made by dissolving 20 g C. P. chromic anhydride (sulphate free) and 1.5 g C. P. anhydrous sodium sulphate in 100 cc water. According to a personal communication from W. M. Peirce, the procedure in etching followed by the metal research division of the New Jersey Zinc Co. is as follows: After polishing, the specimen is (1) washed with (*a*) alcohol, (*b*) ether, (*c*) alcohol and water; (2) transferred wet to the etching solution; (3) rinsed in a water solution of pure chromic acid (no sulphate addition); (4) rinsed in (*a*) running water, (*b*) alcohol, (*c*) ether; and (5) dried with a blast of hot air. Staining results if any diluted etching reagent is allowed to remain on the specimen. A short etch, for about 15 seconds, following the wet fine emery grinding is desirable in order to remove the slightly marked surface before proceeding with the final polish.

In preparing zinc-coated materials for microscopic examination, it is necessary to mount the specimen so as to reinforce and preserve the outside edge of the coating during the grinding and polishing operations. Two methods of mounting recommended by Finkeldey (14) call for the use of (*a*) pure soft zinc, in the form of rolled bars or thin sheets, which is slowly flowed into intimate contact with the surface of the zinc-coated material under pressure applied by a vise and clamps, and (*b*) molten zinc poured at a temperature just above its melting point into a small iron mold containing the specimen secured in the proper position. Method (*a*) is obviously not well adapted for the mounting of bent galvanized wires, sheets or objects of irregular shape. The main objection to method (*b*) is that the zinc coating becomes heated, although this does not constitute a serious enough objection to prevent, in most cases, the use of this method. The procedure for preparing the mounted specimens for microscopic examination is much the same as outlined above. It is however advisable not to try and polish out all the scratches in the iron or steel base, for the shortest possible grinding and polishing time is desired in order that the inevitable difference in level between the soft zinc coating and the relatively hard steel base may be minimized. Another desirable precaution is to avoid having the grinding scratches parallel to the line of contact between the coating and base at any time.

(e) MACROSTRUCTURE AND MICROSTRUCTURE

Macrographs illustrative of chemically pure zinc in the strained and unstrained conditions are shown in Figures 17 and 18 (15). In preparing the macrographs of Figure 17, care was taken in polishing and etching the surfaces of the specimens, cut from cast tensile test bars, so as to ensure that the structures shown were characteristic and that the small grains were not a surface effect. The circular band of very small grains seen near the edge in Figure 17 (*a*) was explained as being the result of recrystallization when the strained material was annealed, the strains having been set up during the machining of the bar. The partial recrystallization noted in the other macrographs is probably due to the same cause. Undoubtedly shrinkage stresses are also set up in castings that are of sufficient magnitude to cause subsequent recrystallization, particularly at the higher annealing temperatures. However, evidence of the original cast structure in Figure 17 (*d*) has not entirely disappeared. To test the assumption that recrystallization was due to annealing after strain, a sample of strain-free zinc was obtained by allowing a quantity of molten metal to freeze and cool very slowly in a crucible. A specimen was cut from this metal, polished and etched, then repolished and etched several times in order to remove any strained surface that may have been produced during operations preceding the final polishing. Figure 18 shows no evidence of any new grains having been formed after this specimen had been heated in an oil bath at 125°, 150°, and 220° C., respectively, for one hour, cooled slowly in the bath, and etched after each heating. This specimen was then heated to 390° C. in air and slowly cooled in the furnace, polished just sufficiently to remove all traces of the previous structure and reetched, with the resulting structure as shown in Figure 18 (*b*). The apparent difference was believed to be due to the removal of a thin layer of metal during polishing, for portions of grains seen in Figure 18 (*a*) may be seen in Figure 18 (*b*). To secure further evidence on this point, the same specimen was annealed again for one hour at 390° C., but in an atmosphere of hydrogen so as to preserve the etched surface. Following a reetching, no new grains were found.

The marked change in the microstructure of zinc that may be obtained by heating to successively higher temperatures is illustrated by a specimen of chemically pure zinc which was used in a thermal expansion determination made at this bureau (15). The specimen, 0.714 cm (0.28 inch) diameter and 30 cm (11.8 inches) long, was cast by drawing the molten metal up inside of a glass tube. The appearance of the fractured end of the sample, from which the thermal expansion specimen was taken, and the microstructure of a polished and etched surface of this sample are shown in Figure 19 (*a*) and (*b*), respectively. The fracture and microstructures of the thermal expansion specimen, after three successive heating cycles to 250°, 310°, and 350° C. are shown in Figure 19 (*c*) and (*d*). The angle of the fracture was always either at 45° or at 90° to the axis, and the fracture was always very smooth and mirrorlike—suggestive of the fracture of single crystal zinc wire described by Mark, Polanyi, and Schmid (24). Thin plates (fig. 19 (*c*)) could be readily pried off with the point of a knife blade. The initial strained condition remaining after casting or the slight strain resulting from the straightening of the specimen during its preparation was evidently sufficient to cause the change from the polycrystalline condition to that of a single crystal during the heating incidental to the determination of thermal expansivity.

Figures 20 and 21 show examples of the microstructure that may be developed in commercial grades of zinc by rolling and drawing operations. Figure 20 (*a*) and (*b*) show commercially pure zinc (99.95 per cent zinc) in the hot-rolled and dead-soft rolled conditions, respectively. It is to be noted that the zinc in the hot-rolled sample is not in the completely recrystallized state while that in the dead-soft rolled sample is. Figure 21 shows the severely deformed structure in a sample taken from a dry cell container. These three micrographs show transverse sections through the thickness of the sheet.

Figure 22 shows the microstructure of three grades of zinc—high grade, intermediate grade, and high lead, in two conditions with respect to "temper," soft and medium. The variation in the relative amount of lead in the three grades and its distribution in the two conditions is very apparent.

(f) EFFECT OF SMALL AMOUNTS OF ALLOYING ELEMENTS ON THE MICROSTRUCTURE OF ZINC

Lead.—Zinc and lead have a limited miscibility in the liquid state, and have been found to form no solid solutions. In freezing, molten zinc containing a small amount of lead first deposits crystals of pure zinc and finally the eutectic of zinc and lead solidifies in the grain boundaries. Figure 23 shows lead as a metallographic constituent in cast zinc in the form of lines of minute coalesced droplets of lead from the divorced eutectic. Since these droplets are separate globules and not extended discontinuities in the metal, and are not brittle, they do not exert any marked detrimental effect on the physical properties of the metal. The globules stretch out, on rolling, and smear over the surface to a certain extent during the preparation of the section for microscopic examination, as illustrated in Figures 22 and 23, thus giving an exaggerated impression of their extent and importance (4, 22).

Iron.—This element forms a compound or solid solution with zinc, containing from 7.3 to 11 per cent of iron, which has a melting point above that of zinc and hence appears as primary crystallites, as shown in Figure 91 on page 158. These crystallites are hard and brittle, and embrittle the zinc when present in any considerable amount. A very small amount of iron, about 0.01 per cent, is held in solid solution by zinc and hardens it to a slight extent. As the result of a change in solid solubility with change in temperature some hardening may also occur by precipitation of finely dispersed particles of the above-mentioned iron-rich constituent (4, 22).

Cadmium.—The limit of solid solubility of cadmium in zinc, depending on the temperature, is 1 to 1.5 per cent. (See Sec. II (f).) Commercial zinc never contains as much as this. Therefore, no distinct constituent attributable to cadmium is present in the microstructure of this material, although distinct crystals of cadmium may be found in cast zinc containing 1 per cent cadmium which is quickly cooled. Figure 23 (*c*) shows the zonal structure which is typical of nonhomogeneous solid solutions of zinc and cadmium. The addition of as much as 1 per cent cadmium may entirely prevent the growth of columnar crystals in cast bars of pure zinc with the result that a fine equiaxed granular structure is formed (4, 22).

Tin.—Tin forms with zinc a very brittle eutectic, which forms thin and fairly continuous films along the grain boundaries. A very small amount of tin seriously embrittles zinc; it is practically impossible to roll zinc containing as much as 0.005 per cent tin. The fact that zinc can be pulverized in a mortar at 200° C., as is frequently stated in the literature, can probably be attributed to the presence of a small amount of this tin eutectic (4, 22).

Copper.—Copper is not found in commercial zinc, although traces of copper may be found in electrolytic zinc of ordinary grade. The zinc lattice will hold in solid solution between 1.5 and 2 per cent copper, depending on the temperature. Zinc is hardened to some extent by the presence of copper in solid solution, although its rolling properties are not adversely affected (4, 22).

Aluminum.—Aluminum goes into solid solution in zinc, the limit of solid solubility being from about 0.25 per cent at room temperature to somewhat less than 1 per cent at the eutectic temperature. Zinc-rich alloys containing aluminum above this amount have a duplex structure, one constituent of which is unstable at temperatures below 256° C. (approximate). A far-reaching detrimental effect on zinc-aluminum alloys is the result of this (4, 22).

Magnesium.—Magnesium forms with zinc a compound, $MgZn_2$, which is very hard and brittle. This compound forms a eutectic with zinc at 4 per cent magnesium which is likewise brittle. One part of magnesium forms twenty-five parts of the eutectic. There is no evidence of magnesium forming a solid solution in zinc. The hardening must, therefore, be attributed to finely dispersed particles of the compound (4, 22).

Manganese and nickel.—These resemble iron in their structural effect on zinc (22).

(g) STRUCTURE OF ELECTRODEPOSITED ZINC

In common with deposits of other metals, electrodeposited zinc exhibits a crystalline structure, which may be visible to the unaided eye, or with a low magnification. The size and character of these crystals are influenced by the conditions of deposition in the same way as are those of other metals. In general, as the cathode polarization is increased the structure tends to change from isolated to conical, broken and finally to powdery deposits. In acid zinc solutions the cathode polarization is relatively low, especially at low current densities, at which, therefore, there is a tendency for the formation of isolated crystals. In alkaline cyanide solutions, however, in which the cathode polarization is high, the deposits are usually fine grained and of the broken or random type.

Metallography

Text reference	Year	Name and title
1	1930	Stillwell, C. W., Clark, G. L., X-ray examination of commercial galvanized iron by a modified reflection method, Ind. Engng. Chem., Analytical Edition, **2**, p. 266.
2	1929	Gough, H. J., Cox, H. L., Behavior of a single crystal of zinc subjected to alternating torsional stresses, Proc. Roy. Soc., **123a**, p. 143.
3	1929	Hoyem, A. G., Tyndall, E. P. T., An experimental study of the growth of zinc crystals by the Czochralski-Gomperz method, Phys. Rev., **33**, p. 81.
4	1929	N. J. Zinc Co., research department, Research Bulletin "Rolled Zinc."
5	1929	Osawa, A., Ogawa, Y., X-ray investigation of iron and zinc alloys, Science Repts., Tohôku Imp. Univ. (Sendai, Japan), **18**, pp. 165–176.
6	1928	Schmid, E., The importance of mechanical twin formation for plasticity and strengthening, Z. Metallkunde, **20**, pp. 421–425.
7	1928	Schmid, E., Wasserman, G., Twin formation in zinc crystals under tensile stress, Z. Physik., **48**, pp. 370–383.
8	1928	Tyndall, E. P. T., Factors governing the growth of zinc crystals by the Czochralski-Gomperz method, Phys. Rev., **31**, II, p. 313.
9	1928	Wilson, T. A., Hoyt, S. L., X-ray analysis of plastic deformation of zinc, Inst. of Met. Div., Am. Inst. Mining & Met. Eng., pp. 241–269.
10	1927	Friauf, J. B., The crystal structure of magnesium di-zincide, Phys. Rev., **29**, II, p. 34.
11	1927	Hoyt, S. L., Plastic deformation of a zinc single crystal, Inst. of Met. Div., Am. Inst. Mining & Met. Eng., pp. 116–132.
12	1927	Mathewson, C. H., Phillips, A. J., Plastic deformation of coarse-grained zinc, Inst. of Met. Div., Am. Inst. Mining & Met. Eng., pp. 143–189.
13	1927	Romig, O. E., Preparation of metallic single crystals and twinning in zinc and zinc single crystals, Inst. of Metals Div., Am. Inst. Mining & Met. Eng., pp. 90–112.
14	1926	Finkeldey, W. H., The microstructure of zinc coatings, Proc. Am. Soc. Testing Materials, **26**, (2), pp. 304–315.
15	1926	Freeman, J. R., jr., Sillers, F., Brandt, P. F., Pure zinc at normal and elevated temperatures, B. S. Sci. Paper No. 522.
16	1926	Owen, E. A., Preston, G. D., Atomic structure of Ag Mg and Au Zn, Phil. Mag., **2**, (VII), pp. 1266–1270.
17	1926	Schmid, E., Increase of tensile strength of single crystals by plastic deformation, Z. Physik., **40**, p. 54; Trans. Am. Soc. Steel Treat., **11**, p. 813; 1927.
18	1925	Peirce, W. M., Anderson, E. A., Van Dyck, P., An investigation of the alleged allotropy of zinc by the X-ray analysis and a redetermination of the zinc lattice, J. Franklin Inst. **200**, p. 349.
19	1925	Phebus, W. C., Blake, F. C., The X-ray analysis of certain alloys, Phys. Rev., **25**, p. 107.
20	1925	Westgren, A., Phragmen, G., X-ray analysis of copper-zinc, silver-zinc, and gold-zinc alloys, Phil. Mag., **50** (VI), pp. 311–341.
21	1924	Simson, C. V., X-ray spectra of amalgams, Z. Physik. Chem., **109**, pp. 183–198.
22	1923	Peirce, W. M., Studies on the constitution of binary zinc-base alloys, Trans. Am. Inst. Mining & Met. Eng., **68**, pp. 767–792.
23	1923–24	Owen, E. A., Preston, G. D., X-ray analysis of zinc-copper alloys, Proc. Phys. Soc., London, **36**, pp. 49–66.
24	1922–23	Mark, H., Polanyi, M., Schmid, E., Elongation of zinc crystals, Z. Physik., **12**, pp. 58–116.
25	1921	Hull, A. W., X-ray crystal analysis of thirteen common metals, Phys. Rev., **17**, pp. 571–588.
26	1920	Mathewson, C. H., Trewin, C. S., Finkeldey, W. H., Some properties and applications of rolled zinc strip and drawn zinc rod, Trans. Am. Inst. Mining & Met. Eng., **64**, pp. 305–376.

4. CHEMICAL PROPERTIES

(a) ELECTROCHEMICAL PROPERTIES

(1) Electrolytic Solution Potential.—The standard potential of zinc as given in International Critical Tables (vol. 6) is -0.7618 volt. This value indicates that, when in the active state, zinc is one of the most active of the common metals; that is, it is very susceptible to solution or oxidization. This property accounts for its very extensive use for protecting iron and steel against corrosion. When zinc is in contact with iron in most electrolytes, the zinc becomes anodic toward the iron; that is, it dissolves and thereby protects adjacent iron against corrosion. The electrolytic protection thus furnished is the origin of the term "galvanizing" as applied to zinc coatings. This subject is discussed in greater detail in a later section. (Sec. 6 (*f*).)

(2) Hydrogen Overvoltage.—In spite of the negative value of its standard potential, pure zinc is not rapidly attacked or dissolved by most solutions, including dilute acids. However, very small amounts of more noble metals, such as copper, tin, and lead, cause the zinc to dissolve much more rapidly. The resistance of pure zinc to acids is explained by the fact that the overvoltage of hydrogen on zinc is higher than on most other metals (7, 9, 11). As, in the absence of a depolarizer, hydrogen must be evolved during the solution of the zinc, and as the potential required for hydrogen to be discharged on zinc is higher than the potential with which the zinc tends to dissolve, almost no solvent action occurs on pure zinc.

If, however, as in the case of the commercial metal, zinc contains impurities upon which the overvoltage of hydrogen is lower than on zinc, the hydrogen will discharge on these impurities and the zinc will continue to dissolve. Similarly the rate of solution of pure zinc in acid can be accelerated by placing in contact with the zinc a metal, such as platinum or copper, which has a lower hydrogen overvoltage than zinc.

(3) Passivity.—In one sense this resistance of zinc to corrosion, in spite of its high solution pressure, may be designated as passivity. The latter property is commonly attributed (for example, in the case of aluminum, chromium, nickel, and iron) to the presence of a film of oxide or adsorbed oxygen on the metal surface. Such a film may also be present on the surface of zinc that is passive on exposure to the atmosphere, but if so, it probably does not play so important a part in retarding further chemical action, as it does on the other passive metals. Actually, when zinc is exposed to severely corrosive conditions (for example, in a salt spray or in a marine atmosphere), a visible coating of basic zinc carbonate forms on the surface and greatly retards further chemical action.

Electrochemical properties

Text reference	Year	Name and title
1	1927	Foxton, F., Shutt, W. J., The activity of zinc chloride in concentrated solution, Trans. Faraday Soc., **23**, pp. 480–488.
2	1927	Isgarischew, N., Titow, P., Notes on the paper by Erich Rabald, Z. Elektrochem, **33**, pp. 211–212.
3	1926	Frölich, P. K., Electrodeposition of zinc from electrolytes containing gelatin and aluminum sulphate, Trans. Am. Electrochem. Soc., **49**, pp. 395–416.

Electrochemical properties—Continued

Text reference	Year	Name and title
4	1926	Rabald, E., Experiments on the influence of gelatin on the static potential and polarization of zinc in zinc sulphate solution, Z. Elektrochem, **32,** pp. 289–294.
5	1925	Walker, W. M., Sorrels, J. H., Breckenridge, J. M., Static potentials of copper in solutions of copper cyanide in sodium cyanide and in potassium cyanide, and of zinc in solutions of zinc cyanide in sodium cyanide, Trans. Am. Electrochem. Soc., **48,** pp. 47–60.
6	1924	Frölich, P. K., The amphoteric character of gelatin and its bearing on certain electrochemical phenomena, Trans. Am. Electrochem. Soc., **46,** pp. 67–83.
7	1924	Westrip, G. M., The hydrogen overvoltage of zinc, J. Chem. Soc. (London), **125** (1) pp. 1112–1121.
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9	1923	Knobel, M., Caplan, P., Eiseman, M., The effect of current density on overvoltage, Trans. Am. Electrochem. Soc., **43,** pp. 55–77.
10	1922	Hughes, W. E., Idiomorphic and hypidiomorphic structures in electrodeposited metal, Trans. Am. Electrochem. Soc., **41,** pp. 317–329.
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12	1920	Mutscheller, A., Colloidal adsorption, J. Am. Chem. Soc., **42** (2), pp. 2142–2160.
13	1919	Blum, W., Factors governing the structure of electrodeposited metals, Trans. Am. Electrochem. Soc., **36,** pp. 213–232.
14	1916	Chaney, N. K., Contact resistance of metal electrodes, Trans. Am. Electrochem. Soc., **29,** pp. 183–202.
15	1914	Titov, A. A., Levi, S. M., Electrolytic deposition of zinc at the surface of the solution, J. Russ. Phys. Chem. Soc., **46,** pp. 909–934, J. Chem. Soc. (London), Abst., **108,**(2) p. 312; 1915. Chem. Abs., pp. 3031; 1915.
16	1913	Marc, R., The influence of colloid additions upon the cathodic and anodic processes in the electrolysis of metal salt solutions (lead and zinc), Z. Elektrochem., **19,** pp. 431–444.
17	1910	Freundlich, H., Novikow, W., The electrolytic formation of zinc films at surfaces, Z. Elektrochem., **16,** p. 394.

(b) CORROSION OF ZINC

The rather complete summary of the technical literature relating to the corrosion-resistance of zinc published by the American Zinc Institute (13) has been used as a basis for the following brief résumé of the subject. For more complete details, this report should be consulted.

The corrosion of zinc under ordinary circumstances, is electrochemical in nature. It takes place readily in water which is free from dissolved oxygen, with the liberation of hydrogen gas except near the freezing point of water (12). According to Evans (13) the electrochemical nature of the corrosion of such metals as zinc, cadmium, iron, and lead in a solution, such as potassium chloride and in the presence of oxygen, manifests itself in four ways: (*a*) The production of an electric current; (*b*) the production of a soluble metallic salt (zinc chloride) at the anodic (unaerated) areas; (*c*) the production of alkali (potassium hydroxide) at the cathodic (aerated) areas; and (*d*) the precipitation of an insoluble hydroxide (zinc hydroxide) as the products from the cathodic and anodic areas meet. Evans states that "it has been proved qualitatively that electrochemical corrosion does occur when zinc is exposed to potassium chloride solutions in the presence of oxygen," and states further that "under the conditions of his experiments at least 61 per cent of the total corrosion was electrochemical."

It is quite generally recognized that impurities in zinc affect its behavior under corrosive conditions. Smithell (1), in commenting on the numerous contradictory statements in the technical literature concerning the corrosion-resistance as well as other properties of zinc, has emphasized the importance of a knowledge of the purity of the metal used. Impurities existing as distinct phases rather than in solid solution, in general, have a more pronounced effect. If the overvoltage of hydrogen on such impurities is lower than that on zinc, corrosion is accelerated. This is the case with copper, iron, and antimony. Lead and tin (1) retard initial corrosion owing to their presence partially in solid solution.

(1) Atmospheric Corrosion.—According to Cyr (22), "spectroscopically pure" zinc is very resistant to tarnishing upon atmospheric exposure. Specimens allowed to stand in the laboratory without any protection have been reported to retain the initial high luster for over two years. In moist air ordinary zinc becomes covered with a film consisting of a mixture of zinc oxide and carbonate. This protects the underlying metal, as it adheres strongly to the metal and is insoluble in water. Zinc is attacked in air containing SO_2, however, as the corrosion products are soluble. Zinc and its alloys with copper are not greatly affected by oxygen, either dry or moist, at ordinary temperatures (13). At temperatures above 180° C., the oxidation of zinc becomes marked, the effect of moist oxygen being different from that of dry oxygen.

Vernon (27) has reported upon the atmospheric corrosion of zinc in both indoor and outdoor exposure. In the indoor tests, in atmospheres described as "basement" and "tank house," he has shown that the relation between increase in weight, resulting from film formation, and duration of exposure is a linear one in both the "short-period" test (110 days) and the "long-period" test (1,300 days). The average rate of attack was 16.2 mg/dm^2/1,000 days (0.00398/dm^2/year) for the basement and 8.5 mg/dm^2/1,000 days (0.0031g/dm^2/year) for the tank house. The difference in rate was attributed to temperature variations rather than to humidity, which factor was believed to be the same within the limits of the conditions used. The microscopic characteristics of the surface film were interpreted as supporting the conclusion which would be inferred from the linear relationship between weight increment and time, that the film has a granular structure, and that diffusion of the atmosphere can take place through interstices of the film.

In the open-air exposure tests, carried out on the roof of the Royal School of Mines, S. Kensington, London, a determination was made of the "erosion" loss; that is, the amount of metal attacked and removed by the rain and the "surrosion" value; that is, the amount of metal attacked but remaining on the surface. The average erosion loss, determined by collecting and analyzing all the rain water which drained off the specimens in tests of 100 weeks' duration, was 0.60 g/dm^2. The average surrosion value was 0.089 g/dm^2, of which 0.035 g/dm^2 represented the metal content of the compounds in the film. The results are summarized in greater detail in Table 12.

Table 12.—*Results of open-air exposure tests of zinc* (*27*)

(Corrosion values after 100 weeks)

Condition of material[1]	Exposure of specimen	Erosion (E) metal removed in rain		Surrosion, nonmetalic portion of film		Surrosion (S') metalic portion of film		Total corrosion $E+S'$	
		g	*g/dm*^{2}	*g*	*g/dm*^{2}	*g*	*g/dm*^{2}	*g*	*g/dm*^{2}
H W	Vertical	1. 195	0. 597	0. 167	0. 083	0. 110	0. 055	1. 305	0. 652
H D	do	1. 095	. 547	. 042	. 021	. 027	. 013	1. 122	. 661
H B	do	1. 149	. 574	. 072	. 036	. 047	. 023	1. 196	. 598
A D	do	1. 158	. 579	. 126	. 063	. 083	. 041	1. 241	. 620
A B	do	1. 213	. 606	. 113	. 056	. 075	. 037	1. 288	. 644
A D	Horizontal	1. 392	. 696	. 125	. 062	. 082	. 041	1. 474	. 737

[1] H, hard rolled; A, annealed; W, surface as received; D, surface polished with fine emery (Hubert No. 1), B, surface polished, finished with 'mops' (buffs) to a bright mirror finish.

The following are the estimated mean values for the principal constituents as based upon the chemical analysis of the residual corrosion product, formed in 100 weeks' exposure:

	Per cent
Zinc carbonate	11. 2
Zinc sulphate (anhydrous)	18. 1
Zinc sulphide	18. 8
Zinc oxide and hydroxide and combined water, by difference	51. 9

The surface of sheet zinc and galvanized sheet in packs sometimes shows evidence of corrosion in the form of a white "bloom." While this is occasionally of a serious nature, it usually serves only to give an unsightly surface appearance. The attack can be explained on the basis of an "oxygen concentration cell" as discussed by U. R. Evans. The inner parts of the film space between the sheets are relatively inaccessible to air (oxygen) and become depleted in oxygen. These areas of low oxygen concentration, in the presence of condensed moisture, are anodic (corrodible) with respect to the outer portions where there is free access of oxygen. Another aspect of this form of corrosion has been observed on the underside of zinc roofs laid in close contact with building paper or sheathing if the humidity within the space beneath the roof is high. The use of an asphalt coated paper will prevent corrosion under such conditions (12).

(2) Corrosion in Water.—Bengough, Stuart, and Lee (29) studied the effect of water on cast zinc; spectroscopically pure zinc, as well as that containing about 0.005 per cent iron, 0.005 per cent lead, and a trace of cadmium were used. They found a measurable amount of corrosion even when the most highly purified zinc and water were used. Evidences of corrosion were usually seen within 24 hours after the metal was immersed. Spectroscopically pure zinc corroded quite as rapidly as Australian electrolytic zinc (0.005 Fe, 0.005 Pb, Cd trace) in $N/10,000$ KCl solution. One of their conclusions was that the method of preparing the surface had an important effect on rate and amount of corrosion. Comparison of results for turned specimens of highly purified spectroscopic zinc with those for electrolytic zinc showed that the influence of purification, within the limits of the experiment, was quite small relative to the influence of surface treatment.

Practically all investigators agree that distilled water has considerably more effect than ordinary tap water upon zinc. Heyn (13) has reported tests made by immersing zinc in distilled water as well as in other solutions. He claimed that the results, particularly with cement extract show that oxygen is necessary for continued attack, whereas Baylis (30) concluded that dissolved oxygen is not essential to the corrosion of zinc. According to Bengough and Stuart (13), "metallic zinc is corroded from four to six times as rapidly by stagnant distilled water as by sea water or by a 2.5 per cent sodium chloride solution, of which the latter two are excellent electrolytes."

After studying the attack of cast pure zinc by distilled water, Bengough (29) reported a relation between contraction cracks and the formation of corrosion pits. He suggested that surface cavities which may remain in zinc even after rolling may be responsible for localized corrosion. On the basis of his experiments with sodium chloride and with magnesium and potassium sulphate solutions, four types of corrosion were identified: (*a*) "Regional corrosion" at the lower part which becomes anodic to the part above, the sharp boundary separating the attacked and unattacked regions being usually horizontal and moving steadily upward; (*b*) "point corrosion" believed to be due to capillary channels opening onto the surface; (*c*) "line corrosion" along old scratch lines; and (*d*) "edge corrosion" along the cut edges of the specimens.

According to Isuardi (62) the attack of zinc in distilled water was only slightly manifested during the first 20 days. Later it increased at a remarkable rate. Of all the metals that he tested (lead, iron, copper, tin, and zinc), zinc was reported to show the highest degree of solubility.

On long exposure rain water attacks zinc probably because it contains carbon dioxide, ammonia, or other impurities. In industrial centers, rain water may often contain sulphur dioxide. Such water is especially severe on zinc. Zinc is readily attacked by carbon dioxide in aqueous solution. Haack (50) has stated that the presence of oxygen is not necessary for the corrosion of zinc by water containing CO_2. Bengough and May (13) have referred to "the remarkable effect the removal of carbon dioxide gas has on the action of sea water on zinc." They stated that "these results suggest that the hydroxide gives excellent protection against corrosion, but that it is liable to attack by dissolved carbon dioxide and conversion into carbonate, which definitely lessens the protective power of the product." The utility of zinc-plated pipe as compared with pipe coated by the hot galvanized process has been studied by Heyn and Bauer (52). According to their results, the electroplated coating was more strongly attacked than the other in distilled water. The tap water had an equal effect on both types of pipe. The presence of carbon dioxide and sulphur dioxide materially hastened the attack in both cases.

Very low concentrations of chlorine in the water supply tend to accelerate the dissolving of zinc from galvanized pipes and tanks. It is interesting to note that "once the process of active corrosion in a fairly new tank has been started by the use of chlorinated water, even raw water will continue the action at a rate much more rapid than would be expected" (13).

A review of the Seventh Report of the Committee on Corrosion to the Institute of Metals gives the following statement concerning the corrosion of zinc (13): "The corrosion of zinc in sea water was found to result in a product consisting mainly of carbonate, hydroxide, and oxychloride; very little soluble zinc chloride diffused away from the metal." The report further states that the oxychloride probably contributes to the protective properties of the scale, and that zinc hydroxide exerts important protective action on zinc even in rapidly flowing water.

Zinc may be used as a protection against corrosion fatigue. It has been reported (5) that zinc surfaces, such as sherardized, galvanized, and electroplated coatings, prevent for a time any of the water of a stream, applied simultaneously with repeated stresses, from reaching the surface of the underlying steel. Thus, the damaging effect of combined stress and corrosion on steel can be prevented or at least delayed. Electroplated specimens were reported to have the same fatigue limit regardless of whether the endurance test was carried out in water or in air. When suitably coated, the fatigue limit of a metal in water will usually range from 40 to 50 per cent of the tensile strength. Hard, brittle, intermetallic compounds which occur in galvanized and sherardized coatings are reported to contribute to premature failure.

The degree of toxicity of zinc in waters is uncertain. However, it has been reported that, when storage of water in zinc-lined tanks is necessary for some time, the addition of large amounts of chalk to the sources supplying the reservoirs (leading to a crust of insoluble carbonate) may be considered advisable (46).

(3) CORROSION IN ACIDS.—*Hydrochloric acid.*—Centnerszwer and Sachs (56) state that etched zinc is more rapidly soluble in hydrochloric acid than smooth zinc, and that zinc which has shown the maximum rate of solution in 2 *N* hydrochloric acid dissolves with decreased velocity in fresh or renewed acid. The rate of solution increases more rapidly than the acid concentration. Pure zinc in a normal state is somewhat passive and under the influence of the solution process only gradually becomes more active (13). Thus, the solution velocity depends on the state, active or passive, of the zinc. The metal may be activated mechanically by means of emery paper. Watts and Whipple (54a) have reported on the effect of oxidizing agents on the corrosion of amalgamated zinc in hydrochloric acid. Specimens of unprotected zinc which dissolved rapidly in hydrochloric acid did not do so in the presence of mercuric chloride. In this case, although the zinc went into solution appreciably, it was displaced by metallic mercury which amalgamated with the remaining zinc. Amalgamation of the zinc did not completely stop corrosion when immersed in hydrochloric acid. When both mercuric chloride and an oxidizing agent were present, the effect was quite similar to that when amalgamated zinc was corroded in an acid solution in the presence of an oxidizing agent.

Nitric acid.—Zinc is readily soluble in nitric acid (13). The velocity of solution of zinc in nitric acid increases regularly with increasing concentration of acid below 25 per cent. It remains approximately constant for concentrations between 33 and 42 per cent, and then diminishes regularly to a minimum value at 68 per cent.

Stansbie (13, 64) has described the reaction of zinc and other metals with nitric acid and has given particular consideration to the mechanism of the reaction and the factors which influence it. A series of copper-zinc alloys (sifted filings), with percentages of zinc of from 0 to 100 per cent were dissolved in dilute nitric acid (specific gravity 1.149) at a temperature of 65° C. The results indicated that as the content of zinc increased, less nitrous acid and more ammonia were formed during the reaction.

Sulphuric acid.—Strong sulphuric acid (95 per cent) exerts no action on zinc until a high temperature is reached. As the acid is made more dilute the action commences at lower temperatures with the evolution of hydrogen either alone or with traces of hydrogen sulphide. The early work of Pullinger (1890, J. Chem. Soc.) on the corrosion of zinc which had been distilled three times and cast into spheres, lead to the following conclusions:

Pure zinc with a perfectly smooth surface was not acted upon by dilute sulphuric acid which had been subjected to prolonged boiling. If the surface had been given a preliminary roughening, however, the metal was readily acted upon, but to a less degree by acid which had been boiled than by those which had not. Oxidizing agents, such as hydrogen peroxide and nitric acid, increased the rate of dissolution.

A reducing agent, such as hydriodic acid, almost entirely prevented any action, but those containing sulphur, such as sulphur dioxide, were without inhibiting effect. It has been suggested that when zinc with a rough surface dissolves in dilute sulphuric acid, persulphuric acid acting catalytically is the cause of the action. If so, pure dilute sulphuric acid would, at ordinary temperatures, be entirely without action upon pure metallic zinc whether the surface of the latter were smooth or rough.

Zinc of very high purity, "spectroscopically pure," has a very high resistance to corrosion in acids. According to Cyr (22), zinc of this kind immersed in a 10 per cent solution of hydrochloric acid, lost only 0.02 per cent by weight, whereas "commercial high-grade zinc" was completely dissolved in the same time (three hours) and "chemically pure zinc" lost 53 per cent of its original mass. Sulphuric acid is somewhat slower in its attack of the "spectroscopically pure" zinc than is hydrochloric acid. Nitric acid was found to attack this zinc very much faster than it did the comparison samples of commercial zinc.

Zinc is inert to gasoline, kerosene, oil, and grease (12). It is entirely inert toward anhydrous alcohol, but is oxidized by mixtures of alcohol and water.

(4) Attack by Miscellaneous Chemicals.—The general action of a number of common solutions and chemical reagents is summarized in Table 13.

Table 13.—*Chemical attack upon zinc* (*13*)

Severe attack		Slight attack	No attack
Acetic acid.	Hydrogen sulphide.	Ammonium hydroxide, hot.	Acetylene.
Ammonia gas (600° C.).	Lactic acid.	Ammonium nitrite.	Alcohol (anhydrous).
Ammonium arsenate, hot.	Magnesium chloride.	Ammonium persulphate.	Chlorine (dry).
Ammonium chloride.	Malic acid.	Calcium chloride.	Dichlormethyl-arsine, ether soluble.
Ammonium phosphate.	Hydrofluosilicic acid.	Ferric chloride.	Formaldehyde.
Benzaldehyde.	Nitrobenzene (in acid solutions).	Iodine vapor.	Hydrocyanic acid(pure liquid).
Benzoic acid vapor (250° C.).	Nitrosyl chloride.	Oxalic acid.	Sulphuryl chloride.
Calcium carbonate (in cement).	Phosphoric acid.	Phenols (in crude tar oils).	Thionyl chloride.
Calcium bicarbonate.	Picric acid.	Sodium nitrate.	
Calcium hydroxide.	Potassium chloride.	Sodium polysulphide.	
Calcium sulphate (moist or in solution).	Potassium dichromate.	Sulphides.	
Cement extract.	Potassium nitrate.	Sulphur chloride.	
Chlorine (only partly dried).	Potassium sulphate.		
Citric acid.	Sodium acetate.		
Cupric salt solution.	Sodium carbonate.		
Dichlormethyl-arsine (+ water).	Sodium chloride.		
Flammon (HF+ ammonium fluoride).	Sodium hydroxide.		
Formic acid.	Sulphur dioxide.		
Hydrochloric acid.			

(c) EFFECT OF IMPURITIES

The effects of the additions of small amounts of iron, lead, cadmium, calcium, or antimony on the corrosion of zinc in an indoor saturated atmosphere are not pronounced (23). Lead has been reported to

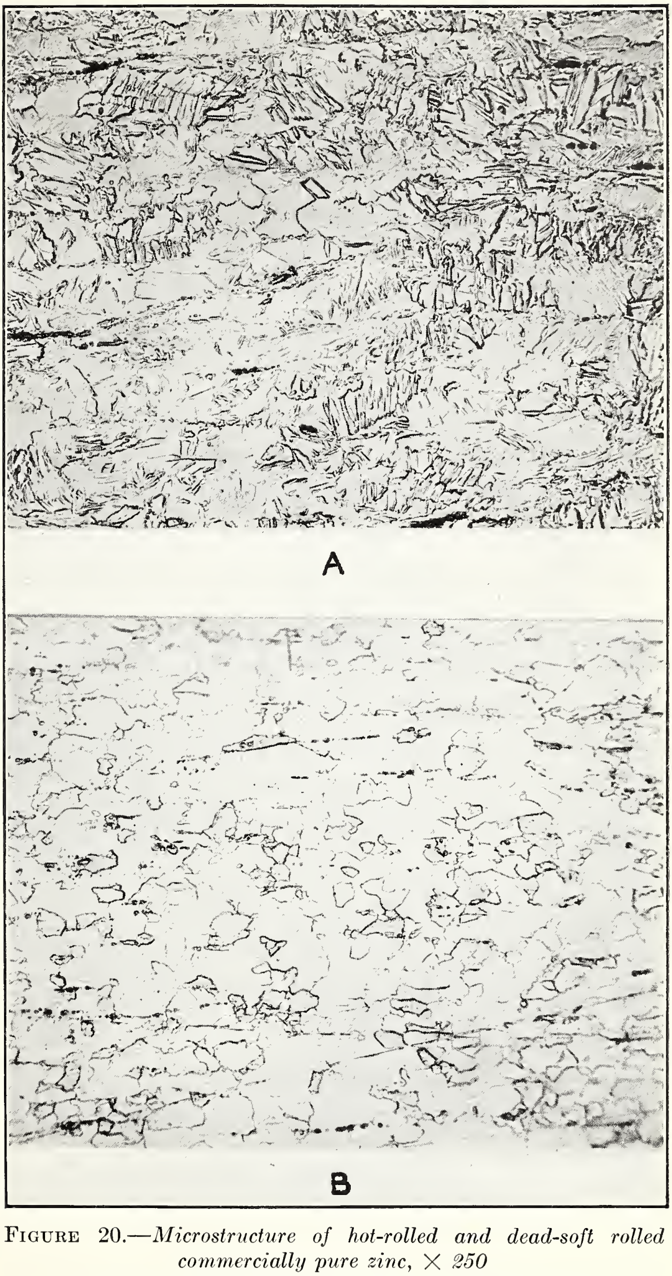


FIGURE 20.—*Microstructure of hot-rolled and dead-soft rolled commercially pure zinc,* × *250*

A, Hot rolled; *B,* dead-soft rolled strip. Etched with a solution containing 20 g chromic acid (CrO_3) and 1.5 g sodium sulphate to 100 ml of water.

FIGURE 21.—*Microstructure of commercial drawn zinc, battery cup, × 500*

Etched as in Figure 20.

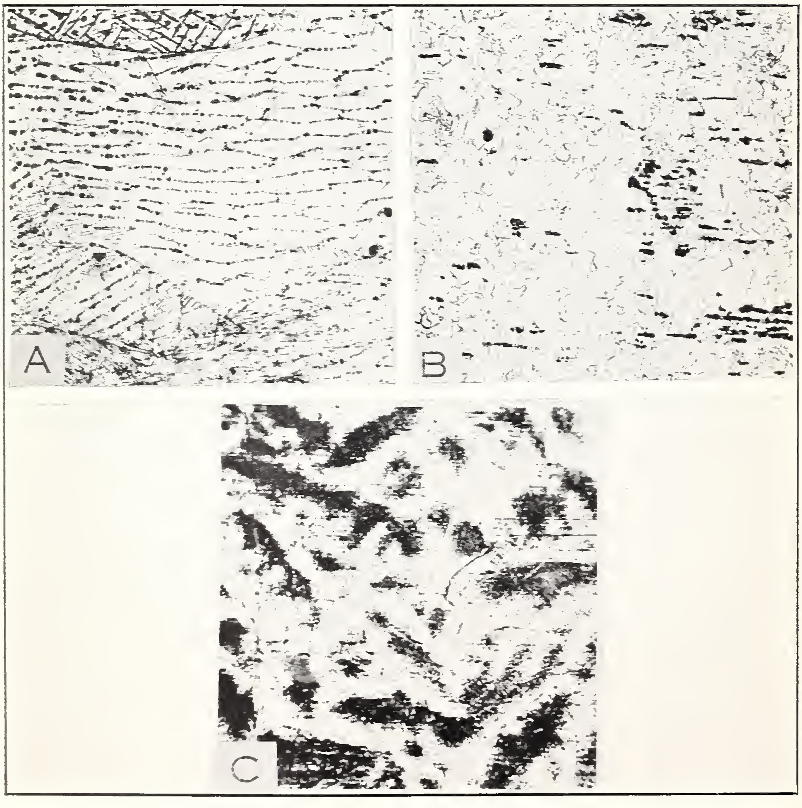


FIGURE 23.—*Effect of small amounts of lead and cadmium on the microstructure of cast zinc*

A, Lead droplets along grain boundaries, × 100; *B*, same after rolling, the lead appears as streaks; *C*, zonal structure in cast zinc containing 1.25 per cent cadmium, × 150. Etched as in Figure 20.

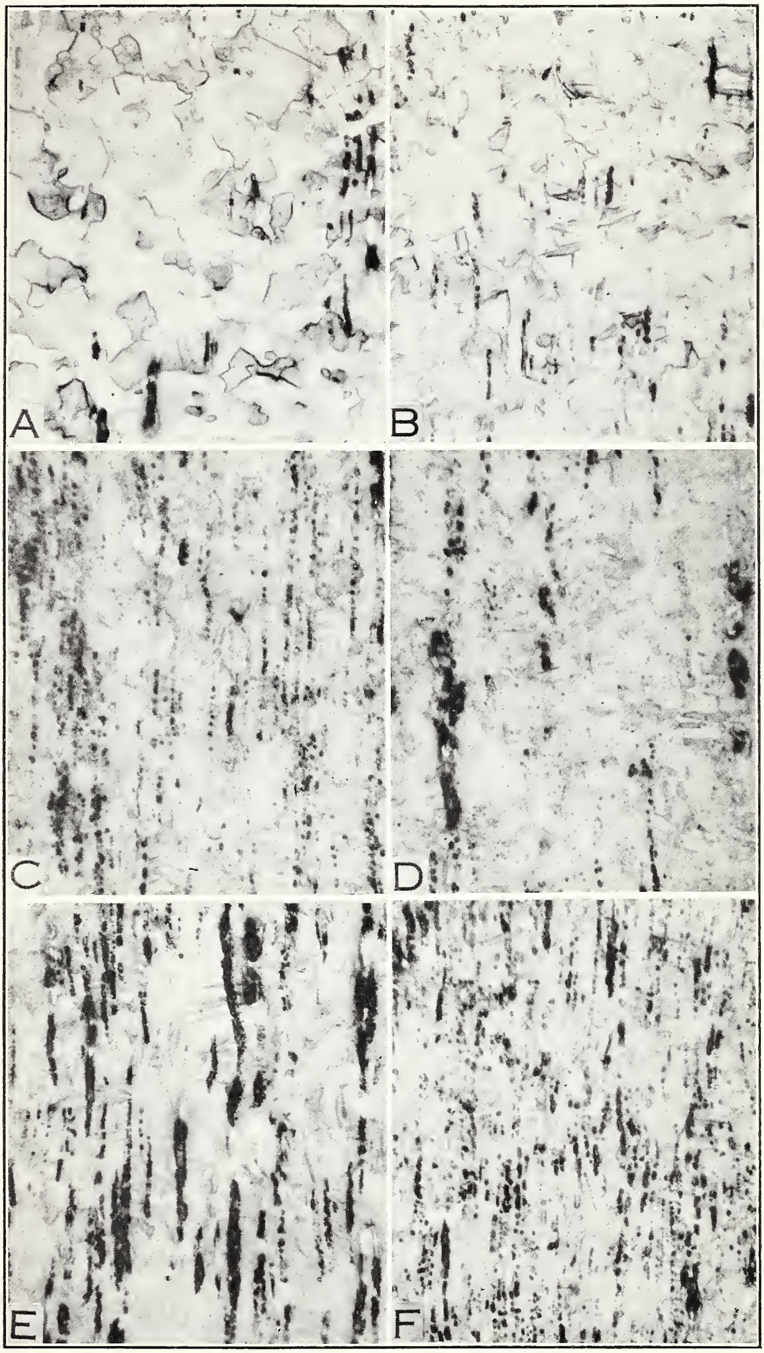


Figure 22.—*Microstructure of three grades of commercial sheet zinc in two conditions of temper, × 250. (Micrographs made by Research Department, The New Jersey Zinc Co.)*

A, B, High-grade zinc of soft and medium temper, respectively; *C, D,* intermediate-grade zinc of soft and medium temper, respectively; *E, F,* high-lead zinc of soft and medium temper, respectively. Etched as in Figure 20.

have a slight protective action. In outdoor exposure the effect of some of the above impurities may be pronounced. Lead affords some measure of protection, while copper or antimony accelerates the corrosion. An antimony content of only 0.07 per cent is said to be unfavorable. The evidence as to the effect of arsenic is not clear. Conflicting statements have been made on this point. Cadmium and iron do not influence the attack to any appreciable extent (23). The effect of the impurities, with the exception of iron, appears to be in line with the results obtained on the corrosion of zinc in dilute acid solutions. It may be concluded that during the winter period, when the surface of the zinc is washed with acid rain water, the corrosion is to some extent of this type. After more prolonged exposure, the

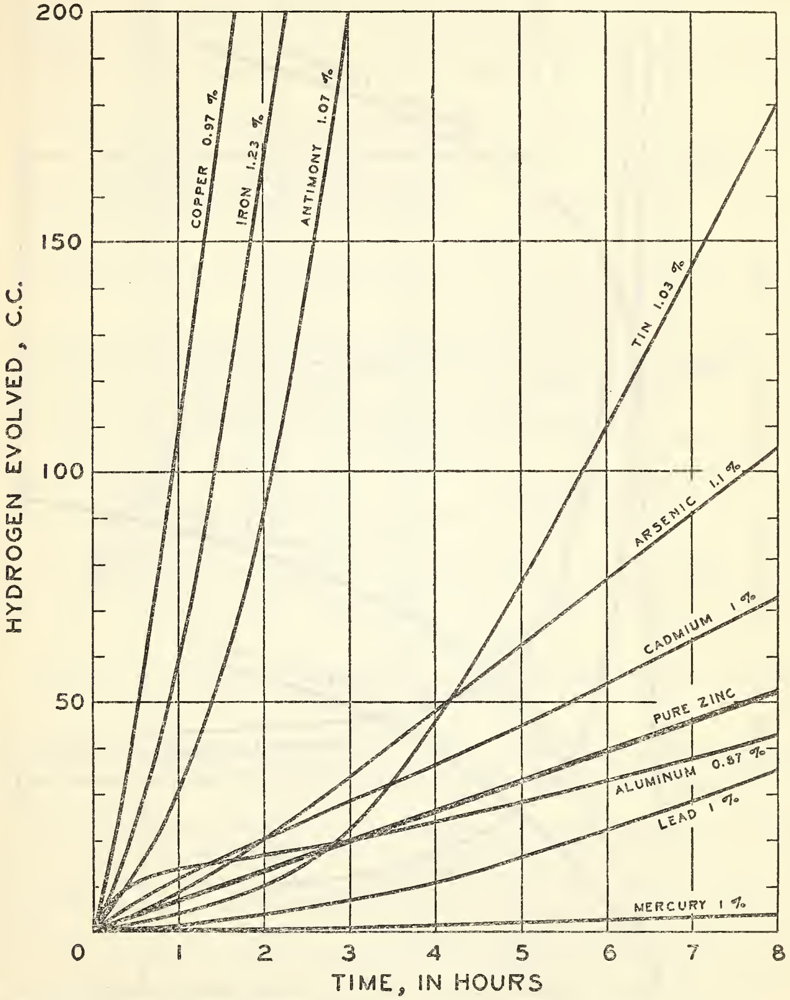


FIGURE 24.—*Effect of added elements on the rate of attack of zinc by N/2 sulphuric acid*

effect of the impurities may diminish owing to the accumulation of the corrosion products.

The effect of impurities on the chemical attack of zinc when immersed in dilute acids and other dilute solutions, particularly chlorides, has been studied by a number of investigators. The results of the work of Prost (59), of Vondracek and Izak-Krizko (33) and of Patterson (23) are outstanding in this field. The general character of the results is shown in Figures 24 and 25, as given by Smithell (1).

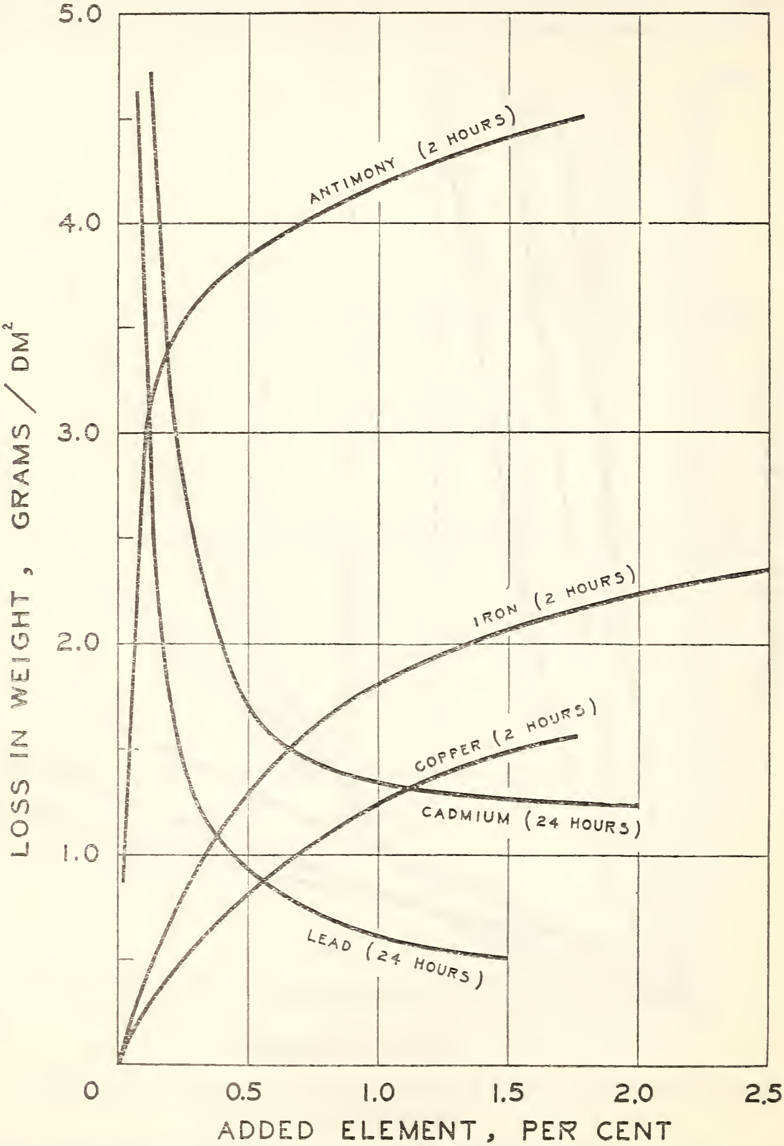
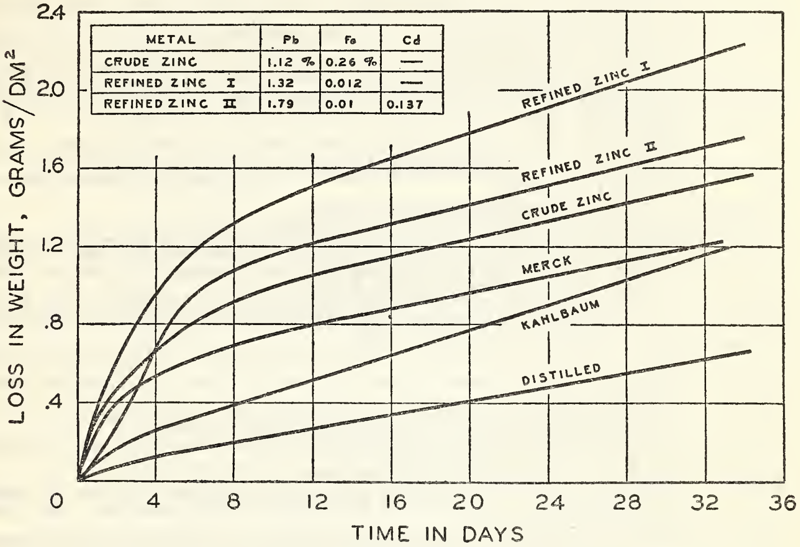


Figure 25.—*Effect of the amount of added elements on the rate of attack of zinc by 0.5 per cent sulphuric acid*

The results recently reported by Harris (4) are in general agreement with these. Harris found that the rate of attack of zinc (99.992 per cent) by a 20 per cent solution of sulphuric acid was accelerated decidedly by additions of copper, iron, and antimony. Additions of cadmium and lead had only a small effect and the addition of aluminum was practically without effect. Harris also reported on the effect of colloids present in the acid. Gelatin had a marked inhibitive effect, whereas sodium silicate had practically none.

Results obtained by Drucker (39) on the effect of an ammonium chloride solution on zinc of various degrees of purity are summarized in Figure 26 as given by Smithell. These results have a direct bearing on the life of the zinc element in a primary battery of the Leblanche type.



METAL	Pb	Fe	Cd
CRUDE ZINC	1.12 %	0.26 %	—
REFINED ZINC I	1.32	0.012	—
REFINED ZINC II	1.79	0.01	0.137

FIGURE 26.—*Rate of solution of various grades of zinc in 10 per cent solution of ammonium chloride*

Prost (59) reported as a result of experiments in a solution containing 5 per cent sodium chloride at room temperature over a period of 18 days, the solution being aerated twice during that period, that samples of zinc containing varying amounts of lead, iron, cadmium, arsenic, antimony, tin, and copper were uniformly corroded. This uniformity of action was possibly due to a protective coating of hydrated zinc oxide which was found to cover each of the plates when it was withdrawn from the solution.

Corrosion

Text reference	Year	Name and title
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(d) CHEMICAL ANALYSIS OF ZINC

The analytical methods in widest use are those of the American Society for Testing Materials.

The usual impurities in virgin zinc (spelter) are lead, iron, cadmium, and arsenic. In recovered metal, bismuth, copper, aluminum, tin, etc., may also occur.

In the analysis of zinc the weight of samples taken should vary with the content of impurities, from 10 grams for low-grade material to 500 grams or more for the higher grades.

The usual procedure in analysis is to treat the sample with a quantity of acid (usually hydrochloric) which is insufficient to dissolve the entire sample, a gram or more being left undissolved. As a rule this undissolved material contains all the lead, cadmium, tin, copper, and part of the other metals in part. The undissolved matter is dissolved in nitric acid and the analysis then completed according to well-known methods.

If small amounts of aluminum, iron, tin, and bismuth are to be tested for, the sample is completely dissolved in hydrochloric acid, and sodium hydroxide is added until a faint turbidity persists after vigorous stirring. After diluting with hot water, a 10 per cent emulsion of magnesium oxide is added in excess, and the solution is kept near the boiling point for 10 to 15 minutes. The precipitate is filtered off, and the separations are made according to established methods.

Zinc dust is evaluated by collecting the hydrogen evolved when a sample is treated with acid, or by dissolving a sample in an acid solution of ferric ammonium sulphate and titrating the ferrous iron thus formed.

The methods of analysis for zinc-base die-casting alloys differ somewhat from those for "spelter." Copper and lead may be separated and determined directly from a solution of the sample in nitric acid. If tin is present it should be filtered off prior to electrolysis for copper and lead; the filter and precipitate are placed in a Kjeldahl flask, decomposed with potassium sulphate and sulphuric acid, diluted, reduced, and titrated with iodine. Aluminum is usually determined on a separate sample. Magnesium is precipitated as phosphate, in the presence of zinc, by adding enough ammonia to keep the zinc dissolved.

(e) TOXICITY

The following opinion on the toxicity of zinc in amounts such as might occur in foods and drinking water has been expressed in a communication to this bureau from the United States Public Health Service:

> *September 6, 1928.*
>
> Inasmuch as zinc is an amphoteric substance it can form two types of compounds. Those compounds, such as zinc chloride or zinc lactate, are formed by the action of an acid medium upon metallic zinc, while those of the type sodium zincate are formed by the action of an alkaline medium.
>
> There is little likelihood that the latter type of compound would be formed by the action of milk or its products upon zinc containers. However, if milk or its products are permitted to come in contact with zinc under conditions which permit souring, compounds, such as zinc lactate, may occur. Moreover, zinc may combine with proteins or free fatty acids.
>
> Zinc salts are generally regarded as being too poorly absorbed from the intestinal tract to produce systemic effects on oral administration (20). This would particularly apply to combinations of zinc with protein or free fatty acids.
>
> There is no doubt about the ability of man to consume small quantities of zinc without apparent deleterious effects. Zinc is present in oysters from the Atlantic Ocean, and in eggs, and in milk it occurs to the extent of about 4 milligrams per quart.
>
> However, zinc is freely soluble in all acids, even water containing carbon dioxide. It has, therefore, been stated that "no zinc or zinc-coated vessel should be used in cooking, nor storing foods that are acid or liable to acid fermentation, lest zinc salts be formed and swallowed in amounts sufficient to irritate the alimentary mucosa" (21).

It should be noted that the statements above refer to zinc taken into the alimentary tract and not to the effects of "zinc" fumes from metallurgical furnaces, etc.

Practically all recorded cases of deaths or active poisoning due to zinc have involved either the chloride or the sulphate, the former being a pronounced caustic, the latter an irritant (13). The argument has been advanced that effects attributed to zinc may in reality be due to lead, cadmium, arsenic, or antimony accompanying zinc from its ores (4, 13).

Toxicity

Text reference	Year	Name and title
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5. PHYSICAL PROPERTIES

(a) ATOMIC PROPERTIES

(1) Atomic Number.—The position of zinc in the period table of the chemical elements is in Group II and in the last half of the fourth period, the first "long" period. Its atomic number is 30. The 30 negative electrons contained are distributed in four shells in order as follows: K, 2; L, 8; M, 18; N, 2, the last being the outermost orbit containing the "valence" electrons.

(2) Atomic Weight, Isotopes.—Values for the atomic weight of zinc (ranging from 65.1066 to 65.44) have been reported by various investigators. The value, 65.38, is now generally accepted, however, for the atomic weight of zinc (5).

Four isotopes of zinc have been identified, the mass numbers of which are 64, 66, 68, and 70 (6, 10).

Atomic weight, isotopes, electrons

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15	1922	Aston, F. W., List of elements and their isotopes, Proc. Phys. Soc. Lond., **34,** p. 197; Chem. Abst., **16,** p. 3253; J. Inst. Metals, **33,** 1925, p. 399.
16	1922	Egerton, A. C., Separation of the isotopes of zinc, Nature, **110,** p. 773; J. Inst. Metals, **29,** p. 683.
17	1921	Baxter, G. P., Hodges, J. H., A revision of the atomic weight of zinc, II. The electrolytic determination of zinc in zinc chloride, J. Am. Chem. Soc., **43,** (1) pp. 1242–1251; Chem. Abst., **15,** p. 3919.
18	1921	Block, L. & E., Spark spectra of zinc, cadmium and lead in the ultra violet, Comptes. Rendus, **172,** p. 803.
19	1921	Walters, F. M., Wave length measurements in arc spectra photographed in the yellow, red, and infra-red, B. S. Sci. Papers No. 411, **17,** p. 161.
20	1920	Lawyer, R. A., The vacuum hot-spark spectrum of zinc in the extreme ultra-violet region. Astrophysical J., **52,** p. 286.
21	1918	Tate, J. T., Foote, P. D., Resonance and ionization potentials for electrons in metallic vapors, Phil. Mag., **36,** pp. 64–76; Chem. Abst., **12,** p. 1943.
22	1916	Baxter, G. P., Grose, M. R., Revision of the atomic weight of zinc, Electrolytic determination of zinc in zinc bromide, J. Am. Chem. Soc., **38,** (1) pp. 868–873; Chem. Abst., **10,** p. 1122.
23	1915	McLennan, J. C., Henderson, J. P., Ionization potentials of mercury, cadmium, and zinc and the single- and many-lined spectra of these elements, Proc. Roy. Soc., Lond., **91a,** pp. 485–491; Chem. Abst., **9,** p. 3155.

(3) SPECTRA.—The complete emission spectrum of zinc consists of several hundred lines, but only a few of the stronger ones are important for spectrochemical analysis. The most sensitive line (raie ultime) for the detection of zinc in arc spectra has a wave length of 2,138.5 A; it is the principal resonance line of neutral zinc atoms and can be found in the spectrum of substances containing less than 0.001 per cent zinc. However, on account of being so far in the ultraviolet where the efficiency of ordinary photographic plates is low, this line is not easy to observe, so that for practical work a group of lines near 3,300 A is more generally referred to. The wave lengths of these lines is 3,282.28, 3,302.53, and 3,344.99 A. The last is the strongest and will reveal zinc when present to about 0.01 per cent. The most sensitive zinc lines in the visible spectrum are at 4,680.20, 4,722.16, and 4,810.53 A, but these are only visible if the concentration of zinc is of the order of 1 per cent or more.

In spark spectra (high potential condensed discharges) the most persistent lines are probably the resonance lines of ionized zinc atoms with wave lengths at 2,025.5 and 2,061.9 A, but since these are too far in the ultra-violet to be recorded easily, other lines are usually looked for. It has been established empirically that the above-mentioned arc spectrum lines are also persistent in spark spectrograms.

Spectra, etc.

Text reference	Year	Name and title
1	1927	Fukuda, M., Reversed spectra of metals produced by explosion under increased pressure, Sci. Papers Inst. Phys. Chem. Res. Tokyo, **6**, pp. 1–47; Chem. Abst., **22**, 1928, p. 729.
2	1926	——, On the new lines of zinc, cadmium, and mercury, Sci. Papers Inst. Phys. Chem. Res. Tokyo, No. 55, pp. 171–176; J. Inst. Metals, **37**, 1927, p. 546.
3	1926	Fujioka, Y., Effect of electric field on the spectral lines of zinc and cadmium, Sci. Papers Inst. Phys. Chem. Res. Tokyo, No. 68, pp. 45–53; J. Inst. Metals, **37**, 1927, p. 546.
4	1926	Pfestorf, G., The determination of the optical constants of metals in the visible and ultraviolet part of the spectrum, Ann. Physik., **81**, IV, pp. 906–928; J. Inst. Metals, **37**, 1927, p. 429.
5	1926	Sawyer, R. A., Beese, N. C., New terms in the spectra of zinc and mercury, Science, **64**, pp. 44–46; J. Inst. Metals, **37**, 1927, p. 547.
6	1926	Smith, D. M., The spectrum of zinc, Nature, **118**, p. 592; J. Inst. Metals, **37**, 1927, p. 546.
7	1926	Wood, R. W., Structure of cadmium and zinc resonance lines, Phil. Mag., **2**, VII, pp. 611–612; J. Inst. Metals, **37**, 1927, p. 535.
8	1925	Von Salis, G., The primary arc spectrum of zinc and cadmium, Ann. Physik. **76**, IV, pp. 145–162; J. Inst. Metals, **33**, p. 407; Chem. Abst., **19**, p. 1226.
9	1925	Winans, J. G., Radiation emitted by optically excited zinc vapour, Proc. Nat. Acad. Sci., **11**, pp. 738–742; J. Inst. Metals, **37**, 1927, p. 546.
10	1924	Ahmad, N., The absorption of hard gamma rays by elements, Proc. Roy. Soc. London, **105a**, pp. 507–519; Chem. Abst., **18**, p. 2106.
11	1924	Harris, R. E., Pole effects and pressure shifts in the lines of the spectra of zinc and calcium. Astrophys. J., **59**, pp. 261–273; Chem. Abst., **18**, p. 3005; J. Inst. Metals, **33**, 1925, p. 407.
12	1923	Hutchinson, R. O., Arc and spark spectra of aluminum, zinc, and carbon in the extreme ultra-violet, Astrophys. J., **58**, p. 290–293; Chem. Abst., **18**, 1924, p. 786; J. Inst. Metals, **31**, 1924, p. 458.
13	1923	Wood, R. W., Vacuum grating spectrograph and the zinc spectrum, Phil. Mag., **46**, VI, pp. 741–750; J. Inst. Metals, **31**, 1924, p. 456.
14	1918–1919	Dearle, R. C., Emission and absorption in the infra-red spectra of mercury, zinc, and cadmium, Proc. Roy. Soc. London, **95A**, pp. 280–299; Chem. Abst., **13**, p. 1559.
15	1918	Tate, J. T., Foote, P. D., Resonance and ionization potentials for electrons in metallic vapors, Phil. Mag., **36**, pp. 64–75; Chem. Abst., **12**, p. 1943.
16	1915	McLennan, J. C., Edwards, E., The absorption of spectra of mercury, cadmium, and zinc vapors, Phil. Mag., **30**, pp. 695–700; Chem. Abst., **10**, 1916, p. 12.
17	1914	McLennan, J. C., On the absorption spectrum of zinc vapor, Phil. Mag., **28**, pp. 360–363; Chem. Abst., **8**, p. 3747.
17a	1912	Kayser, H. S. J., "Handbuch der Spectroscopie."
18	1909	Paschen, F., Infra-red spectra of thallium, aluminum, zinc, cadmium, mercury, and calcium, Ann. Physik., **29**, pp. 625–663, Chem. Abst., **3**, p. 2525.
19	1909	Paschen, F., System series in the spectra of zinc, cadmium, and mercury, Ann. Physik., **30** (4), pp. 746–754; J. Chem. Soc., **98A**, 1910, p. 3; Chem. Abst., **4**, 1910, p. 540.

(4) CRYSTAL LATTICE.—Although previously discussed (sec. 3, Metallography), the following data are repeated here for convenience in reference.

The crystal lattice of zinc is of the close-packed hexagonal type. (Fig. 12.) Measurements made at this bureau on spectroscopically pure zinc showed the nearest distance between atoms in the basal plane, to be 2.65 A (1 A $=10^{-8}$ cm) and c, the "height" of the unit hexagonal cell, 4.93 A. The values are in good agreement with those obtained by Peirce, Anderson, and Van Dyck (4), who used zinc of higher purity (99.993 per cent) than was available at the time of Hull's earlier work (1). Peirce and his coworkers reported the following values: $a=2.657$ A, $c=4.948$ A, $c/a=1.862$, and the nearest distance between atoms in the pyramidal planes as 2.903 A.

Crystal lattice of zinc

Text reference	Year	Name and title
1	1921	Hull, A. W., X-ray crystal analysis of thirteen common metals, Phys. Rev., **17**, pp. 571–588.
2	1923	Wyckoff, R. W. G., A survey of existing crystal structures data, J. Frank. Inst., **195**, pp. 183–210.
3	1925	Freeman, J. R., Sillers, F., Brandt, P. F., Pure zinc at normal and elevated temperatures, B. S. Sci. Paper No. 522.
4	1925	Peirce, W. M., Anderson, E. A., Van Dyck, P., An investigation of the alleged allotropy of zinc and a redetermination of the zinc lattice, J. Frank. Inst., **200**, pp. 349–361.

(5) ALLOTROPY.—Transformation points indicating the existence of allotropic modifications of zinc have been reported variously as occurring at 350°, 330°, 320°, 304°, 170°, and 160°, the usual statement being that there are three allotropic forms existing at different temperatures as follows: α-zinc up to 170° C.; β-zinc, 170° to 330° C.; γ-zinc, 330° to 419° C.

On the other hand, Stockdale (8) and Van de Putte and Thyssen (5) concluded a number of years ago that zinc exists in only one form and Benedicks and Arpi (17) found that distilled Kahlbaum zinc gave curves which are only very slightly convex. They interpreted the breaks occurring with other zincs as being the result of impurities. An investigation at the National Bureau of Standards led to the conclusion that zinc of high purity exists in but one crystalline form (6), on the basic assumption that an allotropic change is accompanied by a change in crystal structure. This zinc contained 0.001 per cent lead, 0.003 per cent cadmium, 0.003 per cent iron, less than 0.00001 per cent arsenic and copper; tin and antimony could not be detected. Peirce, Anderson, and Van Dyck (7) investigated the alleged allotropy of zinc by X-ray methods. Their results disclosed no change in structure between 20° to 400° C. It is quite possible that the small variations in such properties as thermal emf., electrical resistivity (p. 60), etc., noted by proponents of the allotropy theory, were the result of impurities, perhaps certain impurities not ordinarily looked for in analyzing zinc.

Figure 27 from Schulze (10) illustrates the marked peak observed in the electrical resistance curve of a sample of commercial zinc as compared with the smooth curve obtained with zinc of high purity. As Schulze points out, such an effect observed in only a single material may readily give rise to the conclusion that the material possesses allotropy, whereas the more logical conclusion based on the examination of several materials is that impurities in the first material are responsible for the observed effect.

Allotropy

Text reference	Year	Name and title
1	1929	Guertler, W., Anastasiadis, L., On the polymorphy of zinc, Z. Metallkunde, **21**, p. 338.
2	1929	N. J. Zinc Co., Rolled zinc, Research bulletin.
3	1927	Petrenko, G. J., On the polymorphism of zinc, Z. Anorg. Chem., **162**, pp. 251–252; J. Inst. Metals., **38**, p. 385.
4	1927	Petrenko, G. J., On the transformation point of zinc at 175° C., **7**. Anorg. Chem., **167**, p. 411–412; J. Inst. Metals, **29**, 1928, p. 466; Chem. Abst., **22**, 1928, p. 755.
5	1927	Van de Putte, M., Thyssen, H., Supposed allotropy of zinc, Rev. Univ. Mines, **14** (7), pp. 49–57; Chem. Abst., **22**, 1928, p. 2500; J. Inst. Metals, **38**, p. 385.
6	1926	Freeman, J. R., jr., Sillers, F., Brandt, P., Pure zinc at normal and elevated temperatures, B. S. Sci. Paper No. 522.
7	1925	Peirce, W. M., Anderson, E. A., Van Dyck, P., An investigation of the alleged allotropy of zinc by X-ray analysis and a redetermination of the zinc lattice, J. Frank. Inst., **200**, p. 349.
8	1925	Stockdale, D., Allotropy of zinc, J. Chem. Soc., **127**, pp.2951–2956; Science Abst., **29a**, 1926, p. 278; Chem. Abst., **20**, 1926 p. 1344.
9	1925	Editorial, Is zinc allotropic? Metallurgist, November 27, pp. 172–173.
10	1924	Schulze, A., The electrical conductivity of metals, Z. Metallkunde, **16**, pp. 48–54.
11	1923	Losana, L., Upon the allotropy of zinc, Gazz. Chim. Ital., **53**, pp. 539–545; J. Inst. Metals, **30**, p. 438; Chem. Abst., **18**, 1924, p. 347.
12	1920	Bingham, K. E., Allotropy of zinc, J. Inst. Metals, **24**, pp. 333–353; Chem. Abst., **14**, p. 3341.
13	1920	Cohen, E., Bruins, H. R., The metastability of the metals as a result of allotropy and its bearings on chemistry, physics, and the arts,IV, Z. Phys. Chem., **94**, pp. 443–449; Chem. Abst., **14**, p. 2434.
14	1920	Cohen, E., Moesveld, A. L. T., Metastability of the metal world as a consequence of allotropy and its significance for chemistry, physics, and technics, VI, Verslag Akad. Wetenschappen Amsterdam, **28**, pp. 762–766; Chem. Abst., **15**, 1921, p. 3236.

Allotropy—Continued

Text reference	Year	Name and title
15	1919	Lastschenko, M. P., The polymorphism of zinc, Z. Metallkunde, **10,** pp. 253–255; Chem. Abst., **14,** 1920, p. 669.
16	1915	Janecke, E., The transition of the metals tin, zinc, bismuth, cadmium, copper, silver, lead, and antimony determined by means of the new electrically heated pressure apparatus, Z. Physik. Chem., **90,** pp. 313–349; Chem. Abst., **10,** 1916, p. 143.
17	1914	Benedicks, C., Arpi, R., Alleged allotropy of zinc, Z. Anorg. Chem., **88,** pp. 237–254; Chem. Abst., **9,** 1915, p. 260.
18	1914	Cohen, E., Helderman, W. D., The allotropy of zinc, Verslag. Akad. Wetenschappen Amsterdam, **23,** pp. 546–550; Chem. Abst., **9,** 1915, p. 1267; also **22,** p. 532, C. A. 8, pp. 1038, 2515.
19	1913	Werner, M., On the changes of properties in the polymorphic transformations of Tl, Sn, Zn, and Ni, Z. Anorg. Chem., **83,** pp. 275–321.
20	1910	Benedicks, C., Allotropic change in zinc, Metallurgie, **7,** pp. 531–537; J. Inst. Metals, **4,** p. 301; Chem. Abst., **5,** 1911, p. 59.

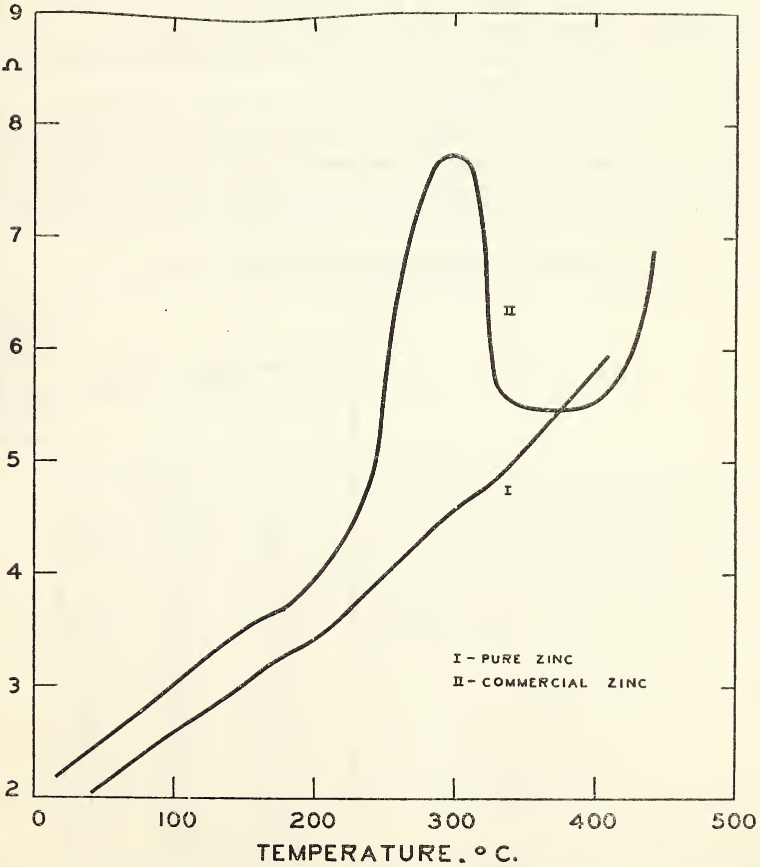

FIGURE 27.—*Electrical resistance of two samples of zinc, illustrating the alleged allotropy of zinc*

(6) DENSITY.—Values quoted for the density of zinc range from about 6.5 to 7.2 g/cm^3. According to Egerton (11) the density of ordinary zinc at 16.3° C. is 7.1400 and the New Jersey Zinc Co. has

determined this at 20° C. as 7.14 g/cm^3 (1). Kahlbaum zinc has been reported to have a density of 7.134 g/cm^3 at 25° C. and zinc containing 0.01 per cent cadmium and 0.01 per cent iron a density of 7.11 g/cm^3 (6)(15). The density of cast zinc has been given as 6.561, 6.9154, and 7.149 g/cm^3 (20). Work of this bureau (3) on cast zinc of high purity (0.003 per cent cadmium, 0.001 per cent lead, 0.003 per cent iron, 99.993 per cent zinc) showed it to have a density of 7.131 g/cm^3 at 25° C.

On rolled zinc of the same purity (99.993 per cent), the New Jersey Zinc Co. has obtained values of 7.135 to 7.150 g/cm^3 at room temperature (1). Recent determinations by this bureau of the density of spectroscopically pure zinc in the form of swaged wire, 0.07-inch diameter, gave 7.133 g/cm^3 at 25° C. Spectrographic analysis made by this bureau of the zinc used in this work showed no contamination except for a very minute trace of cadmium. (See p. 60 for electrical resistivity of this same wire and p. 66 for thermal electromotive force determined on other wires made from the same stock.)

The value of 7.142 g/cm^3 seems to have been widely accepted as an average figure for the density of zinc (1).

Determinations were made at this bureau (3) of the density of a cast tension-test bar under different conditions of heat treatment, and the results (as well as values for scleroscope and Rockwell hardness) are given in Table 14. These data showed that no change in density results from quenching the metal at increasingly higher temperatures.

TABLE 14.—*Density and hardness of pure zinc*

Specimen No.	Quenching temperature	Density at 25° C.	Scleroscope hardness	Rockwell hardness reading on C scale one-eighth inch ball, 60 kg, one minute
	° C.	*g/cm^3*		
20	20	7.130		97
4	61	7.132	8.8	107
5	94	7.131	9.4	
23	120	7.134		
6	142	7.125	9.2	
24	145	7.130		
7	154	7.132	8.2	110
8	158	7.133	7.6	
9	163	7.132	8.6	
15	171	7.130	7.8	
13	180	7.129	9.0	102
14	190	7.130	9.0	
11	212	7.129	9.4	
10	237	7.130	9.6	
12	267	7.133	8.8	107
16	285	7.130	9.2	
17	289	7.131	8.8	
18	302	7.131	8.0	
19	342	7.131	9.2	116
28	(1)	7.132		106

[1] Cooled in crucible

The density of liquid zinc has been given by different authorities as follows:

TABLE 15.—*Density of molten zinc*

Temperature	Density	Authority
° C.	*g/cm³*	
419.4	6.92	(1)
477	6.53	(12)
543	6.47	(12)
580–630	5.81	(18)
600	5.81	(18)

The following equation has been given by Hogness (12) for calculating the density of molten zinc at different temperatures:

$$d = 6.59 - 0.00097\ (t - 419)$$

Hogness stated that the maximum difference between observed and calculated values which he found was 0.1 per cent at the temperatures used, 477° and 543° C.

Zinc vapor has been reported by Ingalls (20) to have a density of 2.36 g/cm^3.

The density of zinc as calculated from X-ray data is 7.19 g/cm^3 (3). The following formula is used: $\rho = mM/V$, in which m is the number of atoms within the unit cell of the crystal lattice structure; M is the mass of the atom in grams (equal to the product of the atomic weight and the mass of one unit of atomic weight, given by the value of 1.649×10^{-24} grams), and V is the volume of the unit cell in cubic centimeters.

Density

Text reference	Year	Name and title
1	1929	N. J. Zinc Co., Rolled zinc, Research bulletin.
2	1928	Matsuyama, Y., Density of molten metals and alloys, Bull. Inst. Phys. Chem. Res. Tokyo, **7**, pp. 1054–1077; Chem. Abst., **23**, p. 1548; J. Inst. Metals, **40**, p. 493.
3	1926	Freeman, J. R., jr., Sillers, F., Brandt, P., Pure zinc at normal and elevated temperatures, B. S. Sci. Paper No. 522.
4	1924	Hoffman, R., Stahl, W., The contraction and density of molten pure zinc, Metall Erz, **21**, pp. 44–45; Chem. Abst., **18**, p. 1769; J. Inst. Metals, **31**, p. 383.
5	1924	——, The density of pure zinc, Metall Erz, **21**, pp. 22–24; Chem. Abst., **18**, p. 1769.
6	1924	Schulz, A., The electrical conductivity of metals, Z. Metallkunde, **16**, pp. 48–54.
7	1923	Brush, C. F., Weight-mass ratios. New gravitational experiments, Proc. Am. Phil. Soc., **62** (3), pp. 75–89; J. Inst. Metals, **33**, 1925, p. 338.
8	1922	Billaz, A., Notes on zinc dust, Industrie Chemique, **9**, pp. 153–157; Chem. Abst., **16**, p. 2102.
9	1922	Bornemann, K., Sauerwald, F., Density measurements of metals and alloys at high temperatures with special reference to the molten state. II, Z. Metallkunde, **14**, pp. 254–258; Chem. Abst., **16**, p. 3844.
10	1922	Brush, C. F., Weight-mass ratios for bismuth and zinc, Proc. Am. Phil. Soc., **61**, pp. 167–183; Sci. Abst., **26a**, pp. 103–104; J. Inst. Metals, **31**, 1924, p. 364.
11	1922	Egerton, A. C., Separation of isotopes of zinc, Naturwissenschaften, **10**, p. 773.
12	1921	Hogness, T. R., Surface tensions and densities of liquid mercury, cadmium, zinc, lead, tin, and bismuth, J. Am. Chem. Soc., **43** (2), pp. 1621–1628.
14	1920	Bingham, K. E., Allotropy of zinc, J. Inst. Metals, **34**, pp. 333–353. Einige wichtige zahlentafeln aus der metallkunde nach daten der Physikalischen Technischen Reichsanstalt, Z. Metallkunde, **12**, p. 179.
15	1919	Adams, L. H., Williams, E. D., Johnston, J., The determination of the compressibllity of solids at high temperatures, J. Am. Chem. Soc., **41**, pp. 12–42.
16	1915–16	Moulden, J. C., Zinc, its production and industrial applications, J. Roy. Soc. Arts, **64**, pp. 495–513, 517–531.
17	1914	Pascal, P., Jouniaux, A., Density of certain metals in the liquid state, Compt. Rendu. **158**, pp. 414–416; Chem. Abst., **8**, p. 1404.
18	1914	Smith, S. W., Surface tension of molten metals, J. Inst. Metals, **12**, pp. 168–209.
19	1913	Griffiths, E. H., Griffiths, E., Capacity for heat of metals at different temperatures, Proc. Roy. Soc. London, **88A**, pp. 549–560.
20	1902	Ingalls, W. R., Production and properties of zinc, Eng. & Min. J.

(7) COMPRESSIBILITY.—The most precise data available on the compressibility of zinc are those of Adams, Williamson, and Johnston (3). The zinc used was in the form of cast cylinders and was described as "Kahlbaum" zinc. Figure 28 from this work, shows the volume changes with increasing pressures up to 12,000 megabars (1 megabar $=10^6$ dynes/cm$^2=0.987$ atmosphere). The compressibility $(k\times10^6)$ decreases with increasing pressure; at 0 megabars, it is 1.74 and at 10,000 megabars, 1.43. The earlier work of Richards (6) showed an average compressibility (K) between 100 and 500 megabars to be 1.5×10^{-6}. Lusanna's value, (4) $K=2.16\times10^{-6}$ at 0 pressure, per atmosphere pressure (obtained by extrapolation) is undoubtedly high.

Compressibility

Text reference	Year	Name and title
1	1930	Maier, C. G., Zinc smelting from a chemical and thermodynamic viewpoint, Bureau of Mines Bull. No. 324.
2	1922	Williamson, E. D., Change of physical properties of materials with pressure, J. Frank. Inst., **193**, pp. 491–513.
3	1919	Adams, L. H., Williamson, E. D., Johnston, J., The determination of the compressibility of solids at high pressures, J. Am. Chem. Soc., **41**, pp. 12–42.
4	1904	Lussana, S., Thermal properties of solids and of liquids, Nuovo Cimento, **7** (5), pp. 355–374.
5	1911	Johnston, J., A correlation of the elastic behavior of metals with certain of their physical constants, J. Wash. Acad. Sci., **1**, pp. 260–267.
6	1909	Richards, T. W., Snell, W. N., Brink, F. N., Bonnet, F., The compressibilities of the elements and their periodic relations, J. Am. Chem. Soc., **31**, pp. 154–158.

(b) ELECTRICAL PROPERTIES

(1) RESISTIVITY.—Recent measurements made at this bureau on zinc of high purity (spectroscopically pure) in the form of swaged wire, 0.07 inch in diameter, showed the resistivity at 20° C. to be 5.916 microhm-cm (1 microhm $=1$ ohm$\times10^{-6}$). The temperature coefficient of resistance of zinc of this same grade, according to recent work of this bureau is 0.00419 at 0° C. for the range 0° to 100° C. The zinc used for the determination was in the form of wire (swaged to 0.07 inch diameter and then drawn to 0.0089 inch diameter) from which was constructed a resistance thermometer of the potential terminal type. The resistance-temperature coefficient was expressed as $\frac{R_{100}-R_0}{100R_o}$, R_{100} and R_o being the resistance of the coil of the thermometer at 100° and 0° C., respectively.

The resistivity of wrought zinc is affected to some extent by the method of mechanical working which has been used as well as by impurities which may be present in the metal. Information on these points is given in Table 16 (1).

TABLE 16.—*Resistivity of sheet zinc* (*1*)

Grade of zinc	Condition of material [1]	Resistivity [2]	Conductivity [3]
		Microhm-cm	*Per cent*
High grade	Cold-rolled strip	6.097	28.27
	Hot-rolled strip	6.06	28.44
Prime Western (1.1 per cent Pb, 0.05 per cent Cd)	Cold-rolled strip	6.14	28.08
Prime Western (1.1 per cent Pb, 0.05 per cent Cd)	Hot-rolled strip	6.12	28.17

[1] Specimen cut parallel to direction of rolling.
[2] Calculated from values given for conductivity (mhos.).
[3] Obtained by dividing the resistivity of copper (International Annealed Copper Standard), 1.7242 microhm-cm, by the resistivity of zinc.

According to Guillet and Ballay (7) the resistivity of zinc is slightly increased by cold-working, presumably as a result of the change in crystal orientation with respect to the direction in which the resistivity is measured. An increase of 3.4 per cent was reported in the resistivity of zinc which had been as severely cold-worked as was possible without causing cracks or splits, over the resistivity of the same material after annealing at 300° C.

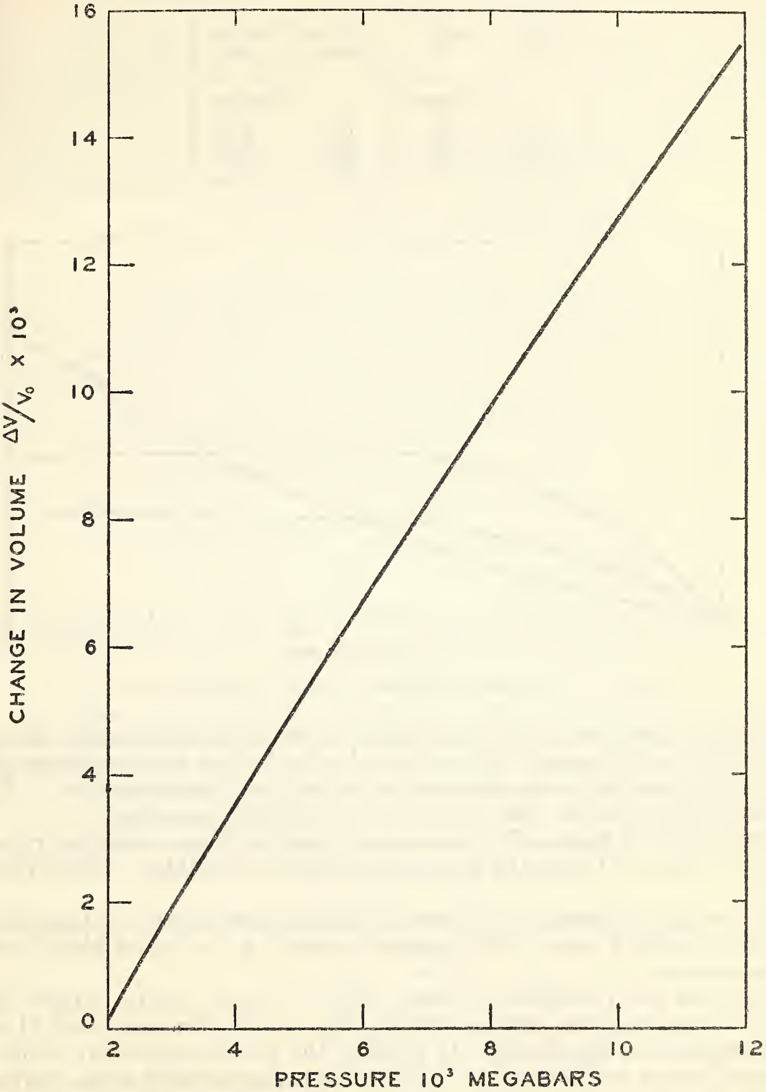

FIGURE 28.—*Compressibility of cast zinc*

The following values for the resistivity of zinc (99.8 per cent) at elevated temperatures have been given by Schofield (4).

TABLE 17.—*Resistivity of zinc at elevated temperatures (4)*

Temperature	Resistivity	Temperature	Resistivity
° *C.*	*Microhm-cm*	° *C.*	*Microhm-cm*
35.0	6.08	107.0	8.15
105.0	8.09	200.0	10.48
105.0	8.08	200.8	10.47
106.0	8.10	350.2	14.50

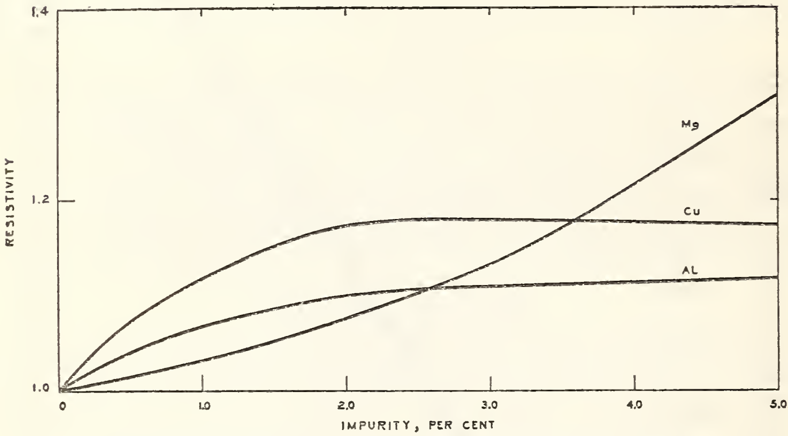

FIGURE 29.—*Effect of impurities on the resistivity of zinc*

Slight variations in the resistivity of sheet zinc measured "across the grain" as compared with values obtained when the measurements are taken parallel to the direction of rolling have been reported. Reliable information on this point is not available, however.

The effect of impurities sometimes found in zinc is shown graphically in Figure 29 from the International Critical Tables. (Vol. VI, p. 140.)

According to Schulz (5), the resistivity of zinc at the melting point is: For the solid phase, 16.35 microhm-cm; for the liquid phase, 35.3 microhm-cm.

Data on the resistivity of zinc, 99.99 per cent purity, within the range of temperature, 20° to 460° C., reported by Petenpol and Miley (2) are given in Figure 30. In making the measurements at temperatures close to and above the melting point, the strength of the surface film on the zinc wire was depended upon to maintain the metal in the form of wire. For purposes of comparison, the resistivity of zinc calculated by use of the equation (Table 18) given in the International Critical Tables (Vol. VI) has also been included in Figure 30. The degree of agreement between the observed and calculated values is apparent from the figure. It will be noted that the agreement was considerably better in the two cases for the molten zinc than for the hot solid metal just below the freezing point.

The results reported for the temperature coefficient of resistance are of particular interest for their bearing on the question of the alleged allotropy of zinc. Pronounced changes in the temperature coefficient within relatively short ranges of temperature, 160° to 180° C. and 320° to 340° C., were reported, whereas the deviations in the resistivity curve within the same temperature ranges were very slight. The temperature coefficient at 0° C. (calculated) for the temperature range 0° to 100° C. is 0.00435, which is considerably higher than the value found by this bureau for zinc of very high purity.

The following equation showing the effect of temperature (above −80° C.) on the resistivity of polycrystalline metals is given in the International Critical Tables (Vol. VI, p. 136) (Wenner):

$$r_t = r_{t'}\ [1 + \alpha\ (t - t')\ 10^{-3} + \beta\ (t - t')^2\ 10^{-6}] \text{ and } t_1 \leqq t \leqq t_2$$

r_t for a liquid is the resistivity at temperature t, and r_t for a solid is the resistance at temperature t of the specimen which at room temperature (t_R) has a length (in the direction of the current) equal to 1 cm and a uniform transverse sectional area of 1 cm^2.

Values for t', r_t, α, β, t_1, and t_2 for zinc as given in International Critical Tables (Vol. VI, p. 136) are as follows:

TABLE 18.—*Constants for the equation showing relation between temperature and resistivity of zinc*

t'	$r_{t'}$	α	β	t_1	t_2	Remarks
° *C.*				° *C.*	° *C.*	
0	5.64 (solid)	3.468	1.16	−80	400	Annealed, very pure.
20	5.916 (solid)					
418	37.39 (liquid)	−.2785	.40	418	850	

The effect of low temperature (below −80° C.) on the resistance of a specimen of polycrystalline zinc (purity not stated) is shown in Figure 31 from data given in International Critical Tables (Vol. VI, p. 129), R and R_o being the resistance (not resistivity) of the specimen at the temperatures t° and 0° C., respectively. Similar information, from the same source, on the effect of low temperature on the resistance of a single crystal of zinc is given in Table 19.

TABLE 19.—*Effect of low temperature on the resistance of single crystals of zinc*

t	100 R/R_o	
	‖ principal axis of crystal	⊥ principal axis of crystal
° *C.*		
−78.2	64.8	68.1
−143.15	40.9	41.8
−183.4		26.0
−188.5	22.1	
−189.1		23.5
−191.1	21.1	22.7
−191.8	20.7	22.4
−194.2	19.6	
−252.6	.74	
−252.7	.741	.758

The resistivity of a metal is affected by hydrostatic pressure. This effect, between 0° and 100° C., is expressed by the following equation from International Critical Tables (Vol. VI, p. 136):

$$R_p=R_o\ (1+a(10)^{-6}P+b(10)^{-n})\ P^2$$

in which R_o and R_p are the resistance of the specimen under pressure of 1 atmosphere (essentially zero) and P, respectively. The pressure range is 0 to 12,000 kg/cm^2.

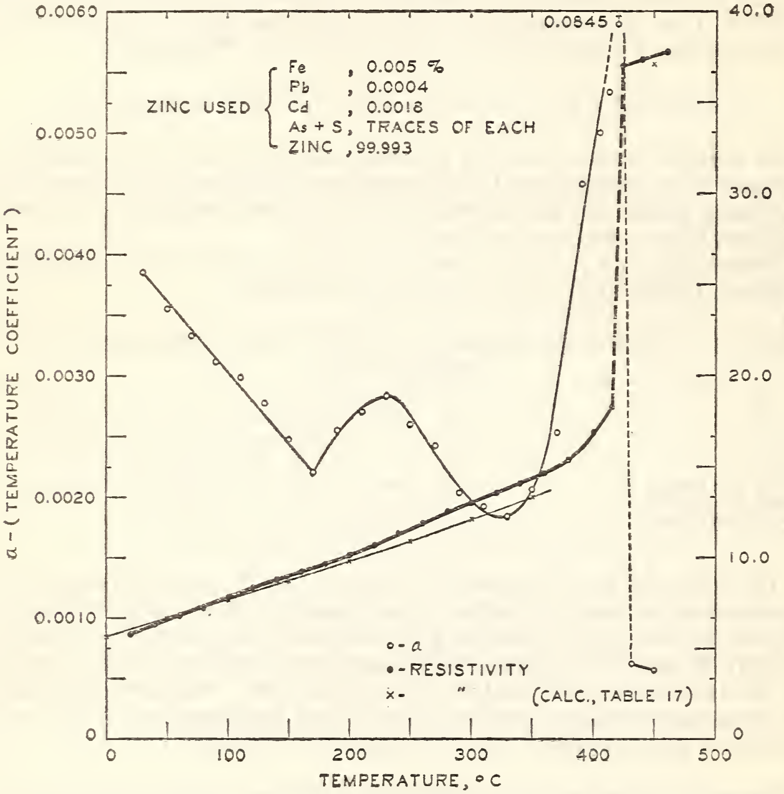

Figure 30.—*Effect of temperature on the resistivity and the temperature coefficient of zinc*

For Kahlbaum's "*K*" zinc, containing a trace of cadmium, iron, and lead, values of *a*, *b*, and *n* are presented in Table 20.

Table 20.—*Constants for equation showing relation between pressure and resistivity of zinc*

t	*a*	*b*	*n*
° *C.*			
0	−5.40	5.8	11
25	−5.404	6.42	11
50	−5.430	7.00	11
75	−5.472	7.58	11
100	−5.524	8.17	11

Electrical resistivity

Text reference	Year	Name and title
1	1929	N. J. Zinc Co., Rolled zinc, Research bulletin.
2	1929	Petenpol, W. B., Miley, H. A., Electrical resistivities and temperature coefficients of lead, tin, zinc, and bismuth in the solid and liquid states, Phys. Rev., **34**, p. 1588.
3	1926	Matsuyama, Y., On the electrical resistance of pure metals in the molten state, Kenzoku no Kenku, **3**, pp. 254–261; Trans. Am. Soc. Steel Treat., **10**, pp. 318–319; J. Inst. Metals, **37**, p. 426; 1927.
4	1925	Schofield, F. H., The thermal and electrical conductivities of some pure metals, Proc. Roy. Soc. **107A**, pp. 206–227.
5	1924	Schulze, A., The electrical conductivity of metals, Z. Metallkunde, **16**, pp. 48–54; J. Inst. Metals, **31**, p. 395.
6	1924	Gruneisen, E., Goens, E., Studies on metallic crystals. II. Specific heat and electrical resistance of zinc and cadmium, Z. Physik., **26**, pp. 235–249.
7	1923	Guillet, L., Ballay, M., The influence of cold-working on the resistance of metals and alloys, Compt. Rendu., **176**, pp. 1800–1802; J. Inst. Metals, **31**, p. 390; 1924.
8	1921	Houghton, J. C., Zinc and zinc-rich alloys, Metal Ind. (London), **18**, pp. 4–7.
9	1920	——, Einige wichtige zahlentafeln aus der metallkunde nach daten der Physikalischen Technischen Reichsanstalt. Z. Metallkunde **12**, p. 179.
10	1918	Gruneisen, E., Electrical conductance of metals at low temperatures, Ber. Physik. Ges. **20**, pp. 36–52; Chem. Abst., **13**, p. 1272.
11	1918	Tsutsumi, H., The variation of electric resistance during fusion, Proc. Tokyo Math. Phys. Soc., **9** (2), p. 349; Chem. Abst., **12**, p. 2274; Sci. Rept. Tohoku Imp. Univ., **7**, pp. 83–105.
12	1915–16	Moulden, J. C., Zinc, its production and industrial applications, J. Roy. Soc. Arts, **64**, pp. 495–513, 517–531.
13	1914	Northrup, E. F., Electrical conduction at high temperatures and its measurement, Trans. Am. Electrochem. Soc., **25**, pp. 373–390.
14	1910	Bornemann, K., Muller, P., The electrical conductivity of metallic alloys in the fluid condition (data on Pb-Zn alloy). Metallurgie, **7**, pp. 396–402; Chem. Zentr. p. 434; 1910 (2); Chem. Abst., **5**, p. 859; 1911; Metallurgie, **7**, pp. 730–740, 755–772; Chem. Abst., **5**, p. 1391.

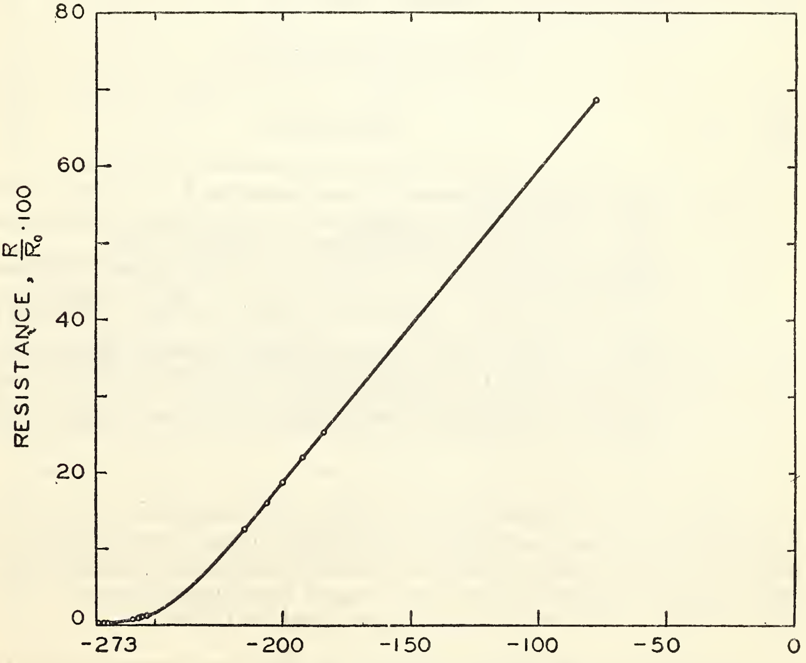

FIGURE 31.—*Effect of low temperature on the resistance of zinc*

(2) THERMAL ELECTROMOTIVE FORCE.—Values of the electromotive force of zinc obtained at this bureau on wire (swaged to 0.07 inch diameter and cold drawn to 0.0365 inch diameter) of "spectroscopically pure zinc" are presented in Table 21.

TABLE 21.—*Thermal electromotive force of zinc-platinum couple*

Temperature	Emf.	Temperature	Emf.
° C.	*International millivolts*	*° C.*	*International millivolts*
0	0.000	225	2.240
25	+.153	250	2.610
50	.331	275	3.002
75	.533	300	3.417
100	.758	325	3.853
125	1.005	350	4.310
150	1.276	375	4.786
175	1.572	400	5.290
200	1.894	415	5.604

The above table gives the emf. set up in the zinc-platinum thermocouple (platinum standard No. 27 was used) corresponding to the temperature of the hot junction when the cold junction was at 0° C. The plus sign indicates that the zinc wire was connected to the positive terminal of the measuring apparatus or that the zinc wire was at a higher potential than the platinum wire.

Thermo-electric properties

Text reference	Year	Name and title
1	1925	Guntherschulze, A., Work necessary to detach positive ions, Z. Physik., **31**, pp. 507–508; J. Inst. Metals, **33**, p. 396.
2	1922	Caswell, A. E., The Hall, Ettingshausen, Nernst, and Leduc effects in cadmium, nickel, and zinc, Phys. Rev. **20**, pp. 280–282; Chem. Abst., **17**, p. 357; 1923.
3	1922	Latimer, W. M., Thermo-electric force, the entropy of electrons, and the specific heat of metals at high temperatures, J. Am. Chem. Soc., **44**, (2), pp. 2136–2148; J. Inst. Metals, **29**, p. 630; 1923.
4	1921	Dhar, N. R., Anomalous phenomena in the electromotive behavior of certain metals, Z. Anorg. Chem., **118**, pp. 75–80; Chem. Abst., **16**, p. 1356; 1922; J. Inst. Metals, **26**, p. 500.
5	1919	Procopiu, S., Deposits of metal of minimum thickness, measured by their electromotive force, Compt. Rendu., **169**, pp. 1030–1031; Chem. Abst., **14**, p.1786; 1920.
6	1918	Darling, C. R., Grace, A. W., The thermoelectric properties of fused metals, Proc. Phys. Soc., **30**, pp. 14–20; Chem. Abst., **12**, p. 1722.
7	1911	Pollitzer, F., The determination of specific heats at low temperatures and their use for the calculation of electromotive forces, Z. Elektrochem., **17**, pp. 5–14; Chem. Abst., **5**, p. 1012.

(3) MAGNETIC SUSCEPTIBILITY.—Zinc is diamagnetic. According to Frivold (5), the magnetic susceptibility (mass susceptibility) of Merck's "pure" zinc showed no marked change as the flux density or intensity of the magnetic field was varied from approximately 110 to 760 oersteds.[4] The results are summarized in Table 22.

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[4] The name oersted was adopted by the International Electro-Technical Commission in Oslo in 1930 to designate the unit of magnetizing force, the gilbert per centimeter.

Table 22.—*Magnetic susceptibility of zinc* (*5*)

Field strength, oersteds (gilberts per centimeter)	Susceptibility $\times 10^6$
113. 5	−0. 126
234. 0	−. 143
364. 2	−. 137
565	−. 1362
761	−. 1371

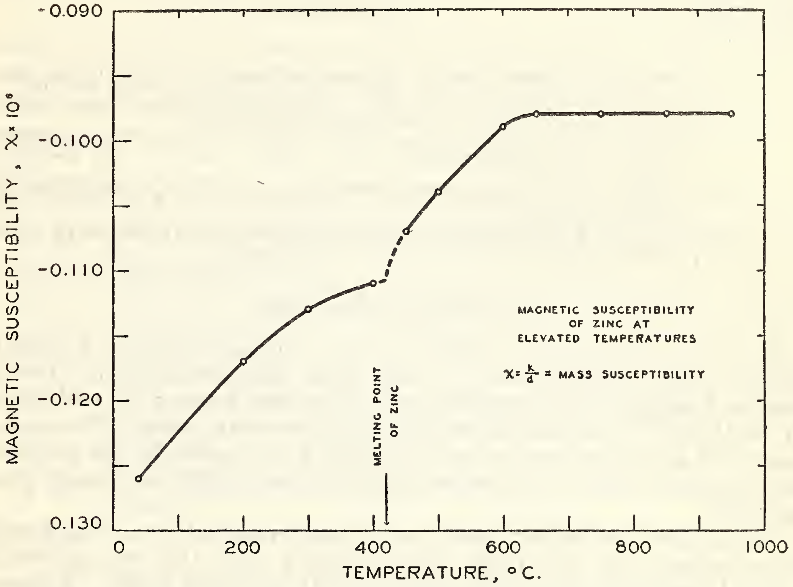

Figure 32.—*Effect of temperature on the magnetic susceptibility of zinc*

The magnetic susceptibility of zinc in single crystals, parallel and perpendicular to the principal crystal axis, is -0.190×10^{-6} and -0.145×10^{-6}, respectively, according to McLennan, Ruedy, and Cohen (2). From these data the magnetic susceptibility for an isotropic aggregate of zinc crystals was calculated to be -0.160×10^{-6}. According to the authors "chemically pure metals were used and, as an extra precaution, these were slowly distilled in a good vacuum." The change in the magnetic susceptibility of zinc with increasing temperature, as based upon the work of Endo (3), is shown in Figure 32.

The following values (Table 23), for the magnetic susceptibility (mass susceptibility) of zinc are given in the International Critical Tables (vol. 6, p. 356) (Honda and coworkers):

TABLE 23.—*Magnetic susceptibility of zinc*

Temperature	Susceptibility ×10⁶
°*C*	
18	−0.157
−170 to 150	−.157
[1] 450 to 600	−.09

[1] Liquid.

Magnetic properties

Text reference	Year	Name and title
1	1928	Brown, H. M., Effect of magnetic fields upon the thermal conductivity of iron, copper, gold, silver, and zinc, Phys. Rev., **32**, pp. 508–514; Chem. Abst., **23**, p. 1026; 1929.
2	1928	McLennan, J. C., Ruedy, R., Cohen, E., Magnetic susceptibilities of single crystals of zinc and cadmium, Proc. Roy. Soc. (London), **121A**, pp. 9–21.
3	1927	Endo, H., On the magnetic susceptibility of some binary alloys at high temperatures, and their equilibrium diagram, Sci. Rept. Tohoku Imp. Univ., **16**, pp. 201–234; J. Inst. Met., **38**, p. 432.
4	1920	Ishiwara, T., Variation of magnetic susceptibility during allotropic transformations and melting of some substances, Sci. Rept. Tohoku Imp. Univ., **9**, pp. 233–241; Chem. Abst. **14**, p. 3567.
5	1918	Frivold, O. E., Diamagnetism in weak magnetic fields, Ann. Physik., **57**, pp. 471–488; Chem. Abst., **13**, p. 2806.

(c) THERMAL PROPERTIES

(1) CHANGE OF STATE (MELTING AND BOILING POINTS, SUBLIMATION).—The melting point of very pure zinc prepared for use as standard samples, has been determined by this bureau (1) and found to be 419.47° C. on the International temperature scale. This value is in good agreement with that of 419.45° C. obtained by the research department of the New Jersey Zinc Co. for spectroscopically pure zinc (2).

Values for the boiling point have been reported by a number of investigators. In the early work of Féry (11) this was given as 1,040° C. which is higher than the present accepted value. Johnson (10) determined the boiling point as lying between 918° and 922° C. and Heycock and Lamplough as 905.7° C., the latter being in close agreement with the value, 907° C., given in the International Critical Tables. (Vol. 1. p. 103.)

Information on the effect of pressure on the boiling point is given in Table 24, based on the work of Greenwood (9).

TABLE 24.—*Effect of pressure on boiling point of zinc*

Pressure	Boiling point
Atmospheres	° *C.*
1.0	918
6.3	1,120
11.7	1,230
21.5	1,280
53.0	1,510

The available data on the sublimation and vapor pressure of zinc have been well summarized by Maier (3) from whose work the data given in Table 25 have been taken.

TABLE 25.—*Sublimation and vapor pressures of zinc*

State	Temperature	Vapor pressure	State	Temperature	Vapor pressure
	° C.	*mm Hg*		*° C.*	*mm Hg*
Solid	25	$1.13.10^{-14}$	Liquid—Continued	700	59.87
	200	$3.82.10^{-6}$		750	123.1
	250	$9.19.10^{-5}$		800	234.5
	300	$1.26.10^{-3}$		850	423.5
	350	$1.13.10^{-2}$		900	720.2
	400	$7.25.10^{-2}$	Normal boiling point	905.4	760.0
			Liquid under pressure	950	1,172
Solid and liquid at melting point	419.5	$1.39.10^{-1}$		1,000	1,828
Liquid	450	.341		1,100	4,013
	500	1.27		1,200	7,842
	550	4.00		1,300	13,960
	600	11.00		1,400	23,080
	650	26.97		1,500	35,640

Change of state, melting, and boiling points

Text reference	Year	Name and title
1	1929	Roeser, W. F., Thermoelectric temperature scales, B. S. Jour. Research, 3, p. 343; (R. P. 99).
2	1929	New Jersey Zinc Co., research department, Research Bulletin, Rolled Zinc.
3	1929	Maier, C. G., Zinc smelting from a chemical and thermodynamic standpoint, Bureau of Mines Bulletin No. 324.
4	1927	Cyr, H. M., Pure zinc, Trans. Am. Electrochem. Soc., **52**, p. 349.
5	1926	Awbery, J. H., Griffiths, E., The latent heat of fusion of some metals, Proc. Phys. Soc. London, **38**, p. 378.
6	1919	Melting points of chemical elements and other standard temperatures, B. S. Circular No. 35 (4th ed.).
7	1919	Guertler, W., Pirani, M., The melting points of pure elements, Zeit. f. Metallkunde, **11**, p. 1; Chem. Abst. **14**, p. 664.
8	1912	Heycock, C. T., Lamplough, F. E. F., Boiling points of mercury, cadmium, zinc, potassium, and sodium, Proc. Chem. Soc., **28**, p. 3; Chem. Abst., **7**, p. 2329.
9	1910	Greenwood, H. C., Influence of pressure on the boiling points of metals, Proc. Roy. Soc., **83A**, p. 483.
10	1908	Johnson, W. McA., Boiling point of zinc, Electrochem. Met. Ind. (Chem. Met. Eng.), **6**, p. 272; Chem. Abst., **2**, p. 2365.
11	1903	Féry, C., Determination of the boiling points of copper and zinc, Ann. Chim. et Phys., **28** (7), p. 428.

(2) THERMAL CONDUCTIVITY.—The thermal conductivity of zinc in cal_{15}/sec. cm° C. at room temperature (18° C.) has been reported as 0.268 (9), and 0.265 (6). According to the International Critical Tables (vol. 5, p. 220), the weighted mean of the best observations on the thermal conductivity of zinc at 0° C. is 1.13 watt/cm° C., which is equivalent to 0.270 cal_{15}/sec. cm° C. (1 watt/cm° C = 0.2389 cal_{15}/sec. cm° C). The Reichsanstalt has reported (8) the value 1.11 watt/cm° C at 18° C.

The effect of temperature on the thermal conductivity of zinc has been studied by a number of investigators. The graph in Figure 33, based largely on the results of Schofield (4) and other data compiled by von Schwarz (5), shows that the thermal conductivity of the solid metal decreases noticeably with increase of temperature. A marked change occurs as the metal is melted. In Figure 33, are also given results recently determined at this bureau by a method quite different from the one ordinarily used. This method depends upon the comparison of the conductivity of the unknown (zinc) with that of a metal whose conductivity has been carefully determined by other means, lead being used as the comparison bar in this case. Data from the International Critical Tables (vol. 5, p. 220), by which the thermal conductivity at a temperature t, lying between t' and t'', may be calculated from the conductivity, K_t', in the temperature range t'–t'' with the aid of the equation

$$(K_t = K_t' \ (1 + 10^{-3} \ \alpha \ (t - t') + 10^{-6} \ \beta \ (t - t')^2),$$

are given in Table 26.

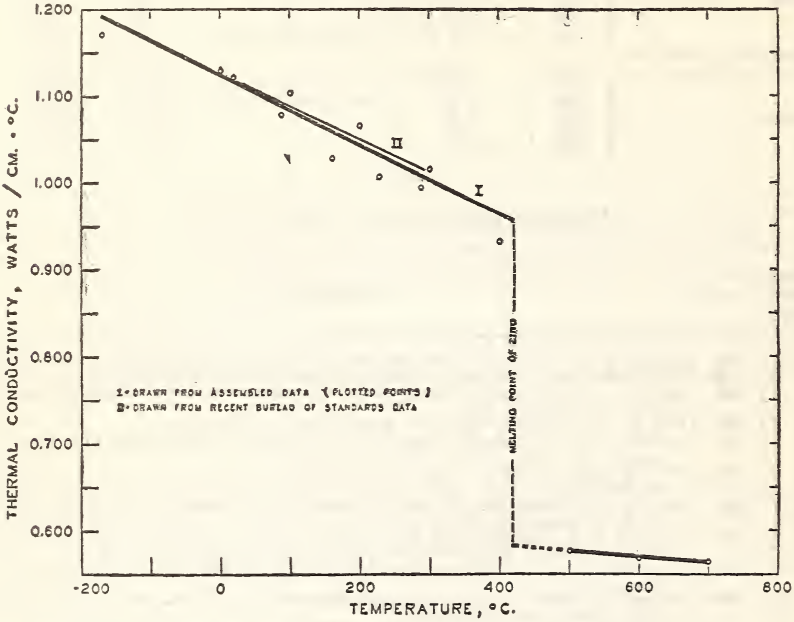

FIGURE 33.—*Effect of temperature on the thermal conductivity of zinc*

TABLE 26.—*Data for the calculation of change in thermal conductivity of zinc with temperature*

t'	t''	K_t'	α	β
° *C.*	° *C.*			
0	100	1.13	−0.15	------------
+18	−125	[1](Ko)1.13	−.081	------------
−125	−170	1.13	−.74	------------
0	420	1.13	−.10	−0.83
420	600	.587	−.13	------------

[1] $K_t = K_o \ [1 + 10^{-3} \ \alpha t + 10^{-6} \ \beta t^2]$.

Lewis and Bidwell (2) have reported the thermal conductivity at room temperature of single crystal zinc (perpendicular to the principal axis) as being 11 to 18 per cent greater than that of polycrystalline zinc at the same temperature.

Bridgman (6) has determined the effect of hydrostatic pressure on the thermal conductivity of hot-extruded rods of zinc of high purity. The application of 12,000 kg/cm^2 resulted in an average increase of 2.5 per cent in the thermal conductivity. The pressure coefficient of thermal conductivity was calculated to be $+0.0_{5}21$. National Bureau of Standards standard zinc (Pb 0.0004 per cent, Fe 0.005 per cent, Cd

0.0018 per cent, Zn by difference 99.993 per cent) was used in these determinations.

Thermal conductivity

Text reference	Year	Name and title
1	1929	Bidwell, C. C., Lewis, E. J., Thermal conductivity of lead and of single and polycrystal zinc, Phys. Rev., **33**, (2), p. 249.
2	1928	Lewis, E. J., Bidwell, C. C., Thermal and electrical conductivity of single and polycrystal zinc, Phys. Rev., **31**, (2), pp. 1111-1112; J. Inst. Met., **40**, p. 474; 1928.
3	1926	Bridgman, P. W., Thermal conductivity and thermal emf. of single crystals and several noncubic metals, Proc. Am. Acad. Arts Sci., **61**, pp. 101-134; J. Inst. Met., **37**, p. 418; 1927.
4	1925	Schofield, F. H., The thermal and electrical conductivities of some pure metals, Proc. Roy. Soc., **107A**, pp. 206-227; J. Inst. Met., **33**, p. 331.
5	1925	Von Schwarz, M., Metallphysik. Handbuch der Werkrafte, Band IV. Herausgeber. P. Krais & G. Wedmann.
6	1922	Bridgman, P. W., Effect of pressure on the thermal conductivity of metals, Proc. Am. Acad. Arts Sci., **57**, pp. 77-127; Chem. Abst., **16**, p. 2443.
7	1921	Houghton, J. C., Zinc and zinc-rich alloys, Met. Ind. (Lond.), **18**, pp. 4-7.
8	1920	Einige wichtige zahlentafeln aus der metallkunde nach daten der Physikalischen Technichen Reichsanstalt, Zeit. Metallkunde, **12**, p. 179.
9	1919	Konno, S., Variation of thermal conductivity during the fusion of metals, Sci. Rept. Tohoku Imp. Univ. **8**, pp. 169-179; Chem. Abst., **14**, p. 1921; 1920; J. Inst. Met., **25**, p. 390; 1921.

(3) THERMAL EXPANSION.—The linear expansion of cast zinc specimens, 30 cm long and 0.714 cm diameter, have been determined at this bureau (7). The zinc was of high purity, containing only 0.001 per cent Pb, 0.003 per cent Cd, 0.003 per cent Fe, and less than 0.00001 per cent As. The results are summarized in Figure 34. Table 27 gives the average coefficient of expansion of this zinc for various temperature ranges.

TABLE 27.—*Average coefficient of thermal linear expansion of zinc*

Temperature range	Average coefficient of expansion for each ° C., $\times 10^6$	
	First heating	Second heating
° C.		
20 to 100	39. 5	38. 7
20 to 150	39. 6	39. 2
20 to 200	39. 7	39. 3
20 to 250	39. 7	39. 4
20 to 300	------------	39. 3

During neither of two heating cycles to 250° and 300° C., respectively, was there any evidence of a transformation point which might be considered as indicative of allotropy. After the first test the specimen was 0.004 per cent shorter than its original length at 20.2° C., and after the second test it was 0.014 per cent shorter than at the start of the second test at 20.1° C.; that is, during the two successive heatings, the cast bar decreased in length approximately 0.018 per cent. The results of these determinations are at variance with those of the dilatation experiments of Losana (12) who reported marked changes at 174° and 315° C. It has been suggested that the apparent transformations reported by Losana may have been due to the presence of impurities (7).

The New Jersey Zinc Co. reports that the linear expansion of rolled zinc varies according to whether the measurements are made in the direction of rolling or across this direction (3). The following data were obtained in the range between 20° and 40° C. on hot-rolled high-grade zinc:

Direction tested	Linear coefficient
With grain	0.000032 per ° C., or 0.000014 per ° F.
Across grain	0.000023 per ° C., or 0.0000098 per ° F.

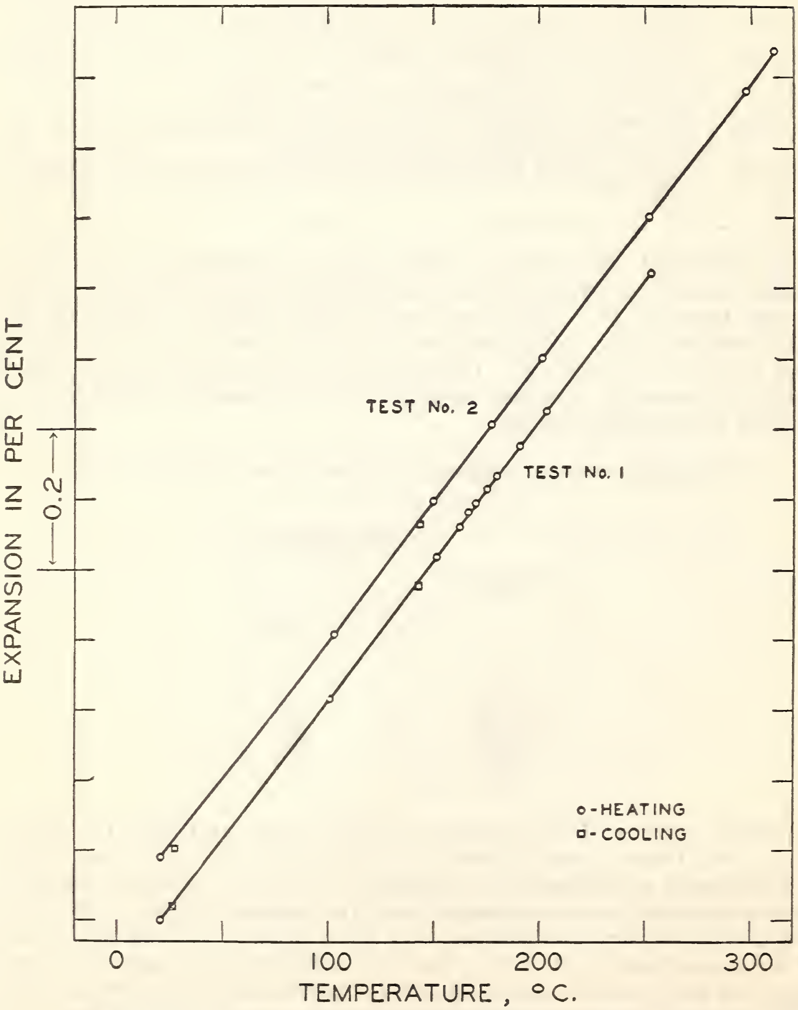

Figure 34.—*Thermal expansion of cast zinc of high purity*

The data in Table 28 on the coefficient of linear expansion are from the International Critical Tables (vol. 2, p. 459) and are to be used in the equation

$$l_t = l_o(1 + \alpha t + \beta t^2 + \gamma t^3 \text{ ------}).$$

Table 28.—*Constants for calculating thermal coefficient of linear expansion of zinc*

	Temperature range	$10^6\times\alpha$[1]	$10^9\times\beta$
	° *C.*		
Zn (purity not stated)	−170 to 60	29.5	21.6
	0 to 300	35.4	10
99.99 per cent (cast)	20 to 250	39.5	----------
Crystals ∥	−160 to 60	57 to 64	----------
Crystals ⊥	−160	6.6	----------
	20	12.6	----------
	60	15.6	----------
	−220 to 60	13.5	2.37

[1] If only α and one temperature are given, $\alpha=\alpha t$; if only α and a temperature range, $\alpha=\alpha_{t_1}^{t_2}$

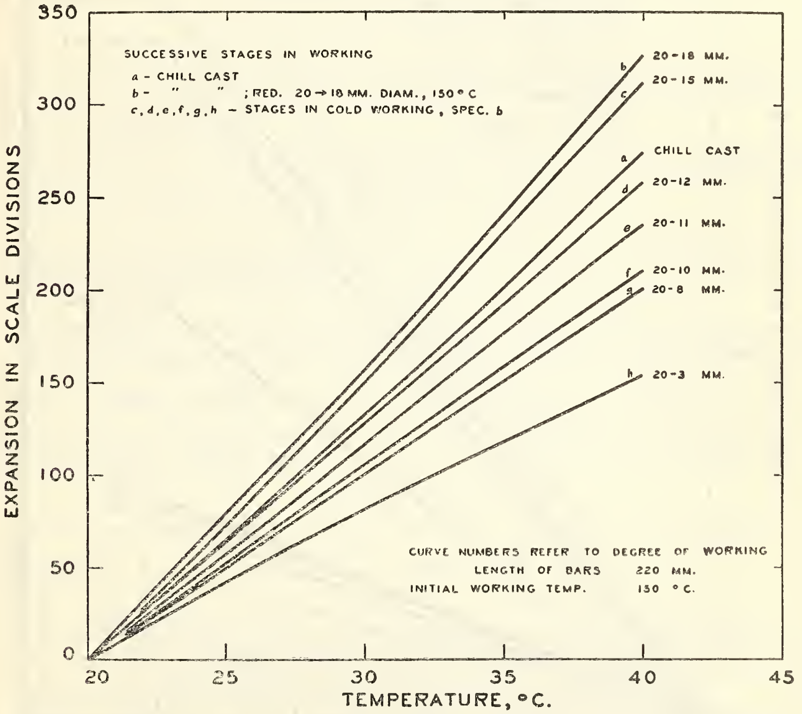

Figure 35.—*Effect of mechanical working on the thermal expansion of zinc*

The bars were reduced from the initial thickness of 20 mm as indicated on each curve.

Jubitz (6) has reported upon the influence of mechanical working on the thermal expansion of zinc. Typical results are shown in Figures 35 and 36. Cylindrical specimens, 220 mm in length, with parallel ends were used. These were cold worked, either by hammering or rolling, after a preliminary working at 150° C., which was found necessary in order to prevent cracking during cold working. The effect of cold working by hammering was similar to that of cold-rolling. It will be noted (fig. 35) that the initial effect of the hot working was to increase the rate of thermal expansion. As the material was cold worked, however, the expansivity of the material decreased. It will be seen from Figure 36 that the upper limit of this effect of hot mechanical working on expansivity is that of the expansivity of single-crystal zinc measured parallel to the principal axis and that the lower limit is the corresponding value determined perpendicular to the principal axis. According to Gruneisen and Goens (8) these values are 64×10^{-6} and 13.3×10^{-6}, respectively. (See also Table 27.)

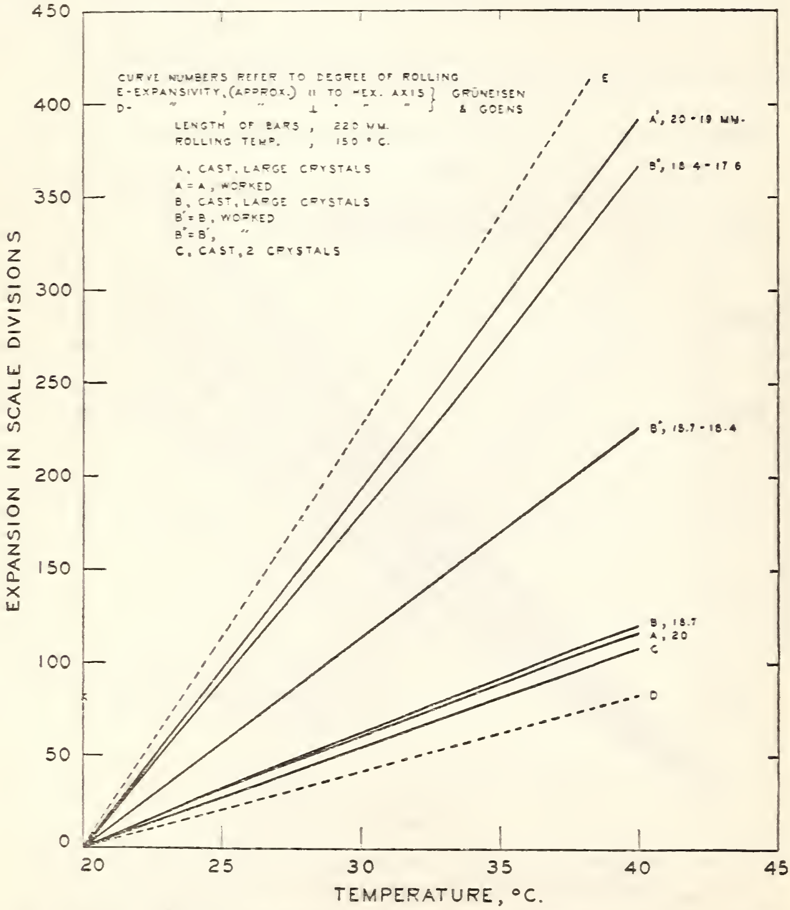

Figure 36.—*Effect of mechanical working on the thermal expansion of zinc compared with the expansivity parallel and perpendicular to the principal axis of a zinc crystal*

The results of Jubitz are in agreement with those of Polanyi on single-crystal zinc wires. According to Polanyi, on stretching a single-crystal zinc wire the hexagonal axis tends to set itself perpendicularly to the axis of the wire. Accordingly, the axis of minimum thermal expansion moves toward the axis of the wire with a resultant decrease in thermal expansion of the wire along its length.

The results of more recent work of Masing on this subject (4) are in agreement with the results reported by Jubitz.

Information on the thermal coefficient of cubical expansion of liquid zinc as based upon the equation

$$V_t = V_\theta(1 + A(t-\theta) + B(t-\theta)^2 + C(t-\theta)^3 \text{ ------})$$

is given by the International Critical Tables (vol. 2, p. 463). Data for zinc (99.9 per cent) are as follows:

Approximate melting point, θ	$10^6 A$	$10^9 B$	Temperature range
° *C.*			° *C.*
419	147	------------	419 to 543
	217	−198	419 to 918

The values 6.59 and 6.92 are also given as the specific gravity of the zinc in the temperature ranges 419° to 543° C. and 419° to 918° C., respectively.

The results of determinations of the specific volume of molten zinc (99.92 per cent) made at this bureau (1) are summarized in Figure 37. For this diagram the following values are given:

	Per cent
Average liquid contraction per 100° C. drop between 720° and 419° C	1. 4
Contraction during solidification	3. 8
Average solid contraction per 100° C. drop between 419° and 20° C	1. 1

According to the International Critical Tables (vol. II, p. 474), the "mold shrinkage," that is, the change in the volume during the fusion of zinc, $100\frac{\Delta V}{Vs}$, (in which Vs = volume of solid at melting point), is equal to 6.5 ± 0.5. This value is higher than that obtained at this bureau. (Fig. 37.)

Thermal expansion

Text reference	Year	Name and title
1	1930	Saeger, C. M., jr., Ash, E. J., Methods for determining the volume changes undergone by metals and alloys during casting, Trans. Am. Fdymen's. Assoc., **38**, p. –.
2	1929	Bauer, O., Sieglerschmidt, H., The expansion of zinc at increasing temperatures, Mitt. der Deut. Material Prufungsanstalten, sonderheft, **5**, pp. 62–63.
3	1929	N. J. Zinc Co., research department, Rolled zinc, research bulletin.
4	1928	Masing, G., Changes produced by rolling, hammering, and drawing zinc and cadmium, Zeit. Metallkunde, **20**, pp. 425–427.
5	1927	Sauerwald, F., Nowak, E., Juritzek, H., The contraction of metals and alloys, Z. Physik., **45**, p. 650; J. Inst. Met., **38**, p. 500; Chem. Abst., **22**, p. 1128.
6	1926	Jubitz, W., Influence of working on the coefficient of thermal expansion of metals, Z. Tech. Physik., **7**, pp. 522–527; J. Inst. Met., **37**, p. 433; 1927.
7	1926	Freeman, J. R., jr., Sillers, F., Brandt, P., Pure zinc at normal and elevated temperatures, B. S. Sci. Paper No. 522.
8	1925	Gruneisen, G., Goens, E., Researches on metal crystals. III. Thermal expansion of zinc and cadmium, Z. Physik., **29**, pp. 141–156; Sci. Abst., **28a**, p. 272.
9	1925	Von Schwarz, M., Metallphysik. Handbuch der Werkkrafte (Band IV), Herausgeber: P. Krais und G. Widemann, Werkkrafte.
10	1924	Friend, J. N., Vallance, R. H., Determination of the thermal coefficients of expansion of some commercial metals and alloys, J. Inst. Met., **31**, pp. 75–78.
11	1923	Polanyi, B., Changes in the structure of metals through cold working, Z. Physik., **17**, p. 42.
12	1923	Losana, L., Sull'allotropia dello zinco, Gazetta Chimica Italiana, **53**, No. 8, p. 539.
13	1921	Houghton, J. C., Zinc and zinc-rich alloys, Metal Ind. (Lond.), **18**, pp. 4–7.
14	1920	Einige wichtige zahlentafeln aus der metallkunde nach daten der Physikalischen Technischen Reichsanstalt, Z. Metallkunde, **12**, p. 179.

(4) Specific Heat.—The specific heat of zinc at different temperatures, as plotted from the data of two different observers, is shown in Figure 38. The two curves here follow quite divergent courses, and a possible explanation for this is the difference in the degree of purity of the zinc used. Values for the specific heat of zinc reported by other observers are as follow:

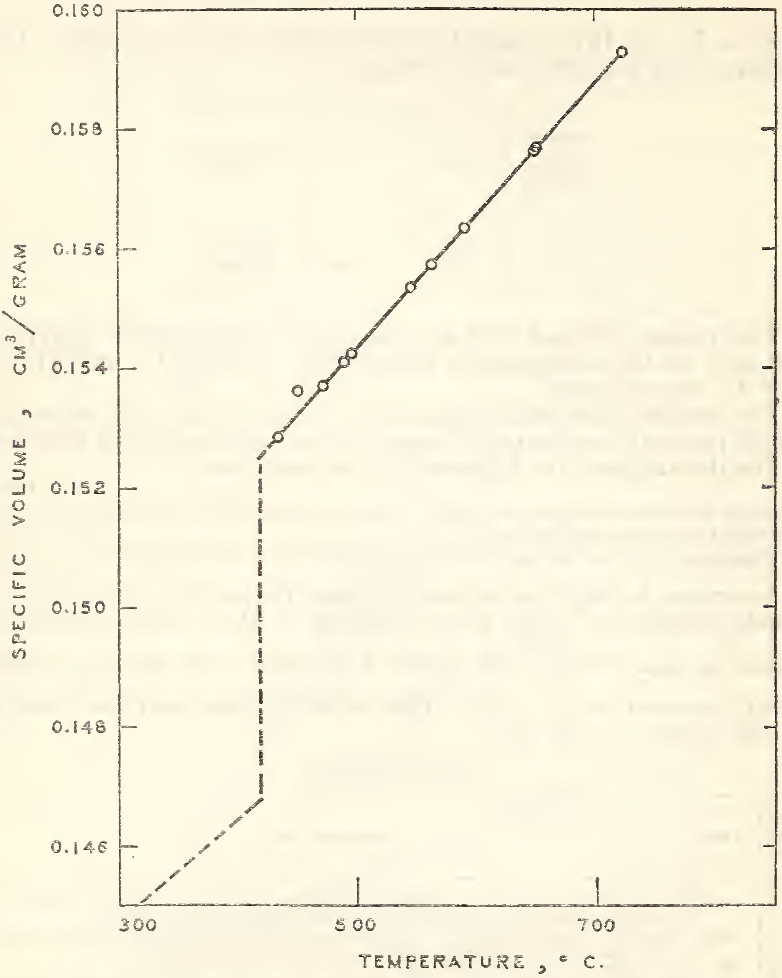

Figure 37.—*Specific volume of zinc at elevated temperatures*

Temperature	Specific Heat	Reference No.
° *C.*	*cal./g/° C.*	
−189.6 to −81.6	0.0792	9
−76.3 to −2.0	.0906	12
1.74 to 20.2	.0949	12

The work of Umino (3) shows that the mean specific heat of zinc (99.948 per cent) increases until the metal is molten, after which the value remains constant. Values as given by Umino are summarized in Table 29.

TABLE 29.—*Effect of temperature on the specific heat of zinc*

Temperature	Mean specific heat	Temperature	Mean specific heat
° C.	*cal./g/° C.*	*° C.*	*cal./g/° C.*
50	0.0940	400	0.1002
75	----------	450	.1548
100	.0946	500	.1522
150	.0958	600	.1473
200	.0961	700	.1444
250	.0979	800	.1423
300	.0981	850	.1409
350	.0995		

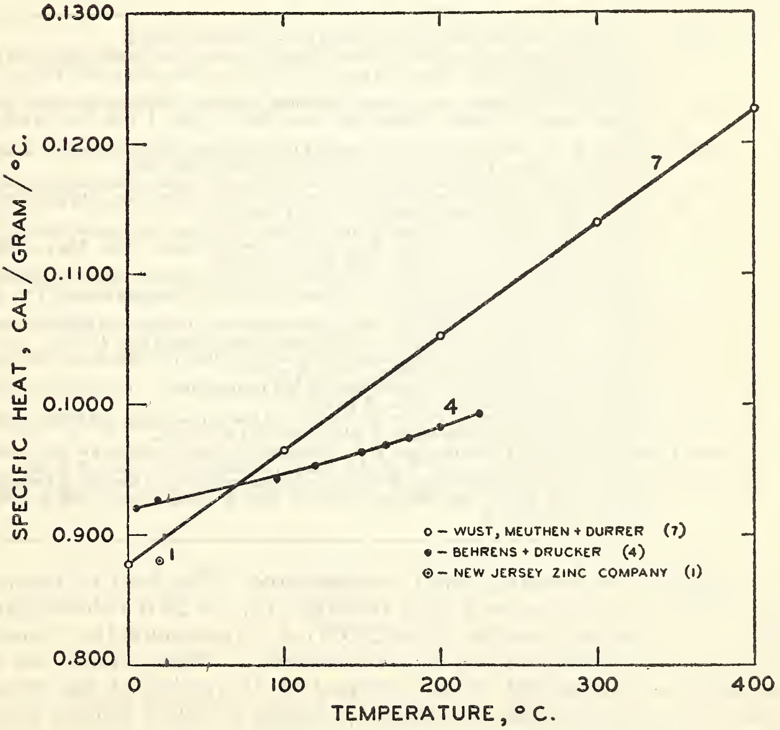

FIGURE 38.—*Specific heat of zinc at elevated temperatures*

According to the extensive work of Behrens and Drucker (4) on drawn wire, no anomalies were exhibited between 0° and 225° C. Hard-drawn and annealed wires gave the same results, as did wires which had been rapidly or slowly cooled from elevated temperatures.

The specific heat of zinc down to the temperature of boiling hydrogen has been determined by Nernst (10) and a curve for the atomic heat (specific heat × atomic weight) as given by him is shown in Figure 39.

Pollitzer (11) studied the specific heat of zinc at temperatures down to −210° C. Some of his results, expressed as atomic heat, are given below.

T	Observed	Calculated
° K.		
68	3.60	3.595
80	4.13	4.17
94	4.58	4.55
207	5.78	5.83

Specific heat

Text reference	Year	Name and title
1	1929	N. J. Zinc Co., research department, Rolled Zinc, Research Bulletin.
2	1928	Bidwell, C. C., A simple relation between thermal conductivity, specific heat, and absolute temperature, Phys. Rev., **32**, pp. 311–314; Chem. Abst., **23**, p. 326; 1929; J. Inst. Met., **40**, p. 491.
3	1926	Umino, S., On the latent heat of fusion of several metals and their specific heats at high temperatures, Sci. Repts., Tohoku Imp. Univ., **15**, I, p. 597; J. Inst. Met., **37**, p. 432; 1927.
4	1924	Behrens, W. U., Drucker, C., A new method for determining the specific heat of metals, Z. Physik. Chem., **113**, pp. 79–110; J. Inst. Met., **33**, p. 336; 1925.
5	1924	Eastman, E. D., Williams, A. M., Young, T. F., The specific heats of magnesium, calcium, zinc, aluminum, and silver at high temperatures, J. Am. Chem. Soc., **46**, pp. 1178–1183; Chem. Abst., **18**, p. 1938; J. Inst. Met., **33**, p. 305; 1925.
6	1919	Iitaka, I., The variation of the specific heat during melting and the heat of fusion of some metals, Sci. Rept. Tohoku Imp. Univ., **8**, pp. 99–114; Chem. Abst., **13**, p. 2802; **16**, p. 3797; 1922; J. Inst. Met., **26**, p. 606; **25**, p. 389; 1921.
7	1918	Wüst, F., Meuthen, A., Durrer, R., The temperature heat content curves for technically important metals, Forschungsarb, auf dem Gebiete des Ingenieurwesens; Ver. Deut. Ing. Publication No. 204, Berlin.
8	1917	Mills, J. E., Molecular attraction. XV, Specific heats of the elements and some energy changes. II, J. Phys. Chem., **21**, pp. 623–643; Chem. Abst., **12**, p. 4; 1918.
9	1911	Koref, F., Measurement of specific heats at low temperatures with the copper calorimeter, Ann. Phys., **36**, pp. 49–73; Chem. Abst., **6**, p. 174.
10	1911	Nernst, W., Investigations of specific heats at low temperatures. III, Sitzb. Akad. Wiss. Berlin, pp. 306–315; Chem. Abst., **5**, p. 2763.
11	1911	Pollitzer, F., The determination of specific heats at low temperatures and their use for the calculation of electomotive forces, Z. Electrochem., **17**, pp. 5–14.
12	1910	Nernst, W., Koref, F., Lindemann, F. A., Researches on specific heats at low temperatures, I. Sitzb. Kgl. Preuss. Akad. Wiss., **12**, **13**, pp. 247–261; Chem. Abst., **4**, p. 2396.
13	1907	Lewis, G. N., The specific heat of solids at constant volume and the law of Dulong and Petit, J. Am. Chem. Soc., **29**, pp. 1165–1168, 1516; Z. Anorg. Chem., **55**, pp. 200–205; Chem. Abst., **2**, p. 5.

(5) HEATS OF FUSION AND VAPORIZATION.—The heat of fusion of zinc, according to Awbery and Griffiths (2), is 26.6 calories/gram. Maier (1) considers that the value 24.09 cal./g represents the "selected comparison of heat-content determinations." Other values for this quantity as determined by the method of depression of the melting point by a solute metal, compiled by Maier (1) after Honda (3) are given in Table 30.

TABLE 30.—*Heat of fusion of zinc, by depression of melting point*

Source	Solute metal	Type of melting curve	Depression for 1 g atom of solute	Heat of fusion
			° *C.*	*cal./g*
Selected	Mg	Simple eutectic	5.98	24.5
	Sb	do	5.83	25.1
	Sn	do	6.05	24.2
Honda	Cd	do	5.36	27.1
	Tl	do	5.40	27.0
Heycock and Neville and Honda	Ag	Solid solution	5.54	25.7
	Al	do	5.53	26.5

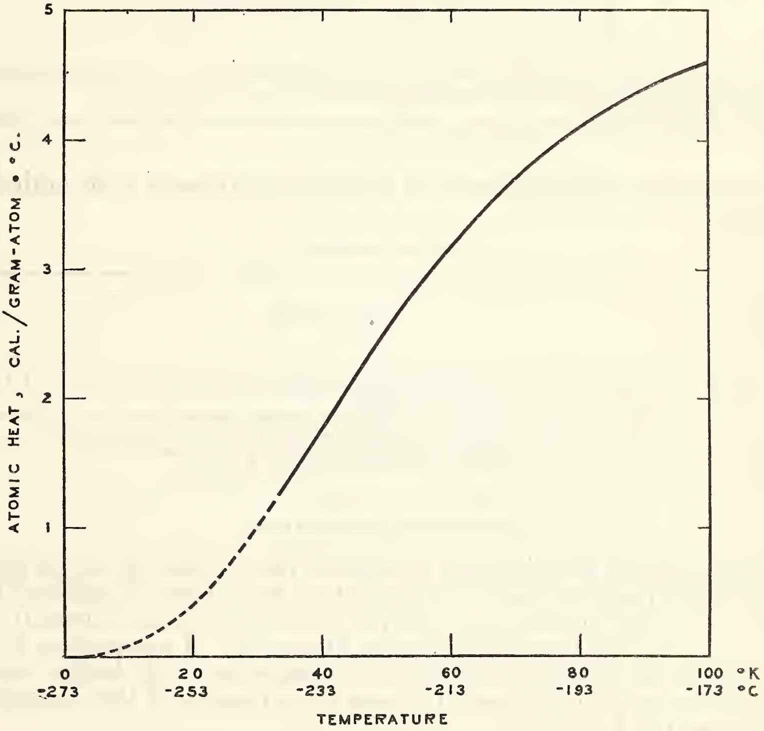

FIGURE 39.—*Atomic heat of zinc at low temperatures*

The calculated values given by Maier for the heat of vaporization and sublimation are, respectively, 30,411 cal./g and 31,569 cal./g.

Heat of fusion

Text reference	Year	Name and title
1	1929	Maier, C. G., Zinc smelting from a chemical and thermodynamic viewpoint, Bureau of Mines, Bulletin No. 324.
2	1926	Awbery, J. H., Griffiths, E., The latent heat of fusion of some metals, Proc. Phys. Soc., London, **38**, p. 378.
3	1925	Honda, K., Ishigaki, T., On the law of depression of freezing points in metallic alloys, Sci. Repts. Tohôku Imp. Univ., Sendai, **15**, ser. 1, p. 219.

(6) Surface tension and viscosity.—Information on the surface tension of molten zinc, from a number of sources, is given in Table 31.

Table 31.—*Surface tension of molten zinc*

Temperature	Capillary constant a^2 [1]	Surface tension	Source
° *C.*	*mm* ²	*dynes/cm*	
450	----------	[2] 755	Hogness (2).
477	23.5	753	Do.
500	----------	[2] 751	Do.
543	23.6	747	Do.
590	24.54	[3] (707.5)	Smith (3).
600	24.99	[4] 787	Bircumshaw (1).
700	24.63	763	Do.

[1] a^2 = radius of capillary tube × height.

[2] Calculated by means of equation $\gamma = 758 - 0.090\ (t-419)$. (The constant in the right-hand member of this equation represents the extrapolated value of the surface tension at the melting point.)

[3] Mean value, at 580°–630° C.

[4] Composition of zinc used: 0.034 per cent Cd, 0.008 per cent Fe, 0.006 per cent Pb, trace Cu, zinc by difference.

Information on the viscosity of molten zinc appears to be entirely lacking.

Surface tension

Text reference	Year	Name and title
1	1927	Bircumshaw, L. L., Surface tension of liquid metals. II, The surface tension of Bi, Cd, Zn and Sb, Phil. Mag., **3** (7), pp. 1286–1294.
2	1921	Hogness, T. R., Surface tensions and densities of liquid mercury, cadmium, zinc, lead, tin and bismuth, J. Am. Chem. Soc., **43**, pp. 1621–1628; Chem. Abst., **16**, p. 181; 1922.
3	1914	Smith, S. W., Surface tension of molten metals (with a very complete bibliography up to 1914), J. Inst. Met., **12**, pp. 168–209; Chem. Abst., **8**, p. 3548.

(d) OPTICAL PROPERTIES

The reflecting properties of a polished flat surface of zinc of high purity (less than 0.05 per cent impurities) have been determined by Coblentz at this bureau (1). The results for wave lengths from 0.2 μ to 2.4 μ (1 $\mu = 10^{-4}$ cm) are given in Figure 40. A comparison with the results of earlier work (2) on the reflection with longer wave lengths, up to 12 μ (infra-red), shows no increase over the maximum value given in Figure 39.

Optical properties

Text reference	Year	Name and title
1	1920	Coblentz, W. W., Reflecting power of monel metal, stellite and zinc, B. S. Sci. Paper No. 379.
2	1906	Coblentz, W. W., Radiometric investigations of infra-red absorption and reflection spectra, B. S. Sci. Paper No. 45.

(e) MECHANICAL PROPERTIES

(1) Tensile properties.—(a) *Tensile strength.*—The various commercial applications of zinc are not dependent upon superior tensile strength in this material. Ordinarily this property is of secondary importance in the application of zinc, nor should too much significance be attached to the percentage elongation as determined by the tension test, since the rate of loading generally used (0.25 inch per minute) is far below the rate of deformation in commercial drawing or fabrication and is no index of ductility required in these operations (1).

Table 32 summarizes information on the tensile strength of commercial cast zinc (spelter) of different compositions (9). Tensile tests were made at the National Bureau of Standards on cast zinc of high purity (0.001 lead, 0.003 cadmium, 0.003 iron, arsenic less than 0.00001, copper, tin, and antimony not detected) at normal and elevated temperatures. The test specimens were prepared by pouring the molten zinc at 430° C. into a steel mold. The results of the tests are given in Table 33.

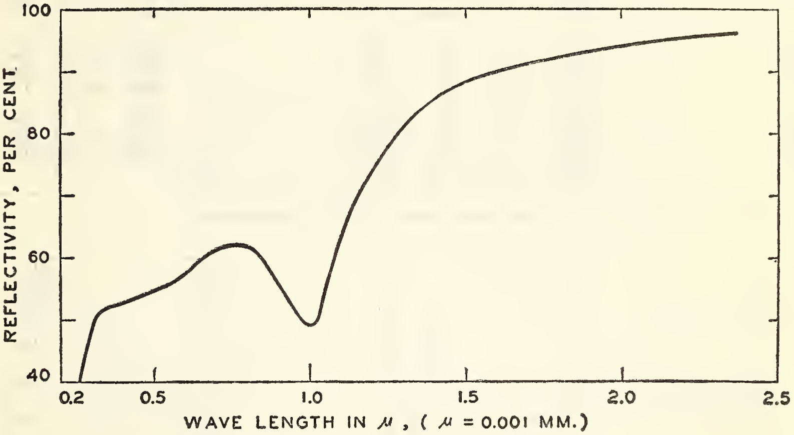

Figure 40.—*Reflectivity of a polished zinc surface*

Table 32.—*Tensile strength of commercial cast zinc (spelter) (9)*

Grade	Composition				Ultimate[1] tensile strength
	Lead	Iron	Cadmium	Zinc	
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Lbs./in.²*
High grade	0.041	0.014	None.	99.95	6,250
	.040	.016	None.	99.94	4,350
Intermediate	.194	.016	None.	99.79	4,350
	.190	.017	None.	99.79	5,100
Brass special	.474	.013	None.	99.51	12,000
	.484	.031	None.	99.48	4,350
Prime western No. 1	1.19	.032	0.250	98.48	7,700
	1.42	.087	.079	98.41	3,700
Prime western No. 2	.68	.010	.274	99.04	10,800
	1.15	.011	.046	98.79	4,700

[1] Average of 4 determinations, "rounded off" to nearest 50 pounds.

TABLE 33.—*Tensile properties of cast zinc of high purity at different temperatures* (3)

(Lead 0.001 per cent; cadmium 0.003 per cent; iron 0.003 per cent; arsenic less than 0.00001 per cent; copper, tin, and antimony not detected)

Temperature of test (° C.)	Ultimate tensile strength	Elongation (2 inch)	Type of fracture
	*Lbs./in.*²	*Per cent*	
25	2,890		Brittle.[1]
25	4,170		Do.[1]
25	4,010	2.0	Do.[1]
25	4,220	2.5	Do.[1]
62	5,180	7.0	Do.[1]
62	6,050		Do.[1]
95	3,700		Do.[1]
100	5,840	28.0	Oblique.
142	4,150		Do.
148	4,180	25.0	Do.
154	4,340		Do.
158	3,960	40.0	Do.
163	3,510	28.0	Do.
163	4,200		Do.
168	3,590	26.0	Do.
170	3,650		Do.
177	3,490	40.0	Oblique.
186	3,120	42.0	Do.
196	3,140	38.0	Do.
200	3,000		Do.
218	2,390	45.0	Do.
243	1,880	70.0	Wedge.
250	1,800		Do.
267	1,390	60.0	Do.
280	1,200		Do.
284	1,200	81.0	Do.
288	950	34.0	Do.
298	900	60.0	Do.
300	950		Do.
342	500	56.0	Do.
350	450		Do.

[1] By "brittle fracture" is meant one characteristic of a brittle cast structure.

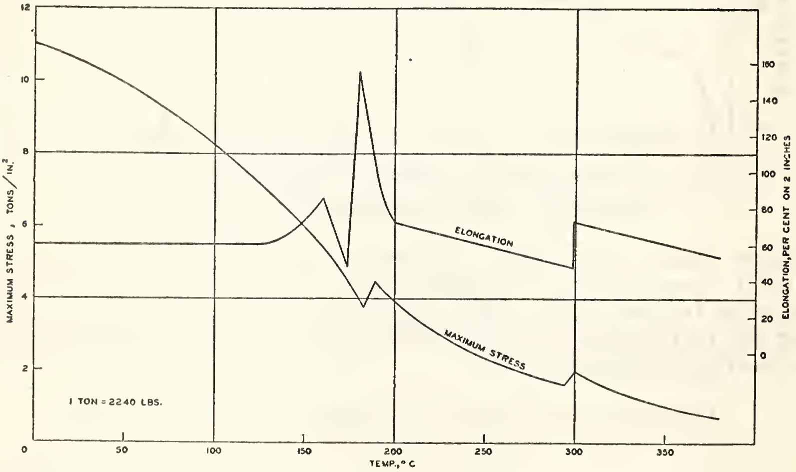

FIGURE 41.—*Tensile strength of zinc at elevated temperatures reported by Bingham*

The marked changes in the tensile strength of zinc at elevated temperatures (fig. 41) and the changes produced in the tensile properties, as measured at room temperature, by quenching from elevated temperatures (fig. 42) reported by Bingham (7) led to the conclusion that zinc exists in several allotropic forms. These results have not been confirmed by later workers on zinc of a higher degree of purity.

Spectroscopically pure zinc (containing less than 0.0001 per cent metallic impurities) in the soft rolled condition; that is, free from strain hardening has a tensile strength of 14,000 lbs./in.² (2) whereas the ordinary grade of commercial rolled zinc in the corresponding condition has a tensile strength of 18,000 lbs./in.² The tensile prop-

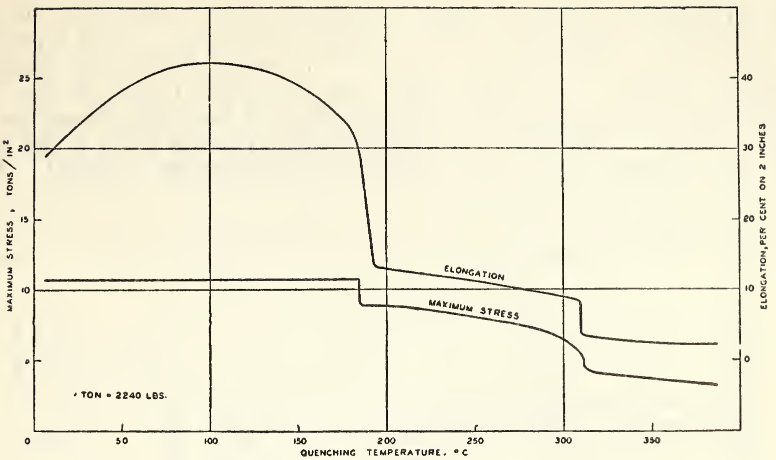

Figure 42.—*Tensile strength at room temperature of zinc quenched from elevated temperatures as reported by Bingham*

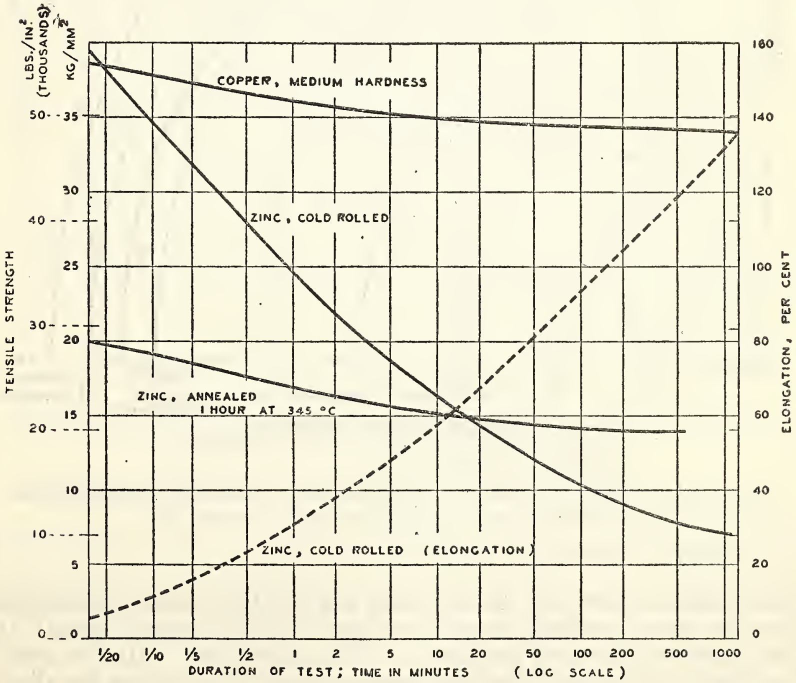

Figure 43.—*Effect of rate of application of load on the tensile properties of zinc*

erties of zinc are noticeably affected by the rate at which the load is applied, as is shown in Figure 43, based on the work of Sachs (4). According to the work of Peirce and his coworkers (1), with a pulling speed as near 0.25 inch/min. as can be obtained, rolled zinc shows a tensile strength, "with the grain," varying from 18,000 lbs./in.^{2} for soft-temper high-grade zinc to 35,000 lbs./in.^{2} for hard-temper prime western zinc. The corresponding elongation varies from 5 per cent for the hardest metal to 65 per cent for the softest material. The "across-grain" strength in every case is a few thousand pounds higher than the corresponding property measured parallel to the "grain" and the elongation is somewhat lower. (The expression "with the grain" made here and in the following pages applies to a direction parallel to the direction of rolling.) Ingall (6) concluded from his work on zinc of 99.954 per cent purity that very definite values for the mechanical properties can not be given. The tensile strength of zinc reduced 77 to 86 per cent by rolling was found to be 13,300 lbs./in.^{2} and after a

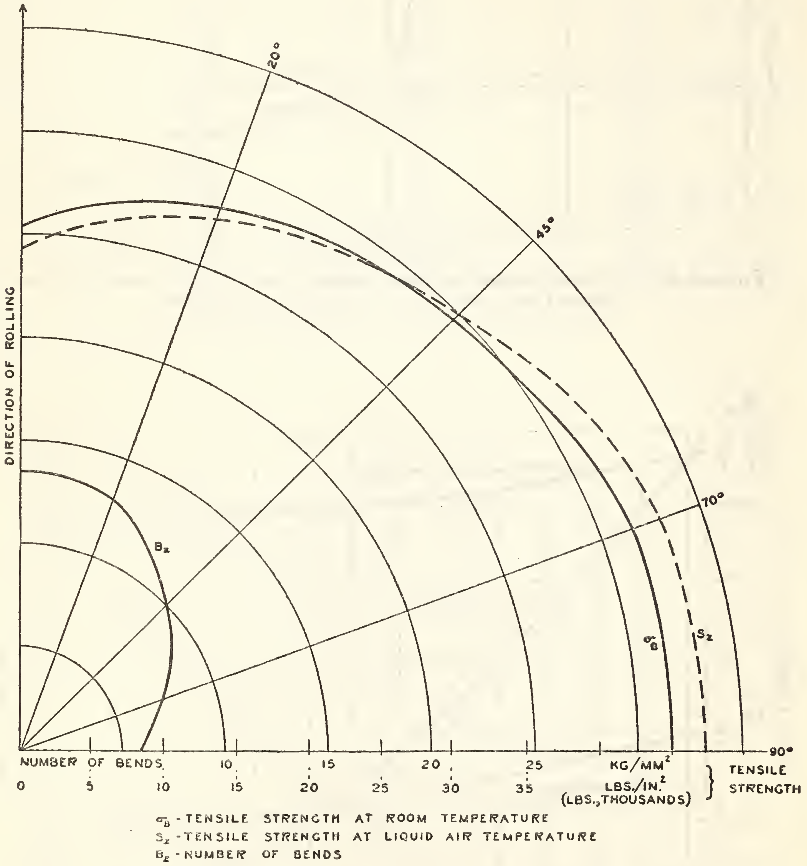

FIGURE 44.—*Effect of orientation of test specimen with respect to the direction of rolling upon the tensile properties of sheet zinc*

(kg/mm^2×1,422=lbs./in.^{2})

reduction of 96 per cent by rolling, 30,200 lbs./in.². A difference of 2,000 to 4,000 lbs./in.² was noted according to the orientation of the specimen with respect to the direction of rolling—the "across-grain" strength being the higher.

Figure 44 from the work of Sachs (4) summarizes the effect upon the tensile properties of the orientation of specimens of sheet zinc with respect to the direction of rolling.

The properties of commercial rolled zinc sheet have been determined by Moore (10), who reported a tensile strength of 24,000 lbs./in.² for sheet not more than 0.05 inch in thickness. (See also "Elastic properties.") The strength of specimens cold rolled from 1.37 to 0.525 mm (0.054 to 0.021 inch) and annealed for 30 minutes at different temperatures as determined by Sachs (4) at room temperature and at the temperature of liquid air, is shown in Figure 45. Similar work has been carried out by Masing and Polanyi (5). Two grades of zinc were used, Kahlbaum "zinc I," containing about 0.2 per cent lead and cadmium, and "Kahlbaum zinc" which was stated to be much purer. Sheet material was obtained by rolling bars to a thickness of 0.07 and 0.1 mm. Some of the sheets were preserved in liquid air until they were tested, and thus represented the freshly rolled condition. Other material was heated for 30 minutes at temperatures between 100° and 400° C. On the basis of the results, it was con-

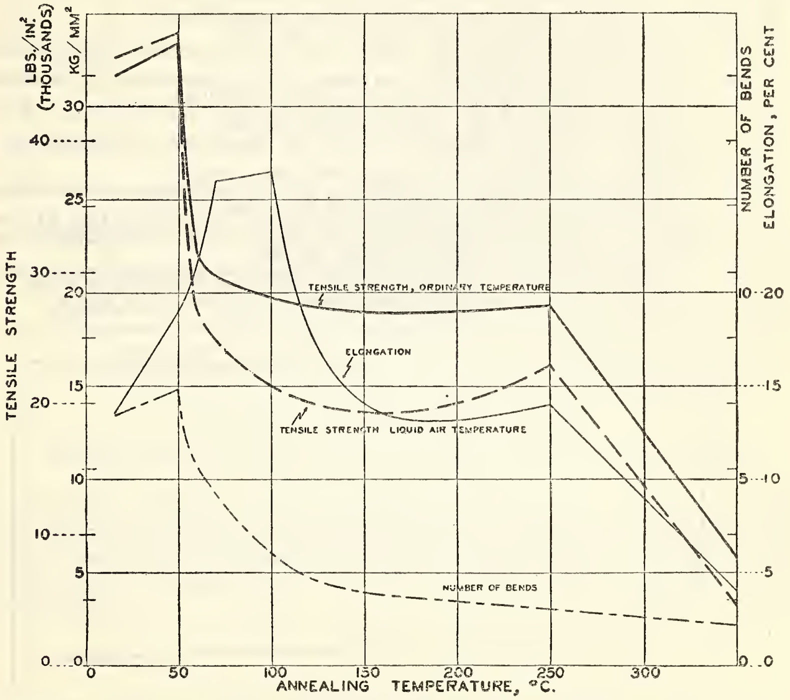

FIGURE 45.—*Tensile and bending properties of annealed sheet zinc at room temperature and at the temperature of liquid air*

(kg/mm²×1,422=lbs./in.²)

cluded that the tensile strength of freshly rolled material is much higher than that of the annealed material. The fine-grained annealed material with an average grain size of $80\mu^2$ had a tensile strength of 15 kg/mm², whereas similar sheet material having a grain size of $50{,}000\mu^2$ had an average tensile strength of 5 kg/mm². The less pure zinc was found to be stronger than the purer material.

Tensile strength

Text reference	Year	Name and title
1	1929	N. J. Zinc Co., research department, Rolled zinc, Research bulletin.
2	1927	Cyr, H. M., Pure zinc, Am. Electrochem. Soc., **52,** p. 349.
3	1926	Freeman, J. R., jr., Sillers, F., jr., Brandt, P., Pure zinc at normal and elevated temperatures, B. S. Sci. Paper No. 522.
4	1925	Sachs, G., Investigations relating to the tenacity of zinc, Z. Metallkunde, **17,** pp. 187–193; J. Inst. Met., **35,** p. 495; 1926; Chem. Abst., **20,** p. 1210; 1926.
5	1924	Masing, G., Polanyi, M., Tenacity of zinc by cold treatment, Z. Physik., **28,** pp. 169–176; Sci. Abst. **28a,** p. 94; 1925; J. Inst. Met., **37,** p. 414; 1927.
6	1921	Ingall, D. H., Relation between the properties and microstructure of pure rolled zinc, J. Inst. Met., **26,** pp. 281–308.
7	1920	Bingham, K. F., Allotropy of zinc, J. Inst. Met., **24,** pp. 333–353.
8	1920	Mathewson, C. H., Trewin, C. S., Finkeldey, W. H., Some properties and applications of rolled zinc strip and drawn zinc rod, A. I. M. M. E., **64,** p. 305–377.
9	1913	Rigg, G., Williams, G. M., Strength of cast zinc in spelter, Am. Soc. Test. Matls., **13,** p. 669.
10	1911	Moore, H. F., An investigation of the strength of rolled zinc, Univ. Ill. Bull., **9,** No. 9; Chem. Eng. **15,** pp. 45–59; 1912; J. Inst. Met., **4,** p. 230; 1915.
11	1911	Faust, O., Tammann, G., The hardening of metals and the determination of their upper and lower elastic limits, 7. Phys. Chem., **75,** pp. 108–126; Chem. Abst., **5,** p. 233.
12	1902	Ingalls, W. R., Production and properties of zinc, Published by Eng. & Min. J.

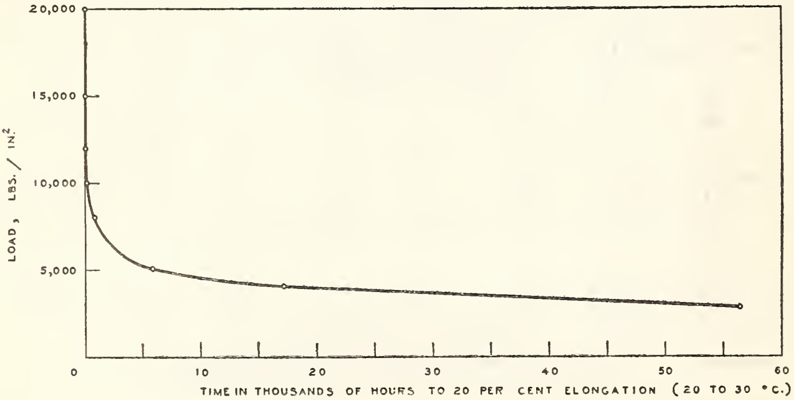

FIGURE 46.—*Creep of soft-rolled zinc (brass-special grade) as determined by the time required for elongation of 20 per cent at any given load*

(b) *Creep.*—The influence of the rate and duration of loading in determining the tensile properites of zinc, as in the case of other soft metals, is very important. Peirce and Anderson (1) have carried out a comprehensive series of static tension tests on various grades of sheet zinc at different temperatures. The general effect of duration of loading on sheet zinc is shown in Figure 46.

A method for presenting concisely the results of static tension tests of this kind, as used by Peirce and Anderson, is shown in Figure 47. During the course of a static test the rate of flow varies, being at first somewhat erratic and rapid and fairly constant thereafter until the elongation is sufficient to cause breaking down. The best numerical index of the flow of any specimen is the portion of the curve where the slope is reasonably uniform. The wide range of values obtained necessitated the use of logarithmic plotting. Hence in this figure, the logarithm of the slope (percentage of elongation per hour) of the curve of Figure 46 has been determined for a number of different loads. A summary of the information relating to the "creep" of zinc obtained in this way for various grades of zinc at different temperatures is given in Table 34.

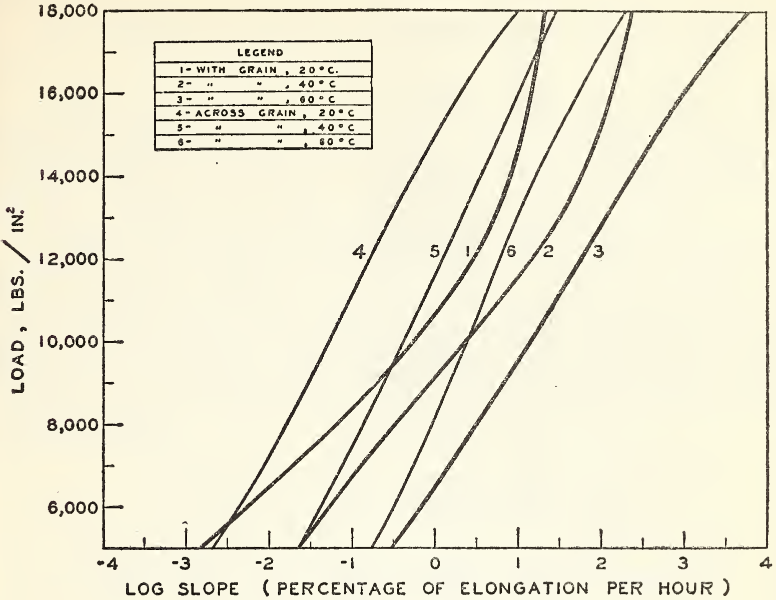

FIGURE 47.—*Creep of zinc under load*

The logarithm of the slope of a creep curve similar to Figure 46 is plotted against the load.

TABLE 34.—*Creep of sheet zinc as determined by static (long time) tension tests*

Metal			"Creep" (per cent elongation/hour)											
			Tests at 20° C. at loads given				Tests at 40° C. at loads given				Tests at 60° C. at loads given			
Grade[1]	Nominal Composition (per cent)	Orientation	5,000 lbs./in.^{2}	8,000 lbs./in.^{2}	12,000 lbs./in.^{2}	18,000 lbs./in.^{2}	5,000 lbs./in.^{2}	8,000 lbs./in.^{2}	12,000 lbs./in.^{2}	18,000 lbs./in.^{2}	5,000 lbs./in.^{2}	8,000 lbs./in.^{2}	12,000 lbs./in.^{2}	18,000 lbs./in.^{2}
High grade—soft	Pb 0.05; Cd 0.002.	[2] W	0.0015	0.0639	2.83	19.8	0.0215	0.325	15.0	240	0.272	3.334	57	6024
		[3] A	.002	.015	.165	10.5	.023	.130	1.20	26.7	.1714	.862	5.714	206.4
High grade—hard rolled	do	W	.0069	.194	1.6	34.3	.100	1.50	7.500	70.6	.800	7.50	50.0	720
		A	--------	.03	.319	2.52	.033	.333	1.710	25.7	.300	2.309	10.80	100
Brass special—soft	Pb 0.3; Cd 0.3	W	.00058	.0155	.577	54.5	.0055	.100	1.060	85.80	.0105	.546	6.024	666.7
		A	--------	.00314	.017	.49	.0023	.0084	.096	1.850	.0094	.100	.400	8.426
Brass special—medium hard	do	W	.0009	.042	.49	10.9	.0092	.308	2.140	23.10	.063	1.72	8.576	214.6
		A	--------	.0052	.078	2.0	.0028	.0414	.321	5.000	.027	.400	1.580	15.02
Brass special—hard	do	W	.0051	.175	.97	6.25	.0667	.428	4.620	30.0	.500	6.02	17.15	250.0
		A	.0025	.130	.705	5.83	.0117	.500	2.400	25.0	.188	3.53	13.33	109.5

[1] Grades as designated in American Society for Testing Materials Specification, soft, medium, or hard rolled.
[2] With the grain.
[3] Across the grain.

Creep

Text reference	Year	Name and title
1	1929	Peirce, W. M., Anderson, E. A., Some practical aspects of creep in zinc, Trans. Am. Inst. Min. Met. Engrs., Inst. of Metals Division, p. 560.

(c) *Elastic properties.*—Information on the modulus of elasticity of spectroscopically pure zinc is lacking. Such determinations as are available have been made on zinc of a somewhat lower degree of purity. A value of 12 to 20×10^6 lbs./in.^{2} has been quoted by Peirce and his coworkers (1) for the modulus of elasticity of zinc.

In Table 35 are summarized the results of tension tests carried out by Moore (3). Although a limit of proportionality ranging from 2,100 to 5,800 lbs./in.^{2} was reported, Moore stated that "zinc, either cast or rolled, is imperfectly elastic" and expressed the further opinion that it was "doubtful if the elastic limit had any special physical significance" (the elastic limit being defined either as the stress at which a permanent set occurred or as the limit of proportionality of stress to deformation).

TABLE 35.—*Tensile properties of rolled zinc* (*3*)

(Speed of pulling=0.5 inch/min. in all cases except first two)

Thickness of rolled plate	Stress at first noticeable set	Proportional limit	Ultimate tensile strength[1]	Modulus of elasticity	Elongation (8 inch)	Orientation of specimen
Inch	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Per cent*	
Cast.	1, 600	2, 100	9, 050	11, 025, 000	Slight.	
1	[2]0+	0+	22, 200	----------------	7. 5	With grain.
1	900	2, 900	21, 350	10, 450, 000	4. 8	Do.
1	900	4, 600	23, 050	10, 370, 000	0. 3	Across grain.
0. 6	0+	4, 200	21, 500	11, 033, 000	16. 6	With grain.
. 6	0+	4, 000	23, 500	10, 780, 000	5. 8	Across grain.
. 25	0+	5, 150	23, 800	12, 767, 000	11. 9	With grain.
. 25	0+	5, 000	22, 250	10, 967, 000	0. 3	Across grain.
. 10	0+	3, 600	22, 300	10, 650, 000	18. 7	With grain.
. 10	0+	5, 500	33, 600	13, 700, 000	14. 3	Across grain.
. 018	0+	5, 800	25, 500	10, 533, 000	--------	With grain.
. 006	0+	5, 100	26, 500	14, 800, 000	6. 5	Do.

[1] "Rounded off" to nearest 50 pounds.
[2] "0+" indicates a stress lower than the lowest reading taken.

Peirce and Anderson (2), in their recent tests made for the purpose of determining the safe maximum fiber stress values for various grades of sheet zinc in calculating the proper purlin spacings for roofs under given loading conditions, have given values for the apparent elastic limit (average of three specimens in each test), the method used being that described by J. B. Johnson in his book, "Materials of Construction." Their results are given in Table 36.

TABLE 36.—*"Johnson's elastic limit" for rolled zinc (2)*

Specimen	Rate of stretch		Stress		Elongation in 2 inches	Temperature
	Below Johnson limit	At rupture	At Johnson limit	At rupture		
	Inch/inch/min.		*Lbs./in.²*	*Lbs./in.²*	*Per cent*	*° C.*
A-w[1]	0.00027	0.030	4,300	18,800	66	12.5–19.5
	.00118	.650	4,000	20,800	49	25
	.0030	.082	5,300	18,300	64	25
A-a	.00023	.033	5,400	22,000	40	20
	.0010	.750	6,300	26,200	36	24.5
	.0027	.092	8,000	24,000	34	25
B-w	.00020	.035	6,200	20,200	38	12
	.00112	.60	5,200	22,200	35	23.5
	.00265	.098	6,500	20,300	35	22.5
B-a	.000182	.039	10,200	29,200	26	13
	.000823	.70	10,200	30,900	22	23
	.00228	.12	10,000	29,200	24	22.5
C-w	.000243	.034	5,200	18,200	49	23.5
	.00107	.65	5,800	21,200	43	23
	.0026	.097	6,000	19,500	33	23
C-a	.000207	.039	10,300	28,200	20	24
	.00095	.75	10,500	29,500	14	23
	.00253	.113	10,500	28,300	19	23

[1] Specimens were cut with the longitudinal axis in the direction of rolling (marked "w") and across this direction (marked "a").
The significance of A, B, and C is as follows:

	Nominal composition	
	Lead	Cadmium
	Per cent	*Per cent*
A, high-grade zinc, soft	0.05	0.002
B, brass special, soft	.3	.3
C, prime western, soft	.8	.15

Elastic properties

Text reference	Year	Name and title
1	1929	N. J. Zinc Co., research department, Research Bulletin, Rolled Zinc.
2	1929	Peirce, W. M., Anderson, E. A., Some practical aspects of creep in zinc, Trans. Am. Inst. Min. & Met. Engrs., Inst. of Metals Division, p. 560.
3	1911	Moore, H. F., An investigation of the strength of rolled zinc, Univ. Ill. Bull., **9**, No. 9; Chem. Eng., **15**, p. 45; 1912.

(d) *Ductility.*—The ductility of sheet zinc is usually determined by means of a cupping test. Instead of the conventional form of test, usually referred to as the Erichsen test in which the sheet is slowly deformed over a spherical nosed tool, a more rapid or "dynamic ductility" test is preferred. The results are claimed to be more nearly comparable with those obtained in shop operations of drawing and stamping. Essentially the test differs from the more familiar Erichsen test in that the cupping operation can be carried out at higher speeds. A series of cuppings are made with increasing depths of cup until rupture of the cupped sheet occurs. The apparatus, as developed in the Research Laboratories of the New Jersey Zinc Co., has been described (2), and this test has been embodied in standard specifications of the American Society for Testing Materials for sheet zinc (1). In Tables 37 and 38 are summarized the ductility and temper of rolled zinc ribbon and of sheet zinc of various thicknesses according to this specification.

TABLE 37.—*Dynamic ductility and temper of rolled zinc strip; A. S. T. M. standards, B 69–29*

American zinc gage	Thickness	Dead soft		Soft		Half hard		Hard	
		Dynamic ductility, minimum [1]	Temper, maximum [2]	Dynamic ductility, minimum	Temper, maximum	Dynamic ductility, minimum	Temper, maximum	Dynamic ductility, minimum	Temper, maximum
	Inch	*Inch*	*Per cent*	*Inch*	*Per cent*	*Inch*	*Per cent*	*Inch*	*Per cent*
3	0.006	0.275	70	0.255	76	0.215	80	0.165	86
4	.008	.280	65	.260	72	.220	75	.170	83
5	.010	.285	60	.265	66	.225	70	.175	80
6	.012	.290	55½	.270	62	.230	65	.180	77
7	.014	.295	52	.275	58	.235	61	.185	74
8	.016	.300	48½	.280	54	.240	58	.190	72
9	.018	.305	46	.285	51	.245	54	.195	69
10	.020	.310	43½	.290	48	.250	51	.200	68
	.022	.315	41½	.295	45	.255	48	.205	65
11	.024	.320	40	.300	43	.260	45	.210	63
	.026	.325	39	.305	40	.265	43½	.215	61
12	.028	.330	37½	.310	37	.270	42½	.220	59
	.030	.335	37	.315	37	.275	42	.225	58
13	.032	.340	36½	.320	36½	.280	41	.230	57
	.034	.345	36	.324	36	.285	40½	.235	56
14	.036	.347	--------	.326	--------	.290	--------	.240	--------
	.038	.349	--------	.328	--------	.295	--------	.245	--------
15	.040	.350	--------	.329	--------	.300	--------	.250	--------
	.042	.352	--------	.330	--------	.300	--------	.250	--------
	.044	.353	--------	.331	--------	.305	--------	.255	--------
	.046	.354	--------	.332	--------	.305	--------	.255	--------
	.048	.355	--------	.333	--------	.310	--------	.260	--------
17	.050	.356	--------	.334	--------	.310	--------	.260	--------

[1] Depth of cup at which failure just occurs.

[2] Temper, as expressed here in per cent, indicates the extent to which the specimen springs out when released at one end after being wrapped closely around a cylindrical mandrel, 2½ inches in diameter; 100 per cent is the highest temper possible. The percentage of the temper is read from the position of the free end of the specimen on the underlying scale graduated empirically to give the temper.

TABLE 38.—*Dynamic ductility and temper of sheet zinc; A. S. T. M. standards B 69–29*

American zinc gage	Thickness	Commercial		American zinc gage	Thickness	Commercial	
		Dynamic ductility, minimum	Temper, maximum			Dynamic ductility, minimum	Temper, maximum
	Inch	*Inch*	*Per cent*		*Inch*	*Inch*	*Per cent*
3	0.006	0.165	83	13	.032	.230	48
4	.008	.170	77½		.034	.235	47
5	.010	.175	73	14	.036	.240	-------
6	.012	.180	69		.038	.245	-------
7	.014	.185	65	15	.040	.250	-------
8	.016	.190	62		.042	.250	-------
9	.018	.195	58½		.044	.255	-------
10	.020	.200	57		.046	.255	-------
	.022	.205	55½		.048	.260	-------
11	.024	.210	54	17	.050	.260	-------
	.026	.215	52½				
12	.028	.220	51				
	.030	.225	49				

See notes under Table 37, p. 91.

Ductility

Text reference	Year	Name and title
1	1930	American Society for Testing Materials Standards, p. 585, Standard specification for rolled zinc, B69–29.
2	1929	N. J. Zinc Co., Rolled zinc, Research Bulletin.

(2) TRANSVERSE STRENGTH.—Rigg and Williams have reported on the transverse strength of cast zinc, a summary of their results being given in Table 39.

TABLE 39.—*Transverse strength of cast zinc*

(Cylindrical specimens, 1.25 inch diameter, were cast in iron molds; distance between supports, 12 inches; load applied at center; speed of testing, 0.55 inch per minute)

Grade of zinc [1]	Deflection [2]	Maximum load [3]	Modulus of rupture [4]
	Inch	*Pounds*	*Lbs./in.^{2}*
High grade	0.25	725	11,650
	.25	650	10,600
Intermediate grade	.30	625	10,150
	.31	750	12,350
Brass special	.29	1,025	16,550
	.21	800	13,100
Prime Western, No. 1	.13	675	11,000
	.13	625	10,050
Prime Western No. 2	.18	1,000	16.250
	.19	650	10,350

[1] See Table 32 for composition.

[2] Average of 4 determinations; the deflection measured is that at which the specimen broke when the maximum load was applied.

[3] Average of 4 determinations, "rounded off" to nearest 25.

[4] $\frac{Wl}{\pi r^3}$, W=load in pounds, l=distance between supports (inch), r=radius of cylindrical specimen (inch); result "rounded off" to nearest 50.

Transverse strength

Text reference	Year	Name and title
1	1913	Rigg, G., Williams, G. M., Strength of cast zinc or spelter, Proc. Am. Soc. Test. Matls., **13,** p. 669.

(3) Compressive Strength.—The compressive strengths of a number of grades of cast zinc have been determined by Rigg and Williams (1). Cylindrical specimens, 1 inch in diameter and 2.6 inches long, were tested on the end and at a speed of 0.0319 inch per minute. Their results are given in Figure 48.

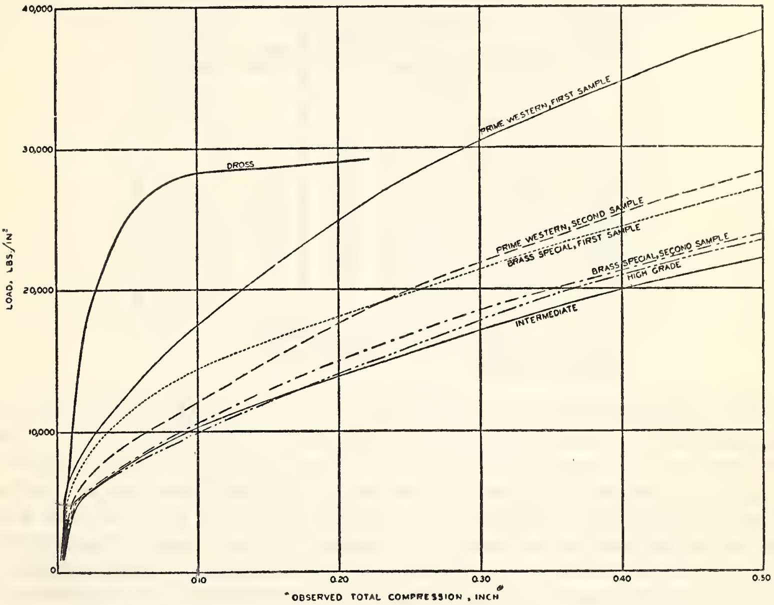

Figure 48.—*Compressive strength of cast zinc*

Compressive strength

Text reference	Year	Name and title
1	1913	Rigg, G., Williams, G. M., Strength of cast zinc or spelter, Proc. Am. Soc. Test. Matls., **13,** p. 669.

(4) Hardness.—Hardness determinations, with a recording type of scleroscope, have been made by this bureau on cast zinc of high purity. The results are summarized in Table 40. On individual specimens the hardness varied in several cases as much as 3 or 4 points and in no case was the variation less than 2 points. Inasmuch as the maximum variation between the average values for all specimens was only 2 points, it was concluded that quenching at different temperatures has no effect on the scleroscope hardness of cast zinc (6).

Hardness tests with a Rockwell machine, using a ball one-eighth inch in diameter and a load of 60 kg applied for one minute, also were made on the same specimens. The results obtained are given in Table 40. It is evident from the data that, within experimental error, there is no change in Rockwell hardness of pure cast zinc annealed and quenched from temperatures as high as 342° C.

TABLE 40.—*Scleroscope and Rockwell hardness of cast zinc of high purity after heat treatment*

(Lead 0.001 per cent; cadmium 0.003 per cent; iron 0.003 per cent; arsenic less than 0.00001 per cent; copper, tin, and antimony not detected)

Temperature of quenching	Hardness		Temperature of quenching	Hardness	
	Scleroscope [1]	Rockwell (C scale) [2] ⅛ inch ball, 60 kg, 1 minute		Scleroscope [1]	Rockwell (C scale) [2] ⅛ inch ball, 60 kg, 1 minute
° C.			*° C.*		
20	----------	97	190	9.0	----------
61	8.8	107	212	9.4	----------
94	9.4	----------	237	9.6	----------
142	9.2	----------	267	8.8	107
154	8.2	110	285	9.2	----------
158	7.6	----------	289	8.8	----------
163	8.6	----------	302	8.0	----------
171	7.8	----------	342	9.2	116
180	9.0	102	(3)	----------	106

[1] Average of 5 determinations on each specimen.
[2] Average of 2 determinations on each specimen.
[3] Cooled in crucible.

The Brinell hardness of cast zinc varies with the grain size and composition of the specimen, according to Anderson (1). Brinell hardness values ranging from 30 for a coarse-grained high-grade zinc to 60 for a fine-grained zinc of prime western grade have been reported.

In Table 41 are summarized Brinell hardness numbers at room and elevated temperatures of specimens of cast zinc of high purity (6). The specimens were disks 2 inches in diameter and about one-half inch thick, cast in a steel mold. All specimens were annealed at 150° C. before the hardness was determined. Satisfactory readings could not be obtained at temperatures higher than that of the supposed allotropic change in zinc, but it is quite evident from the data that no sudden change in hardness, within the limits of error of the method of measurement, occurred over the temperature range studied.

TABLE 41.—*Brinell hardness of cast zinc of high purity at elevated temperatures*

(Lead 0.001 per cent; cadmium 0.003 per cent; iron 0.003 per cent; arsenic less than 0.00001 per cent, copper, tin, and antimony not detected.)

Temperature of test	Brinell hardness [1]	Temperature of test	Brinell hardness [1]
° C.		*° C.*	
20	31.0	160	12.5
110	19.0	170	10.5
120	18.5	180	9.0
130	16.3	190	7.5
140	15.5	200	6.5
150	13.0		

[1] 10 mm ball, 500 kg load, applied for 30 seconds. Average of 3 determinations on each specimen.

For testing rolled zinc less than one-eighth inch thick, the Brinell test is of very doubtful value, according to Anderson (1). On heavier gages of rolled zinc, values have been reported (1) ranging from 40 for hot-rolled zinc (99.94 per cent pure) to 60 for cold-rolled zinc of prime western grade. No satisfactory method for measuring the hardness of zinc in the commonly used gages between 0.006 and 0.035 inch has been devised as yet (2).

The Brinell hardness of zinc of 99.954 per cent purity in various conditions has been reported by Ingall (9). The conventional Brinell method was modified in order to suit it to the material, a load of 200 kg being used. It was noticed that the impression was invariably slightly oval in outline, the major axis being parallel to the direction of rolling. For cast zinc a hardness number of 31.7 was found. The results obtained for rolled zinc are summarized in Table 42.

Table 42.—*Brinell hardness of rolled zinc* (*9*)

(200 kg load, 60 seconds [1])

Thickness of sheet	Reduction by rolling	Hardness after various treatments			
		As rolled	Rolled and annealed one-half hour, 100° C.	Rolled and annealed one-half hour, 150° C.	Rolled and annealed one-half hour, 200° C.
Inch	*Per cent*				
0.366	77.5	29.7	31.7	32.5	30.6
.315	80.5	31.2	31.9	32.5	30.0
.232	85.8	31.2	31.9	32.5	30.2
.188	88.5	32.5	34.2	33.4	31.0
.126	92.3	36.9	37.5	34.0	31.0
.069	95.8	33.4	34.2	32.5	31.2

[1] Diameter of ball not stated.

By means of an indentation method, not fully investigated as yet, Friend and Thorneycroft (3) have studied the hardness of zinc at elevated temperatures. The results are in general agreement with those of other investigators. The authors called attention to a singularity in the neighborhood of 160° C. and its possible bearing on the alleged allotropy of zinc. Metal of 99.9 per cent purity was used.

Hardness

Text reference	Year	Name and title
1	1930	Anderson, E. A., A. S. S. T., National Metals Handbook, Physical Constants of Zinc, p. 808.
2	1929	N. J. Zinc Co., Research Bulletin, Rolled Zinc.
3	1929	Friend, J. N., Thorneycroft, W. E., The resistance of zinc to indentation (a preliminary account), J. Inst. Met., **41**, No. 1, p. 97.
4	1928	Schmid, E., Significance of mechanical twin formation for plasticity and hardness, Zeit. Metallkunde, **20**, pp. 421–425; Chem. Abst., **23**, p. 1375; 1929.
5	1927	Mallock, A., Hardness of alloys, Nature, **119**, p. 669; J. Inst. Met., **38**, p. 432.
6	1926	Freeman, J. R., jr., Sillers, F., Brandt, P. F., Pure zinc at normal and elevated temperatures, B. S. Sci. Papers, No. 522.
7	1923	Ito, K., Hardness of metals as affected by temperature, Sci. Rept. Tohoku Imp. Univ., **12** pp. 137–148; J. Inst., Met., **31**, p. 384, 1924.
8	1922	Kurnakoff, N. A., Achnasaroff, A. N., On the influence of the velocity of cooling on the hardness and microstructure of eutectic mixtures, Z. Anorg. Chem., **125**, pp. 185–206; J. Inst. Met., **30**, p. 494, 1923; Chem. Abst., **17**, p. 1409, 1923.

Hardness—Continued

Text reference	Year	Name and title
9	1921	Ingall, D. H., Relation between the mechanical properties and microstructure of pure rolled zinc, J. Inst. Met., **26,** pp. 281–308.
10	1920	Bingham, K. E., Allotropy of zinc, J. Inst. Met., **24,** pp. 333–353.
11	1920	Mathewson, C. H., Trewin, C. S., Finkeldey, W. H., Some properties and applications of rolled zinc strip and drawn zinc rod, Amer. Inst. Min. & Met. Engrs. ,**64,** pp. 305–377.
12	1918	Lazarev, P. P., The relations between the hardness and other physical properties of elements. The relation between hardness and ultimate strength of elements, Bull. Acad. Sci. Russ., pp. 2241–2245; 1919, pp. 1005–1006; Chem. Abst., **17,** p. 2210; 1923.
13	1918	Smith, E. A., Zinc industry, Longmans Green & Co., London.
14	1915	Schulz, E. H., Recent processes for improving the physical properties of zinc, Chem. Ztg., **39,** p. 547; Chem. Abst., **10,** p. 742; 1916.

(5) IMPACT RESISTANCE.—According to Schulz (1) the impact resistance of zinc is low. Pressed zinc having a tensile strength of 20 kg/mm^2 (28,500 lbs./in.^{2}) and elongation of 30 per cent and more has an impact resistance (single-blow notched-bar impact test) between 0.55 mkg/cm^2 (25.62 ft.-lbs./in.^{2}) and 0.75 mkg/cm^2 (34.94 ft.-lbs./in.^{2}). Schulz has reported the results of a series of tension-impact tests on notched bars of extruded zinc containing 1 per cent lead and 0.2 per cent iron, showing (*a*) that the impact-tensile strength increased from 0.18 to 0.62 mkg/cm^2 (8.39 to 28.88 ft.-lbs/in.^{2}) as the angle of the 5 mm (0.20 inch) v notch was changed from 40° to 120°; (*b*) with a rounded notch (5 mm (0.20 inch) deep, 8.5 mm (0.33 inch) radius) an impact tensile strength of 1.6 mkg/cm^2 (74.63 ft.-lbs./in.^{2}) was obtained; (*c*) by filleting the corners of a rectangular notch, 5 mm (0.20 inch) deep, the impact tensile strength was increased from 0.62 to 1.13 mkg/cm^2 (28.88 to 52.65 ft.-lbs./in.^{2}). Similar results were reported for the conventional single-blow impact test. With a V notch (7.5 mm (0.36 inch) deep), the impact resistance ranged from 0.35 to 0.50 mkg/cm^2 (16.29 to 23.28 ft.-lbs./in.^{2}) as the angle was changed from 40° to 120°. With a rounded notch the impact resistance ranged from 0.52 mkg/cm^2 (24.21 ft.-lbs./in.^{2}) for a notch rounded to 2 mm (0.08 inch) radius to 0.93 mkg/cm^2 (43.32 ft.-lbs./in.^{2}) for a half-round (15 mm (0.59 inch) diameter) notch.

Schulz reported (2) no marked improvement in the impact resistance of zinc resulting from alloying with small amounts of other metals, such as copper or aluminum. Although the tensile strength of extruded zinc was increased decidedly by alloying with 1 per cent of copper (11.5 to 23 kg/mm^2 or 16,350 to 32,710 lbs./in.^{2}), the impact resistance of notched specimens was increased only to 0.73 mkg/cm^2 (34.00 ft.-lbs./in.^{2}) from an initial value of 0.53 mkg/cm^2 (24.68 ft.-lbs./in.^{2}).

Impact resistance

Text reference	Year	Name and title
1	1919	Schulz, E. H., Feidler, R., Einige beitrage zur technologie des press und walzzinks, Forschungsarbeiten auf dem Gebiete des Ingenieurwesens, Sonderreihe M (1), p. 23; Chem. Abst., **15,** p. 2826.
2	1916	Schulz, E. H., Neuere erfahrungen uber wege zur veredelung des zinks, Metall Erz,**13,** pp. 279–287.
3	1913	Rigg, G., Williams, G. M., Strength of cast zinc or spelter, Am. Soc. Test. Matls., **13,** p. 669.

(6) Effect of Temperature on Mechanical Properties.—(*a*) *Tensile strength and hardness.*—Cast zinc of ordinary commercial purity is brittle at normal (room) temperatures; between 100° and 150° C., approximately, it is malleable and ductile and at 200° C. is again brittle and can be broken up by pounding in a mortar (12). This effect, especially at the higher temperatures, may properly be attributed in large measure to the presence of impurities in the metal.

The ductility of wrought zinc at higher temperatures has been studied by Haines (15). The assumption underlying this work, that zinc becomes viscous near the breaking stress, requires modification in light of present-day knowledge of the plastic flow of metals, but the experimental results are of decided interest. They are summarized in Figures 49 and 50. The zinc used was of commercial purity (0.52 per cent lead) in the form of wire approximately 0.88 mm in diameter. The singularity in the ductility of zinc in the region of 100° C. was attributed by Haines to the presence of the lead in the metal.

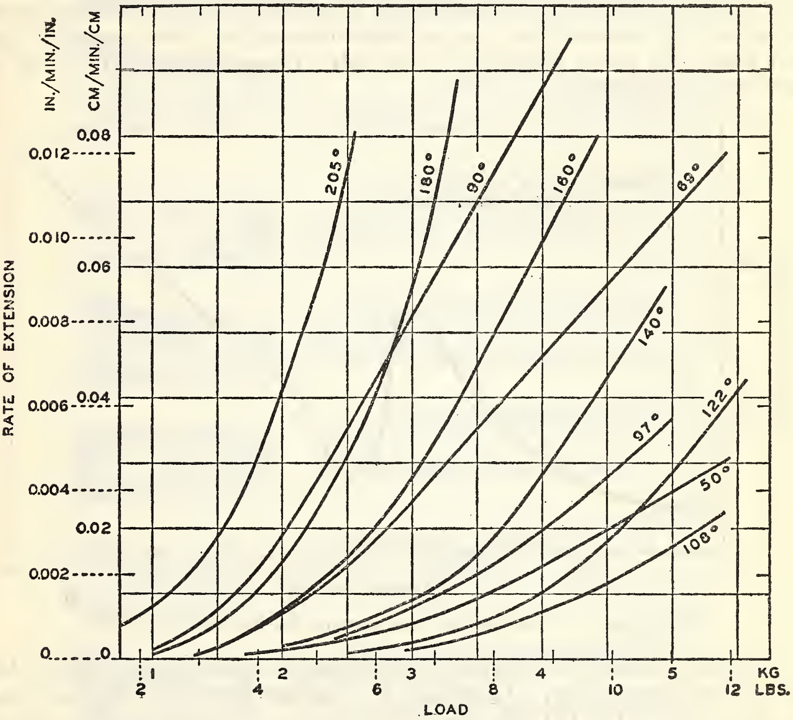

Figure 49.—*Effect of temperature on the ductility of zinc wire*

The tensile properties at elevated temperatures of cast zinc of high purity as determined by this bureau have been discussed (Table 33), in a preceding section. The peculiar and apparently characteristic appearance of the specimen after fracturing by tension is shown in Figure 51.

Mathewson, Trewin, and Finkeldey (10) found a perceptible change in the rate of decrease of the strength of high purity zinc at about 100° C. and a somewhat greater change for less pure material. They concluded that the phenomenon was related to recrystallization of the metal during test. Curves showing the change of tensile strength at elevated temperatures of the two grades of zinc as tested "with the grain" and "across the grain" are given in Figure 52. The corresponding curves showing the effect on ductility are given in Figure 53. The results of the earlier work of Ludwik (13), which was not carried in such detail, are in general agreement with these results.

It has previously been shown (fig. 43) that the tensile strength of sheet zinc determined at room temperature is greatly affected by the rate at which the load is applied. Figure 54, from the work of Sachs (6) summarizing the tensile strength of sheet zinc at the temperature of liquid air, shows that, under these conditions, the properties are not nearly so much affected by the rate of application of the load as at room temperature.

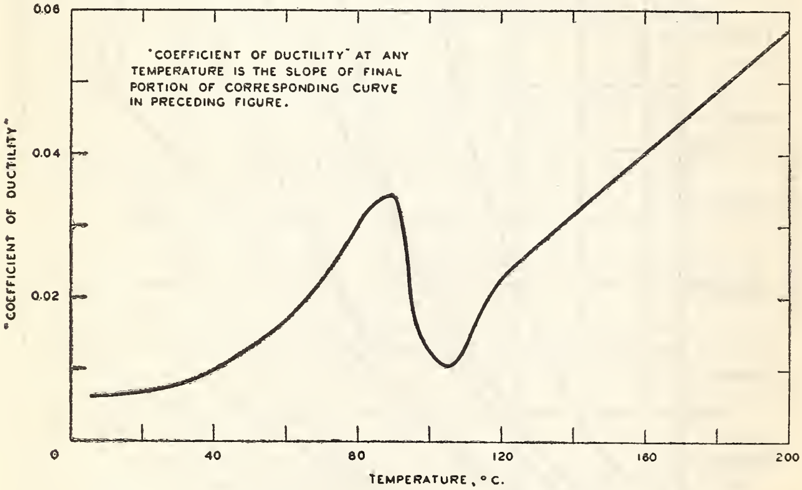

FIGURE 50.—*Ductility of zinc wire at elevated temperatures*

Information on the hardness of zinc at elevated temperatures has been given previously. (Table 41.) Further reference may be made to the work of Ito (8) who has attempted to summarize the relation between Brinell hardness and temperature in the equation: $\log H_2 - \log H_1 = \alpha(t_2 - t_1)$; H_1 and H_2 being the hardnesses at the two temperatures t_1 and t_2, and α the temperature coefficient. With zinc of 99.2 per cent purity the results given in Table 43 were obtained. The value calculated for α was 0.00210.

TABLE 43.—*Effect of temperature on the Brinell hardness of zinc,* (*8*)

Temperature	Brinell hardness	Temperature	Brinell hardness
° *C.*		° *C.*	
−44	85.5	63	50.0
−18	76.0	83	46.0
0	68.3	100	40.4
18	63.6	125	36.5
42	57.0	143	35.0

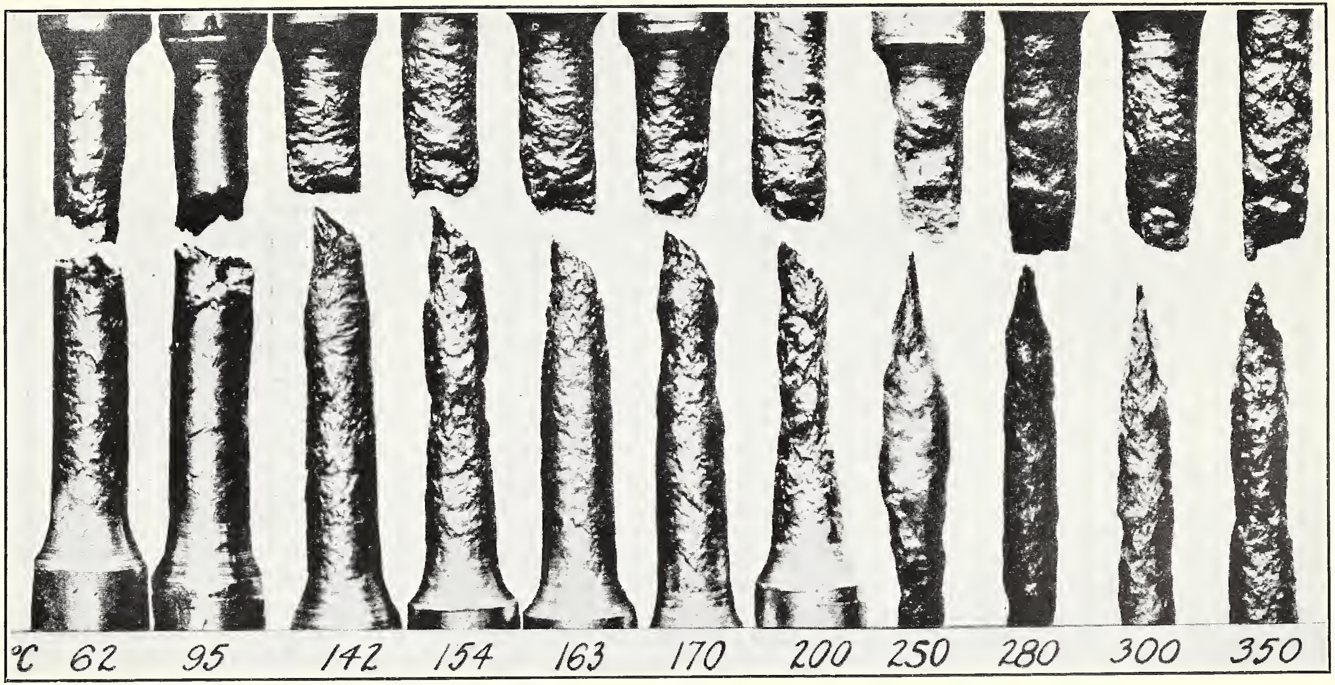

FIGURE 51.—*Appearance of cast zinc broken in tension at elevated temperatures,* × 1⅛

Studies of the "impact hardness" of zinc at elevated temperatures have been made by Sauerwald and Knehans (7). A hemispherical-nosed tup was allowed to drop upon the flat surface, 20 by 30 mm., of the 15 mm. thick hot specimen. The distance of fall was varied to suit the metal under test, but was maintained throughout the series of tests on each metal. The hardness was calculated as the amount of work done in compressing a cubic millimeter of metal, that is, mm. – kg/mm³. The zinc used was annealed at 350° C. previously to testing. The results are summarized in Figure 55. The results, when plotted, define a curve which consists essentially of three linear portions with slight breaks occurring at 70° and 250° C.

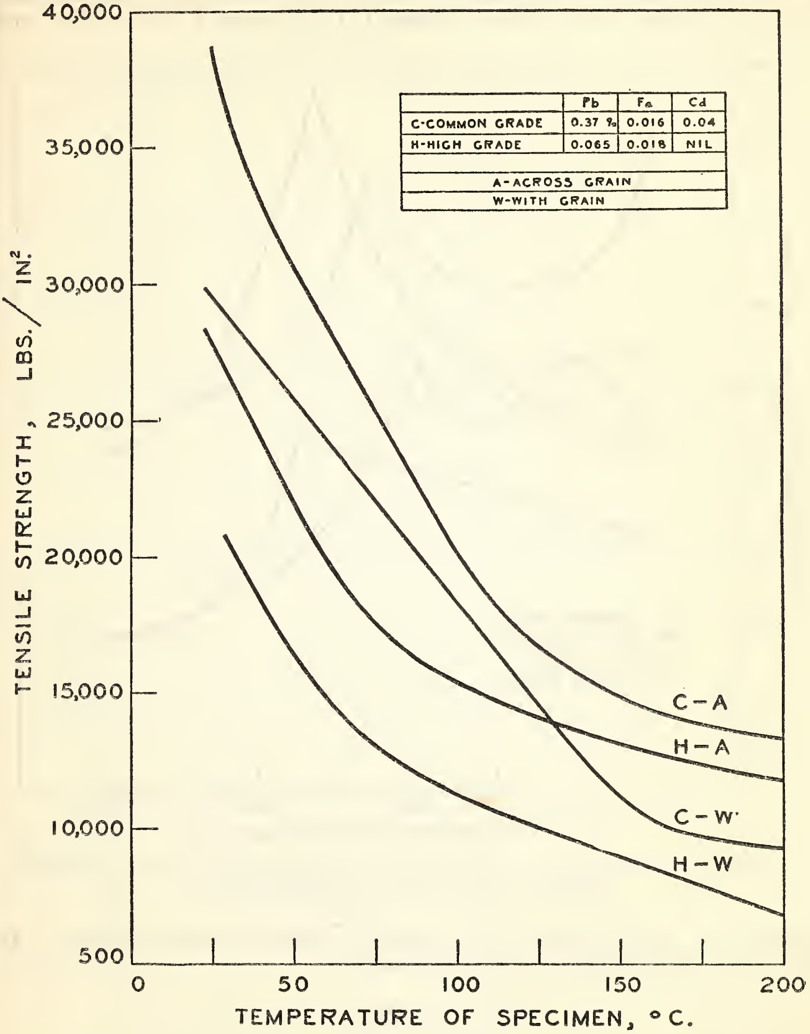

Figure 52.—*Tensile strength of rolled zinc at elevated temperatures as tested "with the grain" and "across the grain"*

Ludwik's studies (11,13) of the indentation hardness of zinc at elevated temperatures carried out by means of a cone instead of a ball have led to conclusions not differing widely from those of the other investigators referred to.

(b) *Rigidity.*—By means of a torsional pendulum consisting of a heavy disk supported between two taut wires, the upper one of platinum, the lower one of zinc, Kikuta (9) determined the rigidity and logarithmic decrement for zinc wire at different temperatures. In this work, the rigidity, n, was defined as:

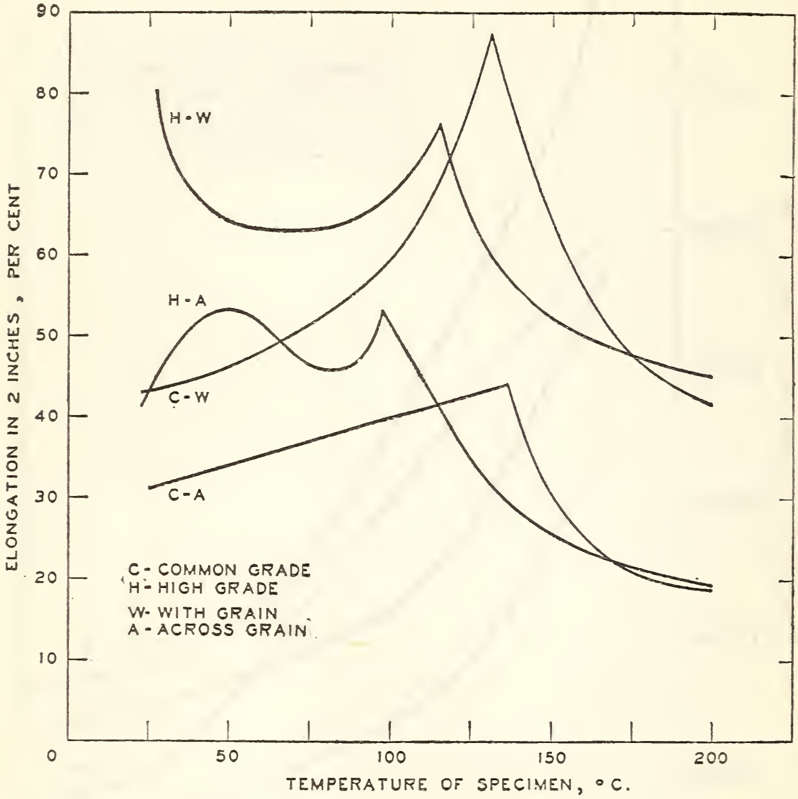

FIGURE 53.—*Elongation of rolled zinc at elevated temperatures as tested "with the grain" and "across the grain"*

$$n = \frac{2la}{\pi r^4},$$

in which l and r equal the length and radius, respectively, of the test wire (zinc) and a, the coefficient of the elastic restoring force corresponding to unit angle twist of the test wire. The logarithmic decrement, λ_2, was defined as

$$\lambda_2 = \frac{\lambda T_1 - \lambda_1 T}{\sqrt{T_1^2 - T^2}}$$

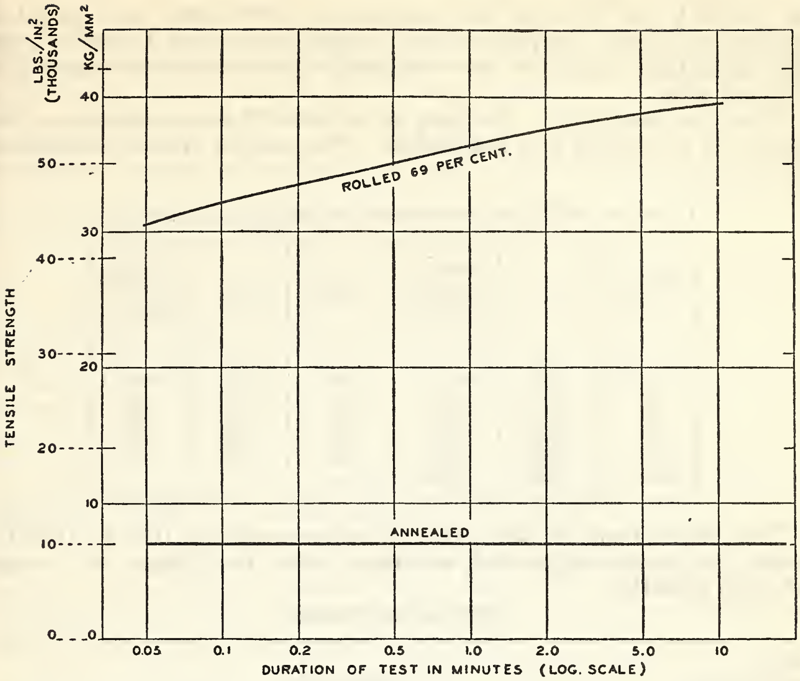

Figure 54.—*Tensile strength of sheet zinc at the temperature of liquid air* (kg/mm² × 1,422 = lbs./in.²)

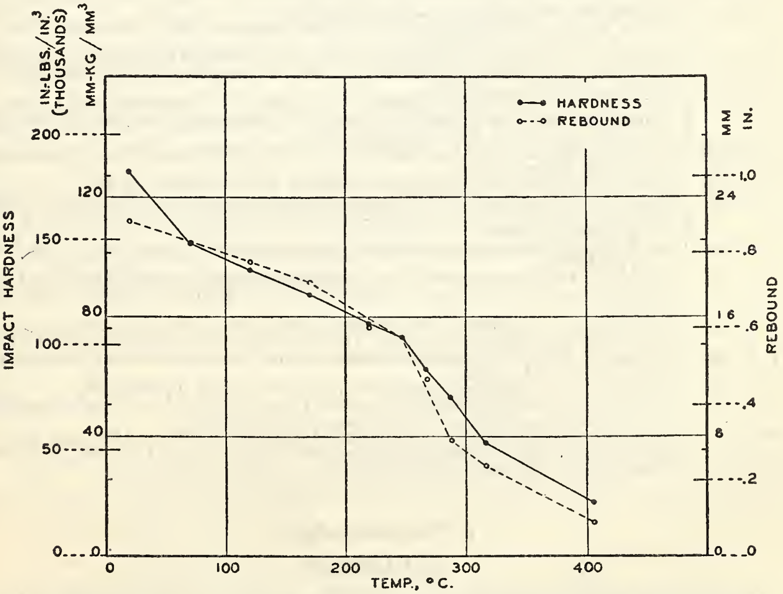

Figure 55.—*"Impact hardness" of cast zinc at elevated temperatures*

in which λ and T equal the logarithmic decrement and period of oscillation of the complete set-up, respectively, and λ_1 and T_1, the corresponding values for the oscillating system after the removal of the test wire.

The zinc used was in the form of wire 0.455 mm in diameter; the purity of the metal was not stated. The results are summarized in Table 44.

Table 44.—*Effect of temperature on rigidity of zinc wire (9)*

Temperature	Rigidity	Logarithmic decrement of oscillation	Temperature	Rigidity	Logarithmic decrement of oscillation
° *C*	$\times 10^{10}$		° *C*	$\times 10^{10}$	
25.5	3.585	0.0511	158	2.173	0.3886
65	3.267	.2046	179	1.713	.4836
80	3.070	.2055	205	1.557	.5280
99	2.780	.2737	227	1.300	.6636
111	2.470	.3086	256	1.193	.7130
124	2.370	.3276	291	1.623	.7910
140	2.200	.3420			

The slight bend in the curve at approximately 100° to 160° C., when the results are plotted, was interpreted by Kikuta as a result of grain growth.

Effect of temperatures

Text reference	Year	Name and title
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2	1929	Peirce, W. M., Anderson, E. A., Some practical aspects of creep in zinc, Tech. Pub. 203, Am. Inst. Min. & Met. Engrs.
3	1927	Goerens, P., Mailander, R., Cold and hot brittleness of steel and some other metals (copper, zinc, nickel), Forschungsarbeiten auf dem Geb. des Ingenieurwesens, No. 295, pp. 18–24; J. Inst. Met., **40**, p. 610; 1928.
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6	1925	Sachs, G., Festigkeitsuntersuchungen an Zinc, Z. Metallkunde, **17**, p. 187.
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8	1923	Ito, K., The hardness of metals as affected by temperature, Sci. Rept. Tohoku Imp. Univ., **12**, pp. 137–148.
9	1921	Kikuta, T., The change of rigidity and logarithmic decrement in different metals and alloys at high temperatures, Sci. Rept. Tohoku Imp. Univ., **10**, pp. 139–154; Chem. Abst., **16**, p. 401; 1922.
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13	1915	Ludwik, P., Tensile properties and molecular homology of metals at higher temperatures, Z. Ver. deut. Ing., **59**, pp. 657–664; Chem. Abst., **9**, p. 3202.
14	1912	Scott, J., Behavior of heated zinc, Met. Ind., **10**, pp. 112–113; Chem. Abst., **6**, p. 1588.
15	1911	Haines, W. B., Effect of temperature upon the ductility of zinc, Proc. Roy. Soc. Lond., **85a**, pp. 526–532; Chem. Abst., **6**, p. 731.

6. TECHNOLOGY

(a) CASTINGS

Zinc in the form of castings is used to only a very limited extent, as in "slush" castings (25,27). Such castings are hollow and are made by pouring the molten zinc into the metal mold, allowing the metal to freeze sufficiently to form a wall of suitable thickness and then pouring out the remaining molten metal from the interior. The rapid development of the die-casting process has very greatly reduced the use of zinc slush castings, especially in this country. They are still widely used for ornamental purposes in European countries. Another important use of zinc in the cast form is in the mechanical testing of wire rope or cable. In making tension tests of wire rope, the frayed-out ends of the rope are securely held in tapered sockets by casting zinc around them (14).

Certain alloys consisting mainly of zinc are extensively used in the cast condition, known as die castings; that is, the molten metal is cast into permanent (metal) molds under considerable pressure. According to Colwell (2), the annual tonnage of zinc-base die castings is greater than that of all of the other alloy die castings combined.

The great variety of purposes for which die castings are used is illustrated by the following list of typical examples: Automobile parts, such as carburetors, speedometers, fuel pumps, radiator caps, body hardware, etc.; parts for household utility machines, such as vacuum cleaners and floor polishers, office appliances, cash registers, tabulating machines, phonographs, radio receiving sets, cameras, motion picture machines, clocks, lighting fixtures, magnetos, motor parts, toys and small scale reproductions, weighing and vending devices. In addition, there are many uses with which the ordinary individual does not come in contact, such as in telephone equipment, various light manufacturing operations, etc.

The die-casting process is especially useful in the manufacture of small parts which must be accurately produced in great numbers; 20,000 parts from the same die is not at all unusual. The number produced from the same die depends, of course, on the complexity of the casting made. Hundreds of thousands of castings of a simple shape from the same die have been made.

By means of metal inserts, the strength of any part of a die casting can be increased as desired, and by the use of cores and other devices, the die casting process has been extended to the production of shapes which are relatively very complicated as compared with that of the early die castings. The process is not economically applicable to small shops where the small number of parts to be made would not justify the preparation of the expensive steel dies required.

The properties of die-casting alloys of zinc base are described in another section of this circular.

Casting zinc and its alloys

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1	1930	Stern, Marc, Colwell, D. L., Die-casting practice, McGraw-Hill Book Co. Die-casting zinc and aluminum, Metal Progress, **18,** No., 5 pp. 58–63.
3	1930	Colwell, D. L., Development of zinc-base die-casting alloys, Proc. Am. Soc. Testing Materials **30,** II, pp. 473–489.
4	1930	Mauny, W. R., Adam, W., Development of electric zinc melting process, Metal Ind., **28,** pp. 118–120.
5	1930	Pack, Charles, Influence of casting practice on physical properties of die castings, Tech Pub. 346, Am. Inst. Mining Met. Eng.
6	1930	Peirce, W. M., Modern zinc-base die casting, Metals & Alloys, **1,** p. 544–546.
7	1929	Curts, R. M., Strength of zinc-base die castings, Iron Age, **124,** pp. 1655–1658.
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Casting zinc and its alloys—Continued

Text reference	Year	Names and title
10	1926	Bedford, E. J., The production of pressure die-castings, Machinery, Lond., **28**, pp. 33–36; J. Inst. Metals, **37**, 1927, p. 716.
11	1926	Kaufmann, A., Pressure die-casting processes, pressure die-casting machines, Z. Ver. deut. Ing., **70**, pp. 285–290; J. Inst. Metals, **37**, p. 716.
12	1925	Ehrmann, E., Production and application of die-cast parts, Z. Metallkunde, **17**, pp. 329–333.
13	1925	Simonds, H. R., Making castings for lighting fixtures, Foundry, **53**, pp. 679–683.
14	1925	United States Government master specification for wire rope, Federal Specifications Board specification No. 297; Bureau of Standards Circular No. 208.
15	1924	Blair, P. W., Die-castings for plumbing work, Metal Ind., **20**, p. 466; J. Inst. Metals **31**, p. 525.
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17	1922	Brauer, H. E., Peirce, W. M., Insuring permanence in zinc-base die-casting alloy, Raw Material, **5**, pp. 337-340; Chem. Abst. **17**, 1923, p. 526; J. Inst. Metals, **29**, 1923, p. 763.
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20	1921	Reinboth, F., The smelting of scrap metal, Metall-Technik, **47**, pp. 21–23; J. Inst. Metals **29**, 1923, p. 788.
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29	1914	Pack, Charles, Modern die-casting practice, Trans. Am. Inst. Metals, **8**, pp. 87–102.

(b) MECHANICAL WORKING

(1) PLASTIC DEFORMATION; RECRYSTALLIZATION.—In the plastic deformation (cold working) of zinc, slip along the basal {0001} plane of the hexagonal lattice is of fundamental importance. In addition, twinning is a very common phenomenon. Mathewson and Phillips (6) have determined the twinning plane to be the pyramidal plane $\{10\bar{1}2\}$ of the hexagonal lattice. The basal plane of the twinned layer, according to these investigators, coincides within a few degrees (4°7′) with the prismatic planes of the hexagonal lattice. Thus, these new basal planes are favorably oriented for further slip to occur. Cold-worked zinc shows abundant evidence of twinning and very frequently cast zinc also, evidently the result of stresses set up in cooling. Romig (7) has shown that the polishing necessary in preparing specimens for microscopic examination may cause abundant twinning in the surface layer, a condition which may not obtain throughout the body of the specimen. The importance of these crystaline changes in the rolling of zinc has been well summarized by Peirce (3):

> The practical result * * * is that when a cast aggregate of zinc crystals is rolled, twinning occurs on such planes as to bring the basal planes of the resulting crystals (considering the twinned portions as new crystals), within a range of position favorable to extension by basal slip in the direction of rolling. This produces a tendency toward uniformity of orientation of the crystals of rolled zinc.

Upon heating cold-worked zinc, recrystallization occurs. Practically all evidence of the twinning disappears and except for any inclusions (insoluble impurities, etc.) in the metal a very uniform structure, consisting of equiaxed zinc crystals, results. Hot-rolled zinc often shows evidence of twinning in its crystalline structure (6), the obvious conclusion being that the annealing incident to the hot rolling was not sufficient to erase the crystalline changes which occurred in the plastic deformation of the metal. Upon annealing, hot-rolled zinc recrystallizes. Mathewson and Phillips have shown that annealed strip zinc is characterized by preferred crystalline orientation. The differences in the properties of rolled zinc as measured parallel to the direction of rolling or normal to this direction may probably be attributed in part to this condition.

Zinc is unlike most metals, in that the temperature of recrystallization is not far above ordinary room temperature. Zinc is not properly classed as a self-annealing metal, however.

Figure 56, after Sachs (10), shows the tensile strength of cold-rolled zinc (reduced 49 per cent in rolling) after being allowed to age at room temperature. After a small initial decrease no further change could be detected in the strength.

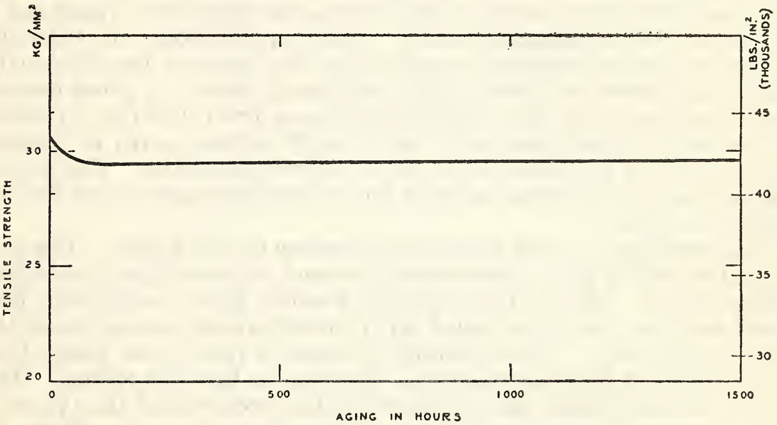

FIGURE 56.—*Tensile strength of cold-rolled zinc sheet, reduced 49 per cent in rolling, allowed to age at room temperature*

(kg/mm^2 + 1, 422 = lbs./in.^{2})

Under certain favorable conditions, such as a strain gradient, selective grain growth will occur in zinc as in other metals. It is well established that this effect may occur in metals at a temperature somewhat below that at which complete recrystallization ordinarily occurs. According to the research division of the New Jersey Zinc Co. (3), "in zinc the effect is so great that in bringing a slightly strained piece of zinc to the recrystallization temperature, it is difficult to pass rapidly enough through the range of temperature at which selective grain growth occurs, to prevent a harmful coarsening of the structure."

Strain hardening by cold rolling is attained only by taking precautions to cool the rolls and use very light reductions. The propensity toward strain hardening is affected by alloying elements in solid solution. Cadmium, in particular, is said to cause a marked increase in this direction.

(2) Commercial Wrought Zinc.—Zinc can be worked mechanically by any of the means ordinarily used for working metal—rolling, extrusion, drawing, pressing, forging, swaging and hammering. Most of the commercial wrought zinc is in the form of rolled strip and sheet, rod and tubing. Wire is made in limited quantities. For the hot-rolling of zinc, the temperature is rather carefully controlled and not allowed to fall below 150°C. The same is true in the extrusion of the metal. A helpful contribution to the rather scanty published information on the mechanics of the rolling of zinc has been published by Labkowitz (2).

Rolled zinc may be classified as strip or ribbon zinc, sheet zinc, and plates.

Since strip zinc is rolled in only one direction, it has a definite "grain" parallel to the direction of rolling. It shows less tendency to crack when bent across the grain, that is at a right angle to the direction of rolling, than when bent with the grain (3).

Since zinc strip of the lighter gages is available in coils, it is readily adaptable for use in continuous-operation machines for deep stamping; high-grade zinc strip having a high "dynamic ductility" value and a low temper value is generally used. Other applications; for example, weather strips for windows, require that the material be stiffer with respect to temper and have a high cold-bend value. A great deal of the commercial strip zinc varies in thickness from 0.006 to 0.10 inch and in width from one-fourth inch to 20 inches; strip of greater thickness is not furnished in so great variety of widths. The length of a coil varies from 100 to 250 feet for the heavier gages to 500 feet for the lighter strip.

"Pack rolling" is used in the manufacture of sheet zinc. The cast slab is first rolled into a sheet which is much thicker than the desired finished sheet. This is then cut into smaller sheets, assembled into a pack and the pack then rolled until the individual sheets are of the desired thickness. "Cross rolling" is used in rolling the pack; that is, it is rolled at right angles to the direction of the first rolling. The "grain" of the finished sheet is therefore less pronounced than in strip zinc. However, sheet zinc, like strip zinc, shows more tendency to crack when bent "with the grain" than when bent "across the grain."

The thickness of rolled zinc is expressed by means of the American zinc gage which differs considerably from the gage system used for sheet iron and steel and for other nonferrous sheet metal. The essentials of this system are summarized in Table 45. The use of this system is being discouraged by at least one of the prominent American manufacturers of rolled zinc (3). The mechanical properties of rolled zinc have been previously given (Table 35, figs. 43 and 51), and the fact emphasized that while the strength of the sheet "across the grain" is greater than "with the grain," the ductility is less. Figure 57 from Sachs (10) gives the tensile strength as determined at room temperature and at the temperature of liquid air of zinc sheet in various stages of reduction in thickness.

TABLE 45.—*American zinc gage for rolled zinc*

Gage No.	Thickness	Weight	Gage No.	Thickness	Weight	Gage No.	Thickness	Weight
	Inch	*Lbs./ft.*^{2}		*Inch*	*Lbs./ft.*^{2}		*Inch*	*Lbs./ft.*^{2}
3	0.006	0.22	12	0.028	1.05	21	0.080	3.00
4	.008	.30	13	.032	1.20	22	.090	3.37
5	.010	.37	14	.036	1.35	23	.100	3.75
6	.012	.45	15	.040	1.50	24	.125	4.70
7	.014	.52	16	.045	1.68	25	.250	9.40
8	.016	.60	17	.050	1.87	26	.375	14.00
9	.018	.67	18	.055	2.06	27	.500	18.75
10	.020	.75	19	.060	2.25	28	1.000	37.50
11	.024	.90	20	.070	2.62			

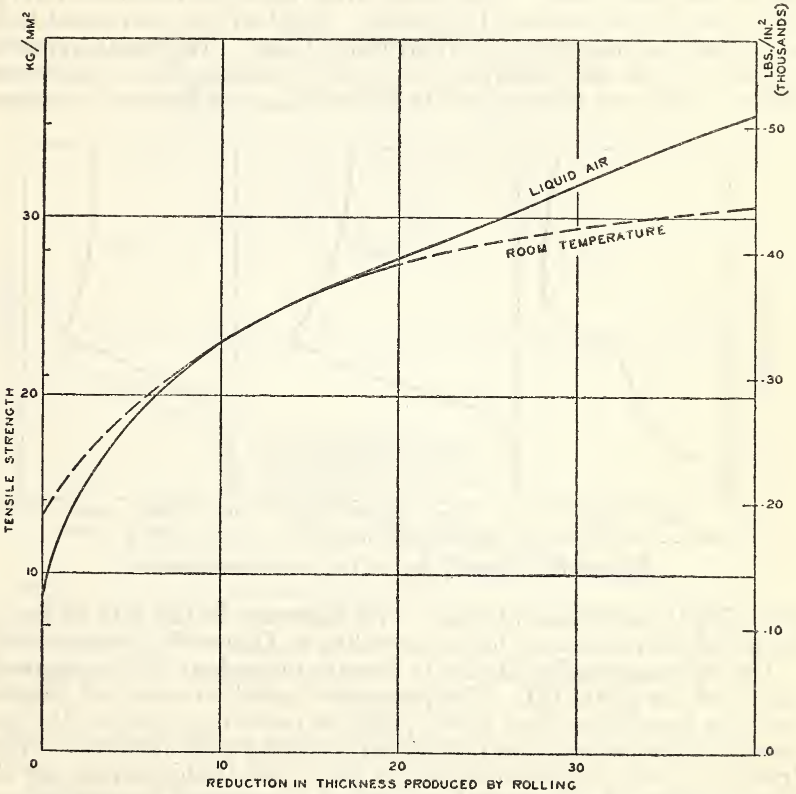

FIGURE 57.—*Tensile strength of sheet zinc in various stages of reduction in thickness*

Rolled zinc one-tenth of an inch or more in thickness is usually termed zinc plate. The use for which such plates are intended does not require that they withstand any severe bending or other forming operations. The maximum thickness of commercial zinc plate is 1 inch. Zinc plates are used principally in boilers as an aid in the prevention of corrosion and in marine use for the electrolytic protection against corrosion of submerged bronze and other copper alloy parts. Zinc plates are also extensively used in photo-engraving.

Rolled zinc can readily be stamped into a variety of articles of different depths and shapes. A few special precautions must be observed (3). The depth of the first cupping should not be more than about 50 per cent of its diameter. Subsequent steps may be taken about the same as in brass. The blank should not differ much in thickness from the desired wall thickness. Generous fillets should be used on the dies. Annealing and pickling during intermediate steps in stamping are unnecessary and may be harmful. In extremely cold weather the zinc should be warmed somewhat (about 125° F. (50° C.)), since there is a marked decrease in the ductility below 70° F. A soap solution is a satisfactory lubricant for the stamping of sheet zinc.

Zinc can be readily extruded into any of the forms for which extrusion is commonly used. The temperature must not be allowed to fall below 150° C. for successful extrusion. Lard oil has been found to be a very suitable lubricant in the extrusion of zinc. The results reported by Coe (12) on the behavior of zinc when subjected to compressive stresses, which are summarized in Figure 58, are of interest in connection with the extrusion of zinc. The difference in the rate of flow of the metal with increasing loads, according to Figure 58, is very marked.

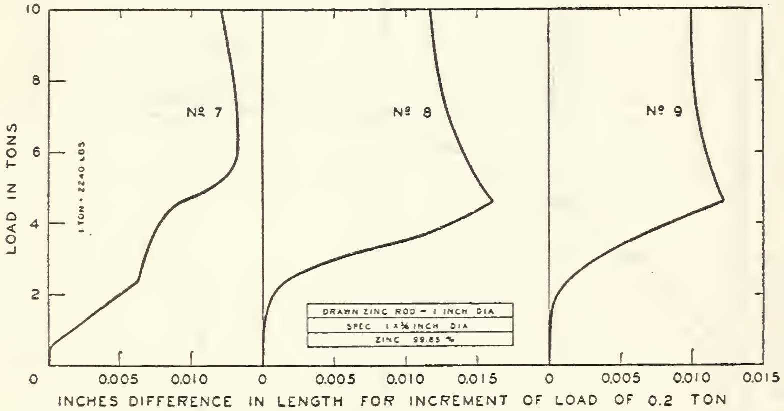

FIGURE 58.—*Rate of flow of zinc under compression*

The drawing quality of zinc is directly dependent on the degree of purity of the metal (3). The presence of small amounts of alloying elements in solid solution in zinc, such as cadmium, increase the propensity of the metal toward strain hardening by cold working. In the drawing of wire of spectroscopically pure zinc at this bureau for the determination of its physical properties, as reported in previous sections, difficulty was encountered on account of the very low degree of strain hardening of the pure zinc. By passing the wire through a bath of ice water directly as it emerged from the die, however, sufficient strength was retained in the wire to make it possible to draw the wire down to 0.0089-inch diameter.

According to Seidl (9), an initially fine-grained uniform structural condition is of great importance in the successful working of zinc. For attaining such a structural condition, he has emphasized the importance of maintaining the correct pouring temperature and the use of thick-walled molds. In some cases, the mechanical working of the metal is facilitated if it is given a preliminary working followed by heating so as to cause a recrystallization of the metal. This is especially desirable for material having large columnar grains.

Schulz and Fiedler (25) have stated that 120° C. is a very suitable temperature for the pressing of zinc. Increase of temperature from 120° to 145° C. had but slight effect upon the tensile strength, but the ductility and impact resistance were materially lowered, evidently on account of the coarse crystalline condition of the material. Some results reported by them for zinc containing 1.3 per cent lead and a trace of iron are given in Table 46.

TABLE 46.—*Tensile properties of pressed zinc* (*25*)

(A 1,000-ton press was used)

[Kg/mm ^{2}×1,422=lbs./in.^{2}]

Temperature of working	Tensile strength	Elongation	Impact resistance (notched-bar, single-blow)
° *C.*	*kg/mm²*	*Per cent*	*m-kg/mm²*
120	18.4–20.6	32–44	Not determined.
130	18.0–18.2	28–37	0.73
140	18.6–18.8	30–34	.76
145	17.7–17.8	22–24	.61

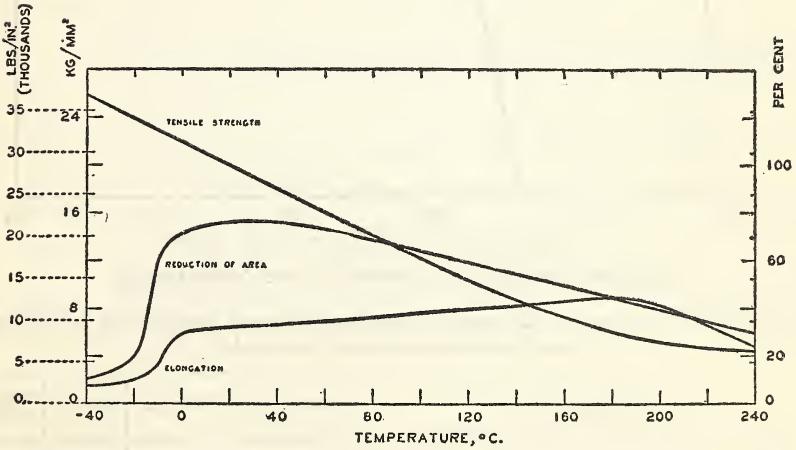

FIGURE 59.—*Tensile properties of hot-pressed zinc as tested at different temperatures*

(kg/mm^2×1,422=lbs./in.^{2})

More complete data on the tensile properties of pressed zinc taken from results published by Hanszel (18) are given in Figure 59. The zinc used contained 1 to 1.5 per cent of lead.

Information on the rate of deformation of zinc during hot forging has been published by Kent (4). Results obtained for zinc, 99.94 per cent pure (lead 0.04 per cent, iron 0.0048, copper 0.008, cadmium 0.008, arsenic 0.0007, and sulphur, tin, bismuth, nil) are given in Figure 60. The hammer used weighed 87.5 pounds, and the maximum blow attainable was 400 foot-pounds.

In Table 47 is given information on the tensile properties of pressed zinc as determined by Hanszel (18) on specimens whose orientation with respect to the axis of the pressed-zinc article was varied.

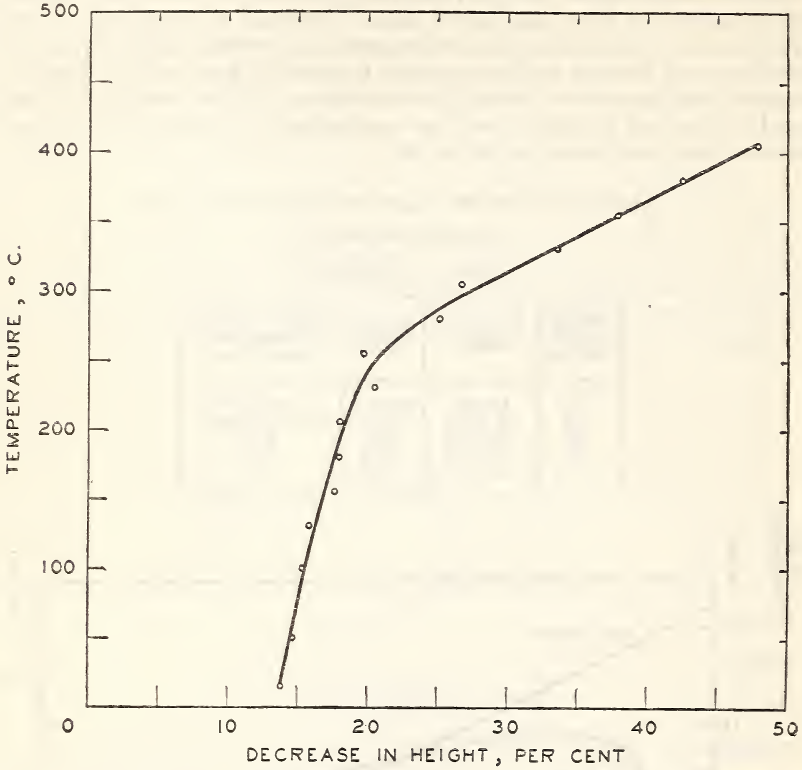

FIGURE 60.—*Rate of deformation of zinc during forging*

TABLE 47.—*Variation in the tensile properties of rods of pressed zinc in different directions throughout the forging (18)*

Working of rods	Position of test specimen	Strength	Elongation
		kg/mm²	*Per cent*
With good surplus and rounding	Coinciding with the axis	19.3	13.4
	Parallel to the axis	19.3	5.6
	Inclined to the axis	17.8	3.4
	Perpendicular to axis	16.3	4.6
With little surplus; material worked only slightly longitudinally.	Coinciding with the axis	23.4	16.0
	Parallel to the axis	21.4	11.0
	Inclined to the axis	7.6	-------
	Perpendicular to axis	18.3	4.6
With little surplus; material worked strongly longitudinally.	Coinciding with the axis	23.4	8.0
	Parallel to the axis	22.9	7.8
	Inclined to the axis	17.8	-------
	Perpendicular to axis	17.8	1.8

Mechanical working, recrystallization

Text reference	Year	Name and title
1a	1931	Schmid, E., Wassermann, G., Über die anisotropie von Zinkblechen, Z. Metallkunde, **23**, p. 87.; Mit. deut. Materialprufungs. Sonderheft, **17**, p. 20–24.
1	1930	Curts, R. M., Uncommon properties of a common metal, Am. Mach., **72**, pp. 413–415.
2	1930	Lobkowitz, G. B., Über walzdruck und energiebedarf an einen zink walzwerk, Z. Metallkunde, **22**, pp. 8–13.
3	1929	N. J. Zinc Co., research division, Rolled Zinc, Research Bulletin.
4	1928	Kent, W. L., The behavior of metals and alloys during hot-forging, J. Inst. Metals, **39**, pp. 209–227; Chem. Abst., **22**, p. 1940.
5	1928	Trewin, C. S., Wrought zinc, Inst. Met. Div., Am. Inst. Mining & Met. Eng., pp. 95–98.
6	1927	Mathewson, C. H., Phillips, A. J., Plastic deformation of coarse-grained zinc, Trans. Am. Inst. Mining Met. Eng., Inst. Met. Div., pp. 143–189; J. Inst. Metals **27**, p. 414.
7	1927	Romig, O. E., Preparation of metallic single crystals and twinning in zinc and zinc single crystals, Trans. Am. Inst. Mining Met. Engrs., Inst. of Met. Div., pp. 90–115.
8	1927	Sauerwald, F., Patalong, H., Rathke, H., The influence upon velocity of vaporization of cold working (of metals) with a note on the melting and transformation points of cold-worked metals, Z. Physik., **41**, pp. 355–377; Chem. Abst., **21**, p. 1731.
9	1927	Seidl, E., Influence of chemical and crystallographic properties of casting metal on behavior during rolling, Mining & Met., **8**, pp. 454–460.
10	1925	Sachs, G., Festigkeitsuntersuchungen an Zinc. Z. Metallkunde, **17**, pp. 187–193.
11	1924	Polanyi, M., Schmid, E., On the structure of worked metals, Z. Tech. Phys., **5**, pp. 580–589; J. Inst. Metals, **33**, p. 380; 1925.
12	1923	Coe, H. I., Behavior of metal under compressive stresses, J. Inst. Metals, **30**, pp. 309–324.
13	1923	Masing, G., Polanyi, B., Ergebnisse der exakten naturwissenschaften, **2**, p. 177.
14	1923	Peter, A., The pressing of nonferrous metals, Z. Metallkunde, **15**, pp. 1–6, 41–46; J. Inst. Metals, **30**, p. 655.
15	1923	Tamman, G., Dahl, K., On recrystallization in alloys which contain a eutectic, Z. Anorg. Chem., **126**, pp. 113–118; J. Inst. Metals, **30**, p. 529; Chem. Abst., **17**, p. 3311.
16	1923	Thomassen, L., Crystal structure of the surface layer of worked metals, Z. Metallkunde, **15**, p. 306.
17	1922	Kramer, W., Zinc sheet rolling mills, Das Metall No. 6, pp. 67–71; J. Inst. Metals, **30**, 1923, p. 652.
18	1921	Hanszel, Veredelungsversuche mit inlandischen metallen. Presszink und zinc-legierungen, Z. Metallkunde, **13**, pp. 209–219, Chem. Met. Eng., **25**, p. 1180 (abstract).
19	1921	Ingall, D. H., Relation between mechanical properties and microstructure in pure rolled zinc, J. Inst. Metals, **26**, pp. 281–308; Engineering, **112**, pp. 489–492; Chem. Abst., **16**, 1922, p. 404.
20	1921	Schulte, W., The pressing and rolling of zinc, Metallbörse, **11**, pp. 880–881; J. Inst. Metals, **36**, p. 615.
21	1921	Schulz, E. H., Melaun, R., Occurrence of a foliated appearance on strips of sheet zinc. Forschungsarbeiten auf dem Gebiete des Ingenieurwesens, Sonder-reihe M (1), pp. 23–27; Chem. Abst., **15**, p. 2826.
22	1920	Harvey, G. S., Story of the rolling of zinc sheets, Metal Work., **94**, pp. 311–312.
23	1920	Masing, G., Recrystallization of tin and zinc. Recrystallization of cold worked metals, Z. Metallkunde, **12**, pp. 457–493; Chem. Abst., **16**, 1922, p. 3857; J. Inst. Metals, **25**, 1921, p. 382.
24	1919	Schulz, E. H., Zeller, O., Formation of a coarsely grained structure in rolled zinc by heating. Forschungsarbeiten auf dem Gebiete des Ingenieurwesens, Sonder-reihe M, Heft, 1, pp. 32–38; Chem. Zentr., **4**, p. 623; J. Inst. Metals, **26**, 1921, p. 490; Chem. Abst. **15**, p. 2826.
25	1919	Schulz, E. H., Fiedler, R., Influence of the forging temperature on the tensile properties of forged zinc, Forschungsarb, Geb. Ing., Sonderreihe M (1), pp. 27–29. Chem. Abst., **15**, p. 2826.
26	1914	Timofeeff, G., Recrystallization of worked zinc, Rev. de Metal, **11**, pp. 127–132; Chem. Abst., **8**, p. 2996.

(3) Effect of Impurities.—According to the research division of the New Jersey Zinc Co. (2), the commonly occurring impurities in zinc, which may adversely affect the rolling properties of the zinc, are cadmium and iron. High-grade American rolled zinc may contain about 0.8 per cent lead, 0.002 per cent cadmium and less than 0.015 per cent iron. In the lower grades, the lead may be as high as 1 per cent, the cadmium range from 0.03 to 0.5 per cent, and the iron be approximately 0.015 per cent. Rolled zinc of foreign origin, in general, is not so pure as indicated above for domestic material. A representative composition (2) is approximately 1.1 per cent lead, 0.07 per cent cadmium and 0.02 per cent iron. The following figures have been published by Kramer (4) on the composition of a number of European sheet zincs. They should be considered as representing single analysis and not average compositions, however.

TABLE 48.—*Composition of a number of foreign sheet zincs (4)*

Designation of material	Lead	Iron	Cadmium	Tin
	Per cent	*Per cent*	*Per cent*	*Per cent*
Upperbank, England	2.55	0.15	0.09	0.05
V. M. G., Belgian	.66	.26	---------	.03
Veille Montagne	2.00	.14	.07	---------
Freeburg, Saxony	1.03	.04	.02	.07
Lazyhütte, Upper Schlezig	1.12	.024	.017	---------
Electrolytic	.06	.01	.005	.02

American experience in the rolling of zinc indicates that (2) the effect of lead is negligible, iron is harmless only when the amount is not greater than 0.015 per cent, and cadmium when not in excess of 0.006 per cent.

The general effect of various impurities in zinc is summarized from various sources as follows:

Lead.—The presence of lead does not seriously interfere in the mechanical working of zinc. According to Freeman (9), zinc becomes "tender" and shows a greater tendency to crack when the lead content exceeds 1.5 per cent. The production of zinc shavings is enhanced by the presence of lead, according to Lones (7), 2 per cent being a desirable lead content for this purpose.

Iron.—The general effect of iron is to render zinc harder, and less malleable. Hence, it may interfere seriously in the working of zinc. This effect becomes very serious with an iron content of 0.2 per cent according to Freeman (9). The research division of the New Jersey Zinc Co. evidently considers the presence of iron more detrimental, since, according to their statements (2), iron in zinc is harmless only in amounts up to 0.015 per cent. The effect of manganese and nickel is of the same general nature as that of iron (2). These two impurities do not commonly occur in the virgin metal, however.

Cadmium.—As an impurity in zinc, cadmium exists in solid solution and has a strengthening and hardening effect. This effect has been reported to reach a maximum at 0.2 per cent of cadmium (2). Smaller amounts of cadmium do not seriously affect the working properties of the metal.

Tin.—The presence of tin in zinc renders the metal harder and more brittle (2, 9).

Arsenic.—This embrittles zinc and also renders the melting of it more difficult, according to Freeman (9).

Antimony.—This has a similar effect to arsenic.

Magnesium.—This metal forms a eutectic with zinc and has an embrittling effect (2).

Sulphur.—Sulphur in the very small amounts ordinarily found does not appear to be deleterious in zinc (6, 11) nor does carbon.

Copper.—This does not occur in virgin zinc except for possible traces in some electrolytic zinc (2). The results reported by Schulz and Melaun (6) (Table 49) give some information on the general strengthening effect of copper on zinc. Information from the same source on the effect of aluminum and copper on the mechanical properties of pressed zinc is summarized in Table 50.

As a result of these and other tests, these authors concluded that aluminum increases the strength of zinc less than copper does, 2 per cent of copper being approximately equivalent to 4 of aluminum, other conditions which might affect the properties of the zinc being the same. Zinc alloyed with aluminum was found to have less ductility (elongation) than zinc alloyed with copper, both having the same tensile strength.

According to the extensive investigations carried out in the research laboratory of the New Jersey Zinc Co., the opposite is true with respect to the relative effect of copper and aluminum, at least in castings. As stated by Peirce (1), "copper in amounts ranging from 2 to 4 per cent or 5 per cent has some strengthening effect, but aluminum is by far the most effective alloying element for improving the strength of zinc." On account of the deterioration which occurs in the aluminum alloys of zinc if certain other metals be present, for example, lead, wrought alloys of aluminum and zinc are not commercially practicable as yet. With the increasing availability of high purity zinc, however, this handicap may, perhaps, be more or less surmounted.

The results given in Table 51 showing the effect of various additions on the mechanical properties of cast zinc have been reported by Schulz (5).

TABLE 49.—*Mechanical properties of pressed zinc alloyed with copper*

Treatment	Diameter of bar	Composition			Tensile strength	Elongation	Reduction of area	Brinell hardness	Impact resistance
		Copper	Lead	Iron					
	mm	*Per cent*	*Per cent*	*Per cent*	*Lbs./in.^{2}*	*Per cent*	*Per cent*		*mkg/cm^2*
Pressed and rolled	50	1.1	1.07	0.12	32,600	43	50	72	0.73
Pressed at about 150° C	40	2.85	1.13	.54	38,300	22	37	64	.62
Rolled	45	1.07	1.10	.14	28,000	31	60	62	.60
Pressed or rolled		(1)	(1)	(1)	25,600	[2] 30		42	.60

[1] Refined zinc. [2] 30 and over.

TABLE 50.—*Mechanical properties of pressed zinc alloyed with aluminum and copper*

(The material was pressed into bars approximately 15 by 15 mm and cold-drawn slightly after pressing)

Composition				Brinell hardness	Tensile properties		Compressive properties			Machinability (depth of drilling, Kessner)[3]
Cu	Al	Fe	Pb		Tensile strength	Elongation	Compression[1] under 5000 kg load	Load for 16.5 per cent compression[2]	Hardness after compression	
Per cent	*Per cent*	*Per cent*	*Per cent*		*Lbs./in.^{2}*	*Per cent*	*Per cent*	*Pounds*		
1.3		0.25	1.22	77	46,800	22.3	49.0	17,600	79	3.2
	3.36	.30	.63	85	53,600	7.0	33.5	21,200	92	5.9
.29	3.00	.20	.90	75	46,800	15.0	47.0	17,200	77	3.1
.31	4.38	.15	.22	70	46,500	25.3	52.2	17,600	71	2.9
1.38	3.80	.25	.17	81	52,800	20.1	37.6	21,000	83	3.4
2.18	4.26	.30	.26	56	40,300	24.7	61.3	(4)	(4)	3.5
2.50	3.49	.20	.70	86	54,600	8.0	33.3	21,200	91	3.4
2.55	4.03	.20	.90	83	55,400	6.5	33.0	20,700	89	3.8

[1] Cylindrical specimen, 9 mm high by 9 mm diameter.
[2] Similar specimen, 15 mm high.
[3] Kessner test, depth of drilling, 6 mm drill and 32 kg pressure, 100 revolutions.
[4] Not determined.

TABLE 51.—*Effect of small amounts of alloying elements on the mechanical properties of cast zinc* (*5*)

[kg/mm²×1,422=lbs./in.²]

Composition		Tensile strength	Brinell hardness	Compression[1]	
Addition	Amount			Load	Deformation
	Per cent[2]	*kg/mm²*		*kg*	*Per cent*
None		2- 3	39	6,500 8,000	48 55
Pb	3		44	16,300	59
Sn	2	3- 7			
	4		41		
	6	8- 9			
Fe	2	4.5	67		
	5			4,000	
Cu	1	6	58	10,700	55
	2		71	10,700	52
	3	13	70	9,800	45
	4		70	8,700	43
	5		73	13,000	54
	6		72	9,500	47
	12			8,400	
Al	3	5- 6			
	4	9-12	72	9,600	52
	7	16			
Cu	2				
Al	3	7			
Cu	3				
Al	6		90		
Cu	6				
Al	3	18	96	17,700	51
Cu	3				
Al	11		116	11,200	44

[1] Cylindrical specimen, 12 mm long by 12 mm diameter.

[2] Approximate. This was the amount added to the zinc.

Effect of impurities on zinc

Text reference	Year	Name and title
1a	1931	Bauer, O., Zunker, P., Einfluss geringer mengen von fremdmetallen auf die eigenschaften von raffinadezink. Z. Metallkunde **23**, pp. 37–45.
1	1930	Peirce, W. M., Modern zinc-base die-casting alloys. Metals & Alloys, **1**, p. 544.
2	1929	New Jersey Zinc Co., research department, Rolled Zinc, Research Bulletin.
3	1925	Stock, Kurt, Redistillation of zinc. Trans. Am. Inst. Mining Met. Eng., **71**, pp. 897–918.
4	1922	Kramer, W., Zinc sheet rolling mills. Das Metall, No. 6, pp. 67–77; J. Inst. Metals, **30**, 1923, p. 652.
5	1921	Schulz, E. H., Versuche mit gusszinklegierungen. Z. Metallkunde, **13**, pp. 177–178.
6	1919	Schulz, E. H., Melaun, R., Effect of copper and aluminum on forged and rolled zinc. (Ueber legiertes Press und Walzzink), Forschungsarbeiten Geb. Ing., Sonderreihe, M (1), pp. 38–42.
7	1919	Lones, T. E., Zinc and its alloys; Pitman Co.
8	1918	Stone, G. C., Effect of impurities on the hardness of cast zinc or spelter. J. Am. Inst. Metals, **21**, pp. 11–14.
9	1915	Freeman, C. C., Influence of impurities on zinc. Eng. & Min. J., **99**, p. 990.
10	1915	Rigg, G., Morse, H. E., Effects of the common impurities in spelter upon slush castings. Trans. Am. Inst. Metals, **9**, pp. 26–56.
11	1902	Ingalls, W. R., Production and properties of zinc. Eng. & Mining J.

(c) SOLDERING

Although zinc can be readily soldered, considerably more care is required than in ordinary soldering operations, as on copper and sheet steel.

Most failures in the soldering of zinc are due to overheating of the metal, whereby the zinc is either melted or its internal structure changed with a resultant weakening of the metal. Only a quick pass of the soldering iron over the metal is needed in order to produce a very stable joint. Less than 500° C. is necessary to get the "iron" to the proper temperature to solder joints in sheet zinc. "Half and half" tin-lead solder with a flux of "cut acid"; that is, zinc dissolved in HCl is customarily used. A solder containing 55 per cent lead, 30 per cent tin, and 15 per cent cadmium has been recommended as being suitable for zinc (2). Its relatively low melting point and high tensile strength make it very desirable for this use.

Soldering zinc

Text reference	Year	Name and title
1	1929	Am. Zinc Inst, Zinc worker's manual.
2	1929	New Jersey Zinc Co., research department, Rolled Zinc, Research Bulletin.
3	1928	Jenkins, C. H. M., The strength of a cadmium-zinc and of a tin-lead alloy solder, J. Inst. Metals, **45**, pp. 21-39.
4	1924	Nikonov, J. P., Soldering zinc die-castings, Am. Mach. (Eur. edn.), **60**, pp. 282-283; J. Inst. Metals, **33**, p. 509.
5	1920	Frew, S. E., Soldering with zinc, Am. Mach., **52**, p. 970.
6	1918	Hendricks, W. H., Soldering of zinc, Metal Worker, **90**, pp. 584-585; Foundry, **46**, p. 557.
7	1918	Peters, E. V., Soldering of zinc, Metal Ind., **16**, p. 497.

(d) WELDING

The welding of zinc is possible and is practiced commercially in the production of zinc tubing. Gas welding is recommended, and is generally used for this work (1). Electric-resistance welding is used to a limited extent for spot welding. In all welded zinc, the structure of the areas adjacent to the weld is very greatly changed and the material seriously weakened. This condition can be remedied in large measure by cold working the welded metal and this should always be done if strength is an important feature. The welded zinc tubing referred to above is cold drawn after welding down to the desired diameter and it is claimed (1) that the final strength of the welded portion does not differ materially from that of the rolled zinc from which the tube is made.

Welding zinc

Text reference	Year	Name and title
1	1929	New Jersey Zinc Co., Rolled Zinc, Research Bulletin.
2	1925	Horn, A., The welding of lead and zinc, and of iron sheets coated therewith, Schmelzschweissung, **4**, pp. 114-116; J. Inst. Metals, 38, p. 596.

(e) MACHINING

The various uses to which zinc is put do not necessitate much, if any, machining of the metal as a rule. The metal has excellent machining properties, however. No special precautions are necessary.

(f) ZINC-COATING PROCESSES

The term "zinc coating," as used here, connotes the process of coating other metals, usually steel or iron, with zinc regardless of the method of application used. The name "galvanizing" is used to refer to the production of zinc coatings on steel and iron by the method of hot dipping.

The zinc-coating industry is, by far, the greatest single user of metallic zinc. According to the American Bureau of Metals Statistics (Table 10), 46 per cent of the zinc used in the United States in 1929 was used for galvanizing purposes (sheets, tubes, wire, wire cloth and structural shapes).

(1) GALVANIZING (HOT DIPPING).[4]—Although there is record of the galvanizing of iron being carried on as early as 1741 in France, it was not until about a century later, with the granting of a French patent, in 1836, to Sorel and an English one to Crauford, in 1837, that attempts were made to develop the process commercially. By the middle of the century, the hand-dipping process had reached a high stage of development. The principal advances since have been along the line of developing the highly specialized mechanical and automatic features of present-day processes.

(a) *Principles.*—In theory, the hot-dipping process is very simple. The fact that molten zinc readily "wets" a clean surface of iron is the underlying principle which makes the process possible. The wetting of the surface occurs because of the dissolving or alloying action of the molten zinc on the iron. To facilitate a uniform wetting of the iron by the zinc, it is necessary that the surfaces be very clean. This is ordinarily secured by pickling the material in dilute acid, a 7 per cent solution of sulphuric acid at about 150° C. being often used for cleaning steel sheets. Other methods, including anodic and cathodic treatment, have been developed and are used especially for relatively small parts which are not of regular size and shape. The cleaning of steel and other metal products constitutes almost an industry in itself and has been highly developed. It will not be discussed here in detail.

It is very necessary that a flux be used to cover that part of the zinc bath where the article to be coated is immersed. Ammonium chloride forms the basis of the most widely used flux. Additions of glycerin were formerly made and tallow is still used. Zinc chloride is coming into wide use as a fluxing bath in the zinc coating of wire and it is also being used for sheets. The use of a flux insures that the surface to be coated is clean and dry as it comes in contact with the molten zinc. The flux is not ordinarily used at the exit end of the galvanizing bath.

The galvanizing of sheet and wire is done mechanically. Various mechanical devices are used in the galvanizing of pipe although the process is not so mechanical as the coating of sheet and wire. Hand dipping is still widely used for miscellaneous shapes, especially castings, structural steel, and fabricated articles, such as those made from sheet and wire. Machines are now in use for the coating of bolts, nuts, nails, and other small articles, the essential feature of which is the removal of excess zinc by shaking or by a centrifuge so

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[4] Reference 32 in the list following this section has been used freely in preparing the résumé given here. For this reason, only a relatively few references appear in the text of this section.

as to leave the threads clean. Then there is no necessity for cutting threads or other contours after coating, a practice which should be avoided if possible.

(b) *Quality of zinc used.*—Zinc of prime western grade (Table 9) is used largely for galvanizing. It has been claimed that difficulties are encountered with higher grade zinc. Recently, however, such grades of zinc are being used.

The initial presence of iron in the zinc is of no importance in galvanizing since, on account of the alloying action of the molten zinc with the walls of the container and the metal to be coated, the bath soon becomes saturated with iron. Crystals of an iron-zinc compound (fig. 91) form slowly, settle, and accumulate in the lower parts of the bath, which becomes very much contaminated. Much of this alloy, termed "dross," floats on a layer of lead in the bottom of the bath, the lead being either an intentional addition or the gradual accumulation of that contained in the zinc that is introduced. On account of its insolubility in zinc and its high density the lead settles to the bottom of the bath. The dross would interfere with the proper working of the galvanizing bath and result in a rough unsightly coating if allowed to accumulate indefinitely. It is necessary to remove it periodically, usually once a week in a sheet mill.

The question of the possible detrimental effect, in galvanizing, of cadmium, the third common impurity in zinc, is still a controversial one.

(c) *Structural characteristics of coating.*—Since alloying between the zinc and iron is the necessary fundamental condition for galvanizing by hot dipping, it follows that the resulting coating is not simply a layer of zinc spread over the surface of the iron. Usually, well-developed layers containing various constituents of the iron-zinc alloy system are to be observed in a cross section of the coating. (Fig. 92.) The temperature of the zinc bath and the length of the immersion period are important factors which determine the relative proportion of alloy layer within any galvanized coating. Immediately adjacent to the steel or base metal is a very thin layer, the composition of which is often represented by the formula $FeZn_3$, although there is still some question as to its exact nature. Stillwell and Clark (8), on the basis of X-ray studies have reported the composition of this layer as Fe_3Zn_{10}. They also reported that the solid solubility of zinc in the iron base is too slight to be detected by X-ray methods. The layer next to this inner one is usually much thicker, and often shows a well-developed fernlike pattern. The composition of this layer is represented by $FeZn_7$. A third, outermost, layer consists largely of zinc, presumably containing iron in solid solution and in which may occur small isolated crystals of the compound $FeZn_7$. Stillwell and Clark reported the outer layers of the galvanized coating to contain $FeZn_7$, a solid solution of zinc in $FeZn_7$, a solid solution of iron in zinc, and a phase with a body centered cubic lattice, the composition of which was not determined.

Since the iron-zinc compounds are relatively hard and nonductile the properties of any hot-dipped coating are, in large measure, determined by the extent to which the alloy layer is developed. It follows, therefore, that sheet material carrying a heavy coating, in which the alloy layer will, in general, be well developed, will not withstand as severe bending as a sheet carrying a much lighter coating.

(d) *Additions to zinc bath.*—Various additions are sometimes made to the galvanizing bath. Aluminum, in the form of a zinc-aluminum alloy, is a common addition, although its use is not favored in this country for sheets. Even small amounts of aluminum, for example, 0.05 to 0.10 per cent, have a noticeable effect on the fluidity of the zinc bath. This effect is more marked with 0.25 per cent of aluminum. As a result the coating is somewhat thinner than when aluminum is not used. Greater uniformity is claimed, however. One marked advantage is claimed for aluminum in the galvanizing of fabricated articles, tubs, pails, vats, etc., that is, the greater fluidity of the molten metal insures that all crevices are completely filled. There is also some evidence indicating that the alloy layer in a galvanized coating produced by aluminum-treated zinc is relatively much thinner than is ordinarily the case. The attack of the zinc on the container is also said to be less. It is well established in the die-casting industry, that zinc base alloys containing aluminum attack the containers of the molten metal much less than commercial zinc does. Coatings made in a zinc bath treated with aluminum often have a characteristic silvery white appearance. Although it has been claimed that the corrosion resistance of such coatings is not so good as that of coatings made without this addition, no conclusive evidence on this subject has yet been published.

Tin is also sometimes added to a galvanizing bath though its use is not so common as that of aluminum. Tin is generally used to "improve" the appearance of the coating. It is used in larger amounts than aluminum and its presence as a eutectic in the zinc coating can sometimes be detected, a circumstance which is not favorable to increased corrosion resistance.

A method used commercially to some extent for minimizing the alloy formation during the galvanizing process is the use of a bath consisting largely of lead with a layer of zinc a few inches thick on the top. The sheet or other material to be coated is inserted through the flux directly into the molten lead and is then withdrawn through the layer of zinc. Such coatings are sometimes referred to as "lead-and-zinc coatings." The entire coating is, in general, only a light one and the alloy layer is very materially reduced in amount.

(e) *Life of pots.*—The "burning out" of the pot at times causes much delay and added expense in the galvanizing industry. There is apparently no marked difference in the materials ordinarily used for the construction of such pots. Low carbon steel plate is in general use. The most important factor, which can be controlled, is the temperature of the zinc bath. A temperature of 450° C. (840° F.) is generally considered a good temperature for galvanizing. Imhoff (4, 19, 27) has written extensively on this and other technical aspects of galvanizing.

(f) *Thickness and treatment of coatings.*—It is not difficult to regulate the thickness of a galvanized coating, within fairly close limits, when the coating operation is a mechanical one as for sheet and wire. In the latter case, the outer part is removed before it has solidified by passing the wire through a "wiper," hence, the name "wiped wire." There is no very practical means of regulating the thickness and uniformity of coating in hand dipping. The fact has already been mentioned that a treatment of the bath with aluminum renders it more fluid, and thus a thinner, but usually a very uniform, coating is obtained.

Attempts have been made to improve the properties of galvanized coatings, especially with respect to flaking on bending, by a treatment of the coated article after the process has been completed. Nothing along the line of a mechanical treatment has proved at all promising. By heat treatment, however, the coating can be considerably modified. The alloy layer is thereby rendered much more uniform in its structure. (Fig. 95.) The heat treatment is simple. The coated material, such as wire, as it emerges from the zinc bath, is passed through a furnace maintained at a temperature somewhat above that of the zinc bath. In one process, used commercially for wire, a temperature of about 675° C. (1,250° F.) is used. Usually the outer zinc-rich portion of the coating is thus converted into alloy. Wire and sheet coated in this way are available commercially. The heat-treated galvanized sheet has been claimed to be especially useful for service at elevated temperatures, such as in oven linings.

(g) *By-products.*—In a modern galvanizing plant, over 10 per cent of zinc is generally converted into dross. In small-scale operations the amount of dross is generally considerably higher than this. Some of the dross is used in the preparation of alloys requiring both iron and zinc. From a great deal of the dross the zinc is recovered by a simple heating process known as "sweating," which serves as a means for recovering much of it in a fairly pure state. Other products, such as "spent flux," zinc skimmings, consisting of zinc oxide, zinc chloride, and ammonium chloride are salable.

(h) *Defects in coatings.*—The most common defects in galvanized coatings are those resulting from incomplete or nonuniform coatings, such as bare spots resulting from incomplete removal of the scale from the surface by pickling or other initial defects in the sheet. Flux spots resulting from the retention of inclusions of the flux may give rise to an unsightly appearance. There has been much discussion concerning galvanized sheets known to the trade as "gray sheets." Such sheets lack the well-crystallized surface or "spangle" which many, though probably erroneously, have come to consider as indicative of high quality in this product. Although the rough and somewhat granular appearance of such sheets may not be so attractive as the spangled surface of the ordinary product, it has not been shown that such sheets are inferior in their corrosion resistance. There appears to be no single factor responsible for the "gray" galvanized sheets. The nature of the base metal has been shown to play some part in this.

(i) *Specifications; galvanized-sheet gage.*—During the past few years there has been considerable activity in the drawing up of specifications for zinc-coated products. Much has been accomplished through the American Society for Testing Materials. A résumé of such specifications is included in the Appendix.

Confusion frequently arises in the mind of purchasers of galvanized sheet materials as to the meaning of the "galvanized sheet gage." (Appendix, Specifications for Zinc-Coated Sheets.) This is a system which has grown up in the industry for representing the weight of galvanized sheets and is very widely used. It differs from the Standard U. S. sheet gage in that the weight of the finished (coated) sheet, regardless of the actual weight of the coating carried, is arbitrarily set as 2.5 oz./ft.^{2} heavier [5] than the weight of the black or uncoated sheet bearing the same gage number. Thus, according to the United States standard sheet gage, a 16-gage sheet weighs 40 oz./ft.^{2} and according to the galvanized sheet gage, 42.5 oz./ft.^{2} This latter weight, however, bears no relation to the weight of the coating actually carried by the sheet, for example, the weight of the sheet from which the zinc coating has been stripped would be 41¾ ounces in case of a ¾-ounce coating (¾ oz./ft.^{2} of sheet), while that of a sheet of the same nominal gage which carried a 2¾-ounce coating (2¾ oz./ft.^{2} of sheet) would be 39¼ ounces.

Galvanizing

Text reference	Year	Name and title
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3	1930	Harvey, W. E., Zinc as a protective coating against corrosion fatigue of steel, Metals & Alloys, **1**, pp. 458–461.
4	1930	Imhoff, W. G., Critical temperature in galvanizing, Iron Age, **125**, pp. 933–935. Crystal forms of galvanizing, dross and zinc-iron alloys, Iron Age, **126**, pp. 1772–1775. Destruction of galvanizing pots, Iron Age, **125**, pp. 294–297. The destructive action of molten zinc, at and above zincing (galvanizing) temperatures, upon metals and alloys. VII. The action upon metallic nickel and nickel alloys. Am. Metal Market, **37**, No. 106, p. 5; Chem. Abst., **24**, p. 3743. The destructive action of molten zinc, at and above zincing (galvanizing) temperatures, upon metals and alloys. VI. The action upon chromium and chromium alloys, Am. Metal Market, **37**, No. 86, p. 6; Chem. Abst., **24**, p. 3205. Estimating galvanizing pot life, Iron Age, **125**, pp. 1154–1155. Factors which affect the brightness of hot-dip zinced coatings, Brass World, **26**, pp. 35–37. Factors affecting the quality of zinc for galvanizing, Metal Ind. **28**, pp. 113–115. Galvanizing dross and zinc-iron alloys, Iron Age, **126**, pp. 1853–1854. Galvanizing pots destroyed by zinc-iron alloys, Steel, **87**, pp. 56–58. Galvanizing pot destruction, Iron Age, **125**, pp. 633–636. Higher the dross, heavier the coating, Heat-Treating & Forging, **16**, pp. 1289–1291. Hot zinc baths for steel, Am. Mach., **72**, pp. 962–964. Pickling principles in galvanizing, Iron Age, **126**, pp. 82–83. The smoothness of zinc coatings, Heat treating & Forging, **16**, pp. 729–731; Bl. Fur. & Steel Plant, **18**, pp. 1154–1156. Temperature of galvanizing bath affects dross production, Iron Tr. Rev., **86**, p. 65. Zinc alloys destroy galvanizing pots, Steel, **87**, pp. 47–48.
5	1930	Prunzel, W., Investigations on the decrease of the zinc deposit in hot galvanizing as caused by additional metals, Stahl Eisen, **50**, p. 1173.
6	1930	Schulz, E. H., On the so-called white rust on galvanized iron materials, Stahl Eisen, **50**, pp. 360–362.
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8	1930	Stillwell, C. W., Clark, G. L., X-ray examination of commercial galvanized iron by a modified reflection method, Ind. & Engng. Chem., **22**, p. 266.
9	1930	Whitehead, L. D., A pure zinc galvanizing process, Iron-monger, January 24; May 24.
10	1930	Wright, L. K., Limitations of cadmium and zinc coatings, Am. Mach., **73**, p. 919.
11	1930	Editorial, The smoothness of zinc coatings, Metallurgist, **6**, pp. 159–160. (Supplement to the Engineer, Oct. 31.)
12	1930	Report of Sectional Committee on Zinc Coating of Iron and Steel. Proc. Am. Soc. Testing Materials, **30**, p. 241.
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14	1930	Editorial, Galvanizing, Metallurgist, **6**, p. 60 (Supplement to the Engineer).
15	1929	Bablik, H., Acids used in galvanizing work, Iron Age, **123**, pp. 879–880.
16	1929	——, European hot sheet galvanizing, Iron Age, **123**, pp. 811–812.
17	1929	Beutel, E., Kutzelnigg, A., Uber einige verfahren zur oberflachenentzinkung von messing und tombak, Z. Metallkunde, **21**, pp. 412–413.
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[5] Care should be used to distinguish between (1) ounces per square foot of surface, (2) ounces per square foot of sheet (coated on both sides). One ounce of zinc per square foot of surface is equivalent to 0.0016 inch, or 0.001 inch is equivalent to 0.6 ounce per square foot.

Galvanizing—Continued

Text reference	Year	Name and title
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22	1929	White, F. G., Galvanizing sheets for stampings, Metal Stampings, **2**, pp. 655–658.
23	1928	Bailey, C. L., Galvanized iron protects gold, Am. Zinc. Inst. Bull., **11**, (7–8), pp. 45–46, 62, J. Inst. Metals, **41**, p. 603.
24	1928	Epstein, M., Design of galvanizing furnaces, Iron Age, **121**, pp. 1151–1152.
25	1928	Ginsberg, I., Using gas for hot zincing, Brass World, **24**, pp. 278–280.
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27	1928	Imhoff, W. G., The destructive action of molten zinc, at and above zincing (galvanizing) temperatures, upon metals and alloys, Am. Metal Market, **35**, 2d sec. pp. 10–13; Chem. Abst., **23**, 1929, p. 1608. The extent of the field of zinc coating, Brass World, **24**, pp. 148–150. Heating problems in hot galvanizing, Heat Treating & Forging, **14**, pp. 1197–1199; Obtaining a satisfactory zinc coating, Iron Age, **122**, pp. 811–814.
28	1928	Krause, E., Metallschutz in der galvanotechnik unter besonderer berucksichtigung der sogennanten zwischenschichten vor der galvanisierung, Korrosion Metallschutz, **4**, pp. 153–157.
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31	1928	Timmerman, E. D., The estimation of zinc pick-up in hot galvanizing, Can. Chem. Met., September.
32	1928	Rawdon, H. S., Protective metallic coatings, Am. Chem. Soc., Monograph No. **40**, Chem. Catalog Co., New York, N. Y., pp. 26–29, 55–103. This book contains an extensive bibliography up to 1928.

(2) Zinc Cementation (Sherardizing).[6]—(a) *Principles.*—It has long been known that it is possible to cause alloying of certain metals by heating them together at a temperature below that of the melting point of either. The process is known as cementation, and certain aspects of it appear in a number of metallurgical processes of antiquity. The application of the principle to the formation of zinc coatings is comparatively recent (1900). It was then accidentally discovered that some steel specimens which had been annealed while covered with zinc dust, used as a supposedly inert material for excluding the air, were covered with an adherent zinc-rich coating. The process has been developed commercially and is known as "sherardizing" after Sherard Cowper-Coles who made the discovery and fostered the development.

The process is particularly well suited for small finished parts, such as bolts, nuts, screws, small castings, etc. It is not used to any extent on semifinished materials, such as sheet and wire. It is used, however, very considerably for electrical conduits.

After the usual preliminary cleaning, the articles are packed in zinc dust in a container or drum, which can be closed and made fairly air-tight, and are heated for several hours. Often the heating is done electrically by coils embedded in the walls of the container, although other means of heating are also employed. It is necessary that the zinc dust shall not completely fill the container, but that a slight "rumbling" between the specimens and the zinc dust can take place as the drum is rotated upon its axis during the heating period. This ensures the formation of a uniform coating on all sides of the specimen to be coated. Agreement has not been reached as yet as to the exact mechanism of the process. Evidence has been advanced to show that intimate contact of the two metals while heated is

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[6] Reference 6 has been used freely in the résumé given here.

sufficient to account for the result, whereas some investigators have attemped to show that the slight volatilization of zinc at the temperature used is necessary and sufficient to account for the transfer of zinc from the zinc particles to the steel surface on which the alloy is formed.

(b) *Zinc dust.*—Commercial "blue powder," a form of zinc dust, containing approximately 85 to 90 per cent zinc and 5 to 8 per cent of zinc oxide, which is a common product in zinc smelting, is generally used for sherardizing. Additions of new dust, for example,10 per cent, must be made from time to time and other additions have been used at times, such as a special form of powdered zinc or some inert material to prevent caking of the extremely fine zinc dust when heated. The iron-oxide scale which gradually accumulates in the used dust must be removed occasionally. As in all alloying reactions, temperature has a marked effect upon the rate of formation of the coating. A temperature of 350° to 375° C. (660° to 705° F.) is favored in commercial practice. Three hours at this temperature is sufficient to give a coating 0.0025 inch in thickness, which is considered sufficient for ordinary service.

(c) *Character of coating.*—A sherardized coating is essentially an alloy of zinc and iron. Sometimes evidence of two alloy layers can be seen in the microstructure. The average iron content of the coating, 8 to 10 per cent, is in fair agreement with that of the compound $FeZn_7$ (10.9 per cent). The fact that there is considerable mechanically entrained zinc in the outer part of a sherardized coating will account for the fact that the iron content is somewhat lower than that of the compound. The iron content increases as the cementation temperature is increased.

When sherardized articles are exposed to the weather, the coating becomes dark and often a superficial "bloom," suggestive of iron oxide, forms. If the iron content is relatively high the surface has a rusty appearance. This might be mistaken in a cursory examination for corrosion of the base metal. That such is not the case can be readily demonstrated, however.

Sherardizing

Text reference	Year	Name and title
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2	1929	Petrie, A. P., Sherardizing, Metal Ind. (London), **34**, pp. 483–484; Metal Ind., **27**, pp. 328–329.
3	1929	Roll, F., Zinc coatings by spraying and sherardizing, Das Metall., **50**, pp. 73–75.
4	1929	Silberstein, J., A comparison between metal-coating processes, Brass World, **25**, pp. 170–171.
5	1928	Lead, H. N., Sherardizing for rust-proofing aeroplane parts, Can. Machy., **39** (11), pp. 42–43; J. Inst. Metals, **40**, p. 560.
6	1928	Rawdon, H. S., Protective metallic coatings, Am. Chem. Soc. Monograph No. 40, pp. 30–32, 104–112. Chemical Catalog Co., New York, N. Y. An extensive bibliography up to 1928 is given.

(3) ELECTROPLATING.—(a) *Uses.*—Zinc plating, which is often referred to as "electro galvanizing" or "wet galvanizing" has come into extensive use for protecting iron and steel against corrosion. The coatings are practically pure zinc, except in special cases when other metals, such as cadmium or mercury, are intentionally added

to the baths. For a given thickness of zinc it has been claimed that the pure zinc coating furnishes more protection than does one containing a zinc-iron alloy, such as a hot-dipped coating. It is generally conceded (16), however, that about the same degree of protection is afforded against the corrosion of iron and steel by a given thickness of zinc, regardless of the method of application.

One advantage of zinc plating is that it is possible to control readily the average thickness of the deposits by regulating the current density and time of plating. Actually electroplated coatings are practically always thinner than those applied by other methods. Relatively thin coatings, for example, with an average thickness of 0.0005 inch (0.013 mm), which can readily be produced by plating, are adequate for many types of moderate exposure. Very thick coatings can generally be produced more cheaply by other methods.

Zinc plating does not produce entirely uniform distribution on irregularly shaped articles. For such purposes the cyanide solutions with their better "throwing power" (14, 18) are more useful than the sulphate or choride baths. The latter are, however, cheaper to prepare and operate. Plating is not effective for coating the inside of long pipes or other articles with very deep recesses, unless special anodes are inserted. It is valuable for threaded parts, because it does not fill up the threads.

Zinc plating is now applied extensively in the automobile industry to nuts and bolts, tire rims, and other parts requiring protection against corrosion without the fine appearance of nickel or chromium. It is employed for coating steel wire, and the metal strips used for fabrication into BX cable. Concealed steel parts of electrical switches and their supports are usually plated with zinc or cadmium. Steel hardware and springs for outdoor exposure are often zinc plated. Steel parts for airplanes are usually plated with zinc or cadmium. Parts of artillery ammunition fuses are generally zinc plated. Steel wire cloth is generally plated with zinc for use in window screens.

(b) *Methods of plating.*—As indicated above, zinc can be deposited from acid or alkaline solutions. The composition and properties of the two kinds of baths are quite different. Information on typical zinc plating baths is given in Table 52.

Acid baths.—Acid zinc baths have as their principal constituent a simple zinc salt, usually zinc sulphate or chloride, the sulphate being most extensively employed because it is cheaper and more easily crystallized than the chloride. The latter is, however, more soluble and its solutions have higher conductivity. In either case relatively high concentrations of zinc are used, for example, from 2 to 4 *N*.

The acidity or pH of electrolytic zinc baths is important because it influences the conductivity, the cathode efficiency, the anode efficiency, and the character of the deposits. In the electrowinning of zinc, (p. 8), where insoluble anodes are used, and where high cathode efficiencies are obtained at high-current densities, it is customary to employ solutions in which the free sulphuric acid is 2 or 3 *N*. In zinc plating, however, the soluble anodes used would be attacked chemically by the strong acid and rapidly consumed with a resultant decrease in acidity and increase in zinc content.

Thompson (8) found that the favorable range of acidity for zinc plating is from about pH 3.5 to 4.5. At a lower pH, with the current densities used in plating, the cathode efficiency is low, and the anode corrosion excessive; whereas at a higher pH the deposits are likely to be dark and spongy. Approximate pH measurements in this range may be made colorimetrically with brom phenol blue. No doubt some salt errors are involved, similar to those found with indicators in nickel plating baths (5). For accurate control, as for research, electrometric measurements with a hydrogen or quinhydron electrode will be more reliable.

It was found by Thompson that boric acid has practically no buffer action in zinc solutions at a low pH. Acetic acid (or sodium acetate) is effective in this range, and is sometimes used in zinc plating. Aluminum salts, which are very common additions to zinc baths, serve as buffers, because $Al(OH)_3$ starts to precipitate at a pH of about 4, and this prevents the pH from greatly exceeding that value until all the aluminum has been precipitated. A small amount of this precipitate is unobjectionable, although its appearance serves to indicate that an addition of acid is necessary.

Owing to the purely chemical attack of the anodes, the pH of a zinc plating solution usually increases appreciably, even in the course of a working day. More frequent adjustments of pH are needed than in nickel plating. It is customary to add small amounts of hydrochloric acid or sulphuric acid one or more times daily.

It is possible to increase greatly the conductivity of the zinc baths by the addition of chlorides or sulphates of sodium or ammonium. In such solutions higher current densities can be used without producing rough or tree-like deposits.

It is not feasible to improve the relatively poor throwing power of acid zinc solutions, because the cathode polarization is low and does not increase greatly as the current density is raised, even when salts with a common ion are added. These solutions are, therefore, chiefly useful for plating on articles of simple shapes.

Addition agents are commonly added to zinc baths in order to produce smoother or brighter deposits (21). Among them are glue, dextrin, licorice, and beta-naphthol.

Alkaline baths.—It is possible to deposit zinc from solutions consisting of sodium zincate, Na_2ZnO_2, or of the double cyanide, $Na_2Zn(CN)_4$. The baths actually used for plating contain both compounds together with an excess of sodium hydroxide or sodium cyanide. Such baths may be prepared by dissolving zinc cyanide in sodium hydroxide, or zinc oxide in sodium cyanide. During operation of these baths sodium carbonate is formed. This may arise from the absorption of carbon dioxide by the free alkali or cyanide present, hydrolysis of the sodium cyanide, or oxidation of the sodium cyanide. Some authors (17) report that the presence of much carbonate is detrimental, while others favor its addition.

The throwing power of cyanide zinc solutions is much better than that of the acid baths (14, 18). Hence, the cyanide solution is better adapted for plating irregularly shaped articles. The deposits usually have a fine structure, and it is claimed (18) that they furnish better protection against corrosion than do those from acid baths.

Organic addition agents are often added to cyanide zinc baths to improve the deposits. In recent years a small amount of mercury is sometimes added to the baths, either by dissolving mercuric oxide or by using zinc anodes containing about 2 per cent of mercury (11).

It is claimed that brighter deposits are produced, especially on cast iron.

More recently the deposition of zinc alloys containing about 5 to 10 per cent of cadmium has been advocated. It has been reported that the deposits are brighter and furnish more protection against corrosion of steel than either zinc or cadmium (3).

TABLE 52.—*Typical zinc-plating baths*

ACID BATHS

Reference No.	Composition	Concentration		
		N	g/l	Oz./gal.
1	Zinc sulphate ($ZnSo_4\cdot7H_2O$)	1.7	240	32
	Ammonium chloride (NH_4Cl)	.3	15	2
	Aluminum sulphate, $Al_2(SO_4)_3\cdot18H_2O$	.25	30	4
	Licorice		1	.13
2	Zinc sulphate ($ZnSO_4\cdot7H_2O$)	3.0	410	54
	Sodium sulphate (Na_2SO_4)	1.0	75	10
	Aluminum chloride ($AlCl_3\cdot6H_2O$)	.25	20	3
3	Zinc sulphate ($ZnSO_4\cdot7H_2O$)	2.50	360	48
	Ammonium chloride (NH_4Cl)	.60	30	4
	Sodium acetate ($NaC_2H_3O_2\cdot3H_2O$)	.10	15	2
	Glucose		120	16

CYANIDE BATHS

Reference No.	Composition	*N*	g/l	Oz./gal.
4	Zinc cyanide, $Zn(CN)_2$	1.0	60	8
	Sodium cyanide ($NaCN$)	.5	23	3
	Sodium hydroxide ($NaOH$)	1.3	53	7
5	Zinc oxide (ZnO)	1.0	45	6
	Sodium cyanide ($NaCN$)	1.5	75	10
	Sodium hydroxide ($NaOH$)	.3	15	2

Zinc plating

Text reference	Year	Name and title
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5	1929	Blum, W., Bekkedahl, N., The measurement of pH in nickel plating solutions, Trans. Am. Electrochem. Soc., **56**, pp. 291–317.
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Zinc plating—Continued

Text reference	Year	Name and title
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(4) ZINC SPRAYING.—The coating of metals by spraying zinc upon them is a commercial process, although it has not been developed in this country to the extent that it is reported to have been abroad. The process is essentially a mechanical one. The surface to be coated is first cleaned and roughened slightly, both purposes being accomplished usually by one operation—sand blasting. The spraying of the zinc on this prepared surface is done by means of a "gun" which is essentially a device for producing very fine droplets of zinc (or perhaps vapor) as it is melted and for projecting them onto the surface. In the ordinary process zinc wire is passed through the gun, melted at the forward end, and the drop of molten metal is broken up mechanically by a blast of air or other gas which also serves to spray the metal over the surface. Electrical heating may also be used in the zinc-spraying process.

The spraying process is not suited commercially for coating semifinished material, such as sheet, wire, and pipe. It is particularly adapted for coating a completed assembly and its use abroad for bridges, locks, boats, and the like has been described. The spraying process has been developed to the point where it is practically automatic for the spraying of small parts, such as bolts, nails, screws, washers, small castings, etc., within a closed cabinet, and can be carried out continuously, with very little supervision being required. The coating of defective spots in other zinc coatings or other unavoidable bare areas, such as cut edges and rivets, for example, in an assembled sheet metal culvert, is a very useful application of the spraying process. Another advantage is the ease with which a duplex coating can be applied as, for example, one of zinc and aluminum which has been found very much more effective in protecting steel against corrosion by sulphurous gases than a plain zinc coating is.

In structure, sprayed zinc coatings show no distinctive or significant features. No alloying with the base metal can be detected, and the adherence appears to be entirely mechanical. The thickness can be very readily increased as desired, but very thick coatings are brittle and flake readily from the surface they are intended to protect.

An excellent and very complete account of the process has been published by Turner and Budgeon (20).

Metal spraying

Text reference	Year	Name and title
1	1930	Bablik, H., Grundlagen des verzinkens, feuerverzinken, galvanisches verzinken, sherardisierin, spritzverzinken, Berlin: J. Springer.
2	1930	Binder, R. L., Sprayed molten metal coating process and results, J. Frank. Inst., **210,** pp. 173–217.
3	1930	Jones, E. O., Protective coatings for iron and steel, Chem. Age (London), **22,** Feb. 1, pp. 8–9.
4	1930	Pessel, L., Sprayed molten cadmium coatings in gasoline storage tanks, Ind. & Engng. Chem., **22,** pp. 119–121.
5	1930	Salmony, A., Schoop's metal spraying process in a new form, Tek. Tids. (Stockholm), **60,** pp. 375–376.
6	1929	Kalpers, H., The metal coating of small iron parts, Dinglers Polytech. J., **1,** 344, pp. 100–102.
7	1929	Kutscher, G., Surface protection through sprayed metallic coatings, Maschinenbau, **8,** pp. 543–545.
8	1929	Nicolardot, M., Metallization and its use in the gas industry, J. Usines Gaz., **53,** pp. 483–486.
9	1929	Schoop, M. U., Metal coating of combustible substances, Chemische Fabrik., **2,** p. 537.
10	1928	Parkes, R. A., Recent developments in metal spraying, Metal Ind. (London), **32,** pp. 201–203, 249–251.
11	1927	Binder, R. L., Coating by molten-metal spraying, Machinery, **34,** p. 169.
12	1927	Ballard, W. E., Metal spraying, Metal Ind. (London), **30,** pp. 191–192, J. Inst. Metals, **38,** p. 456; Chem. Abst., **21,** p. 1960.
13	1927	Jurgenson, The metal spray process in gas works, Gas. Wasserfach., **70,** pp. 395–396; Chem. Abst., **21,** p. 2057.
14	1927	Karg, H. R., Problems of metal spray methods, Korrosion Metallschutz, **3,** p. 110–112; Chem. Abst., **21,** p. 2650.
15	1927	——, The truth about the metal spray process, Das Metall., **48,** pp. 1–3, 9–10, 13–14, 17–18; J. Inst. Metals, **38,** p. 456.
16	1927	Kutscher, G., Painting or metal spraying, Deut. Malergewerke (42), 1926; Korrosion Metallschutz, **3,** p. 45; J. Inst. Metals, **38,** p. 456.
17	1927	Lowenstein, Metal spraying by acetylene in practice, Autogene Metallarbeitung, **20,** p. 136–145; J. Inst. Metals, **38,** p. 456.
18	1927	Proctor, C. H., Metal on plaster and wood., Metal Ind., **25,** p. 69.
19	1927	Rawdon, H. S., Protective metallic coatings, Am. Chem. Soc., Monograph No. 40, pp. 40–54, Chem. Catalog Co., New York. A good bibliography is contained in this book.
20	1926	Turner, T. H., Budgeon, N. F., Metal spraying, Chas. Griffin & Co., London. A very complete bibliography is given in this book.

(5) TESTING OF ZINC COATINGS.—Most laboratory methods for testing zinc coatings consist in determining the amount (weight) of coating and the uniformity of its distribution. Methods which have been adopted for this by the American Society for Testing Materials are summarized in the Appendix (p. 206).

In Figure 61 are summarized the results of salt spray tests on zinc-coated soil and in Figure 62, those of simulated atmospheric corrosion tests. For comparison a few sprayed lead coatings are included. Aside from showing the marked superiority of the zinc coatings over lead coatings of the kind tested, the results fail to show any very pronounced differences in zinc coatings of approximately the same weight. Concerning the behavior of zinc coatings of different kinds when exposed to the weather, there is, as yet, insufficient evidence which would show that there is any marked difference in coatings of the same weight under such conditions. It is to be recognized that the mechanical properties of the different coatings differ decidedly. The ability of the coating to withstand deformation must always be taken into consideration in estimating the probable life of any galvanized article unless the coating has been done subsequently to fabrication. Electroplated coatings, as a rule, withstand severe deformation much better than any of the others and for this reason are used in some special cases where the fabrication operations entail severe bending, etc. In any estimate of the probable life of zinc coatings when exposed to the weather, consideration must be given to the general climatic and local atmospheric conditions as well as to the weight of coating. Hubbell and Finkeldey (3) on the basis of existing data have given some general recommendations concerning the kind and weight of coating for various service conditions:

1. For all outdoor and severe indoor service use only materials galvanized by the hot-dip process. Sheet and wire products should be purchased under specification to secure heavy enough coating to give long life. All articles whose manufacture requires severe deformation should be galvanized after fabrication.

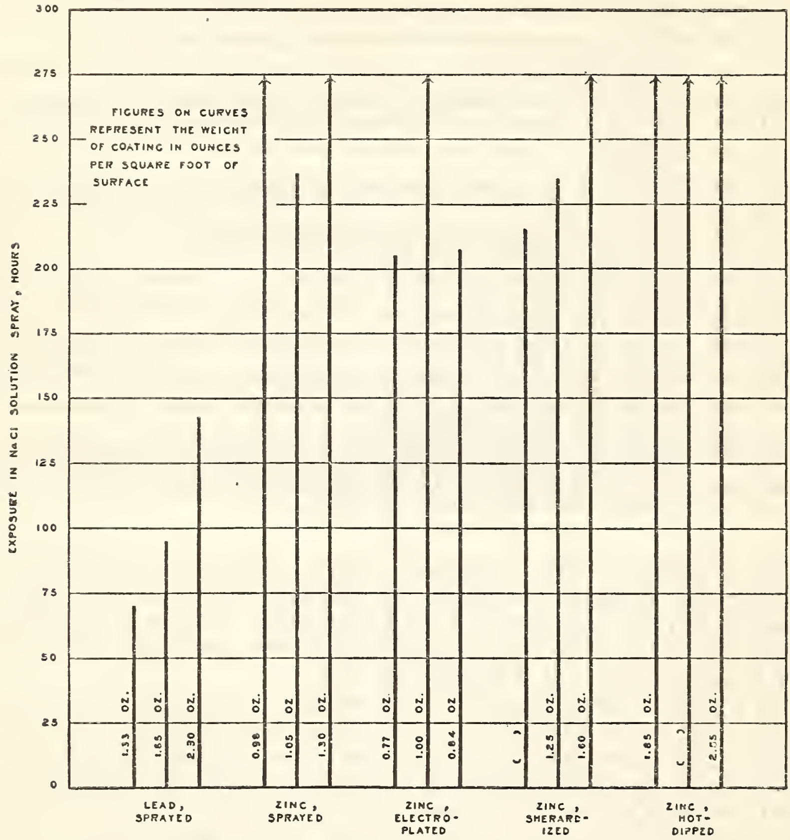

FIGURE 61.—*Results obtained with a spray corrosion test on sheet steel zinc-coated by different methods*

The arrow heads indicate that the material had not failed when the test was closed. In other cases, the length of the line gives the life of the material as determined by failure of the coating. The weight of the coating was accurately determined by weighing the cleaned sample before and after coating.

2. For semiprotected outdoor and equivalent indoor exposures sherardized or light weight hot-dipped coatings are satisfactory. Sherardizing is especially adapted to small castings, fittings, bolts, and nuts.

3. For indoor exposures under normal conditions electrogalvanized coatings will be satisfactory.

In the light of the satisfactory behavior for service in semiprotected exposures of articles which have been suitably plated, the exclusion of plated coatings from recommendations may be questioned.

Hubbell and Finkeldey have also given an estimate of the life which may reasonably be expected from galvanized coatings. (Table 53.)

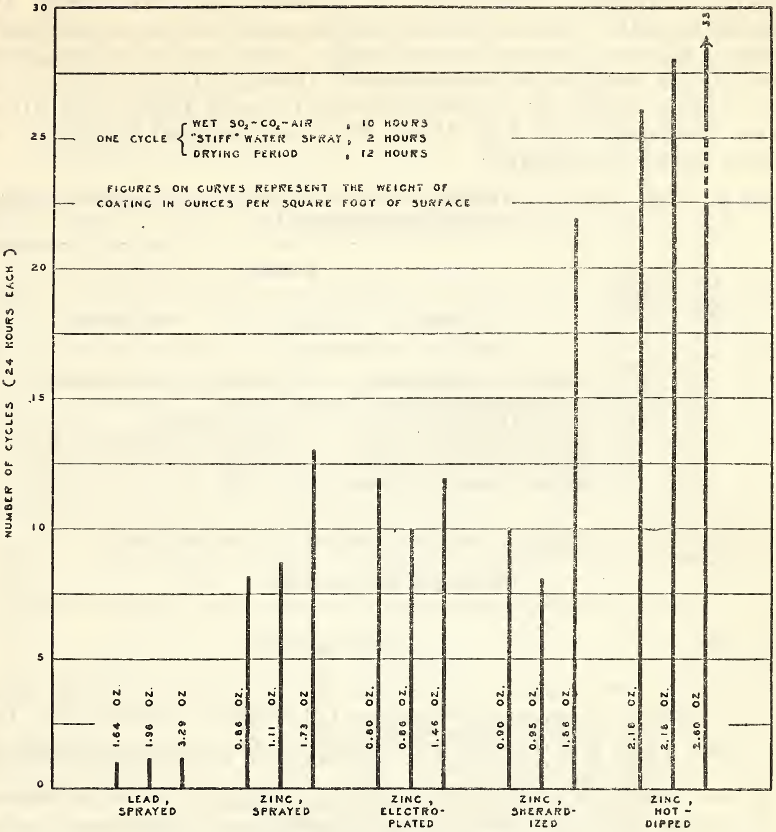

FIGURE 62.—*Results obtained in a simulated atmospheric corrosion test of zinc-coated sheet steel*

The corrosive atmosphere consisted of 100 volumes air, 5 volumes CO_2, and 1 volume SO_2, and was maintained over water, at 55° C. Compare Figure 61.

TABLE 53.—*Estimated life of unpainted zinc-coated products exposed to the weather (3)*

Class of material	Estimated life, in years, under atmospheric conditions			
	Rural	Sea-coast	Semi-industrial	Heavy industrial
Commercial rolled zinc sheet 0.020 inch thick	50–75	50	20–30	10–15
Galvanized product, 1.25 ounces coating per square foot of surface	30–35	20–25	15–20	8–10
Galvanized product, 1.0 ounce per square foor of surface	20–25	15	10–15	6– 8
Galvanized product, 0.6 ounce per square foot of surface	8–10	5– 8	5	3– 5
Galvanized product, 0.2 to 0.3 ounce per square foot of surface	3– 4	2– 3	1– 2	1

Results which have been recently reported by the American Society for Testing Materials (1) on the behavior of galvanized sheets exposed to the weather indicate that the estimated life given in Table 53 may be somewhat high in some cases. In Table 54 are summarized results which have been obtained in exposure tests of galvanized sheets in a "heavy" industrial atmosphere, at Altoona, and Pittsburgh, Pa. (Brunot Island). The material exposed in each location was as nearly identical as is commercially practicable. For similar materials exposed to the weather for approximately the same time in other locations, State College, Pa. (rural conditions), Sandy Hook, N. J. (temperate seacoast), and Key West, Fla. (semitropical seacoast), no failures have been reported.

TABLE 54.—*Life of galvanized coatings on sheets: Results of exposure tests in a heavy industrial atmosphere* (*1*)

No. of sheets [1]	Gage of sheet	Weight of coating [2]	Results	
			Altoona	Brunot Island
		Oz./ft.^{2}		
10 [3] 12	16	2.5	No failures of coating to date	No failures in coating to date.
18	22	2.5	3 out of 18 failed in 3.5 years	Do.
18	22	2.0	10 out of 18 failed in 3.5 years	1 out of 18 failed.
18	22	1.5	All failed, average life 3 years	16 out of 18 failed in 3.5 years.
18	22	1.25	All failed, average life, 2.4 years	All failed, average life, 3.2 years.
14	22	.75	All failed, average life, 1.9 years	All failed, average life, 2.2 years.
10	28	.75	All failed, average, life, 2.1 years	Do.

[1] At each location.

[2] Oz./ft.^{2} of sheet; divide by 2 for oz./ft.^{2} of surface for comparison with data of Table 53.

[3] 10 at Altoona.

Testing of zinc coatings

Text reference	Year	Name and title
1	1930	Report of Committee A-5, Subcommittee VIII, Field Tests of Metallic Coatings, Proc. Am. Soc. Testing Materials, **30**, Pt. I, p. 233.
2	1928	Rawdon, H. S., Protective metallic coatings, Am. Chem. Society Monograph No. 40, chapter 13, Chemical Catalog Co., New York, N. Y. This book contains an extensive bibliography.
3	1926	Hubbell, J. P., Finkeldey, W. H., Rolled zinc and zinc-coated products for industrial structures, Trans. Am. Inst. Chem. Eng., **18**, pp. 51–64.
4	1926	Accelerated corrosion tests of zinc-coated products, Report of Committee A–5, Subcommittee VII, Proc. Am. Soc. Testing Materials, **26**, Pt. I, p. 144.

(g) SURFACE FINISH: COLORING, PAINTING, PLATING

(1) CHEMICAL COLORING.—The color of weathered zinc is a soft gray. Other colors may be produced artificially, either by simple immersion in a suitable solution or by electrolytic means. Solutions of copper are often used for darkening the surface by producing different shades of brown or black. Of the numerous methods given in books on the coloring of metals, the following solutions have been especially recommended for use in the coloring of zinc (1):

By electrodeposition, with a current of 1 ampere per square foot, in the following solution at 45° C., a good adherent black can be obtained. About two minutes is usually required to obtain a good black.

Nickel ammonium sulphate	8 oz./gal. (60 g/l)
Zinc sulphate	1 oz./gal. (7.5 g/l)
Potassium sulpho-cyanate	2 oz./gal. (15 g/l)

Immersion for about five seconds in the following solution, at 70° to 75° C., gives a fairly good black which may be used if the high lights are to be intensified by removal of the coloring at such spots by brushing:

Sodium hydroxide	4 oz./gal. (30 g/l)
White antimony trioxide	½ oz./gal. (3.7 g/l)

A similar result may be obtained by use of the following solution, the action of which is much slower, a 30-minute dip being suggested:

Single nickel salts	10 oz./gal. (75 g/l)
Sodium sulphate	15 oz./gal. (112 g/l)
Ammonium chloride	1¾ oz./gal. (13 g/l)
Boric acid	2 oz./gal. (15 g/l)

Zinc colored by any of these means is intended for indoor use only. When exposed freely to the action of the weather only a short life may be expected.

(2) Painting.—In order to paint, lacquer, or enamel zinc successfully, the smooth surface should be roughened by pretreating or by weathering (1, 2). Pretreatment consists in (*a*) removing oil, grease, or any other matter on the surface which may prevent the paint vehicle from wetting the surface, and (*b*) etching or artificially roughening the surface so as to provide increased anchorage of the paint, lacquer, or enamel to the surface. Whenever practicable, natural weathering for a period varying from two to six months (depending on the exposure) is always preferred to any pretreatment, with the possible exception of a very light sand-blast. This latter treatment should be used wherever it is practicable for it gives the best results.

When weathering, scratch brushing, or sand-blasting can not be employed, oil, grease, etc., may be removed by the use of organic solvents. Where the material can be treated in tanks, the same solution employed for cleaning articles to be plated may be used.

Roughening of the surface of material which can be treated in tanks is accomplished by etching with a solution of hydrochloric acid, ammonium nitrate, and water. Where material can not be handled in tanks the etching can be combined with the cleaning by use of a solution of alcohol, toluol, hydrochloric acid, and carbon tetrachloride. Bright acid dipping may be accomplished by use of a 1 per cent sulphuric acid solution, by a water solution of ammonium chloride, by a mixture of sulphuric and nitric acids or by a mixture of sulphuric and nitric acids with sodium chloride.

The occasional practice of treating galvanized steel with a copper salt should not be used as the copper film will accelerate the corrosion of the zinc.

Coloring and painting

Text reference	Year	Name and title
1	1929	New Jersey Zinc Co., Rolled zinc, Research Bulletin.
2	1925	Culbertson, C. C., Painting zinc and galvanized iron after producing artificial weathering, Bull. Am. Zinc Inst., 8 (6–7), pp. 10–11.

(3) Electroplating of Zinc.—Owing to the marked tendency of zinc to tarnish on exposure, it is customary to plate it with some other metal, such as nickel or chromium, to improve its appearance. When efforts were first made to plate nickel on zinc under the usual conditions of nickel plating, it was found that the surface became black. This behavior is due to the tendency of zinc to deposit nickel by immersion. To overcome it, it was customary to "strike" the zinc

with nickel; that is, to deposit an initial layer of nickel at a high current density (5).

It was early learned that the addition of salts, such as sodium citrate, to the nickel bath retarded the tendency for deposition by immersion (6). Later (4) it was found that this effect of citrate is due to a reduction in nickel ion concentration (probably through complex ion formation) and to a consequent increase in cathode polarization. The same effect can be accomplished by the addition of a salt with a common ion; for example, sodium sulphate to a nickel sulphate bath. In general, in order to prevent deposition by immersion it is necessary to apply a cathode potential at least equal to the potential (about −0.8 V) with which zinc tends to go into solution. The addition of the sodium citrate or sulphate reduces the current density at which this desired potential is reached.

When chromium coatings are desired on zinc or zinc-base die castings it is customary first to plate them with nickel by the above methods, and then to apply chromium in the usual way. It is possible to deposit chromium directly on zinc, but very difficult to obtain bright chromium deposits. The dull chromium coatings can be buffed to a bright surface. It is claimed that such coatings furnish very good protection upon die castings.

Other metals, such as copper, silver, and gold, may be applied to the nickel plated zinc more satisfactorily than directly to the zinc. A thin copper coating is sometimes applied to the zinc before the nickel, but it is of doubtful value, and may actually decrease the protective value of the nickel, on account of the accelerating action of copper upon the corrosion of zinc.

Plating of zinc

Text reference	Year	Name and title
1	1930	Curts, R. M., Uncommon properties of a common metal, Am. Mach., Apr. 12, pp. 413–415.
2	1929	Anderson, E. A., Reinhard, C. E., The plating of rolled zinc and zinc-base die-castings, Research Bulletin, The New Jersey Zinc Co.
3	1928	Proctor, C. H., Nickel-plating sheet zinc in a nickel-ammonium chloride solution, Monthly Rev. Am. Electroplaters Soc., **15**, (3), pp. 8–12; J. Inst. Metals, **41**, p. 568.
4	1925	Thompson, M. R., The nickel plating of zinc and zinc-base die-castings, Trans. Am. Electrochem. Soc., **47**, pp.163–185.
5	1923	Graham, A. K., The electrodeposition of nickel on zinc, Trans. Am. Electrochem. Soc., **44** pp. 347–357.
6	1916	Hammond, L. D., The electrodeposition of nickel, Trans. Am. Electrochem. Soc., **30**, pp. 103–131.

(h) MISCELLANEOUS, GRANULATION

Considerable amounts of zinc are used in the "disintegrated" form, such as is produced by pouring the molten metal into cold water. This is known under various trade names, such as mossy zinc, feathered zinc, and others. Zinc in this form has a variety of chemical uses, a principal one being the "stripping" of old photographic fixing or "hypo" baths for recovery of silver. Other uses include the burning of zinc for the production of different color effects in the manufacture of face brick, and for the removal of soot from chimneys.

Miscellaneous

Text reference	Year	Name and title
	1929	New Jersey Zinc Co., Zinc, metals, and alloys.

II. ALLOYS OF ZINC

1. BINARY SYSTEMS, CONSTITUTION AND RELATED PROPERTIES

The most important of the binary alloy systems, from the industrial standpoint, are those of aluminum, copper, and iron. The constitutional diagrams of the alloys with gold and silver are strikingly similar to that of the zinc-copper system while those with nickel and cobalt show some resemblance to that of zinc and iron. The attempt has been made to correlate the properties as have been given for the alloys with the constitutional diagram. Naming the alloy systems by giving zinc first, for example, zinc-copper, though contrary to ordinary usage in many cases, is believed to be justified in a discussion dealing primarily with zinc.

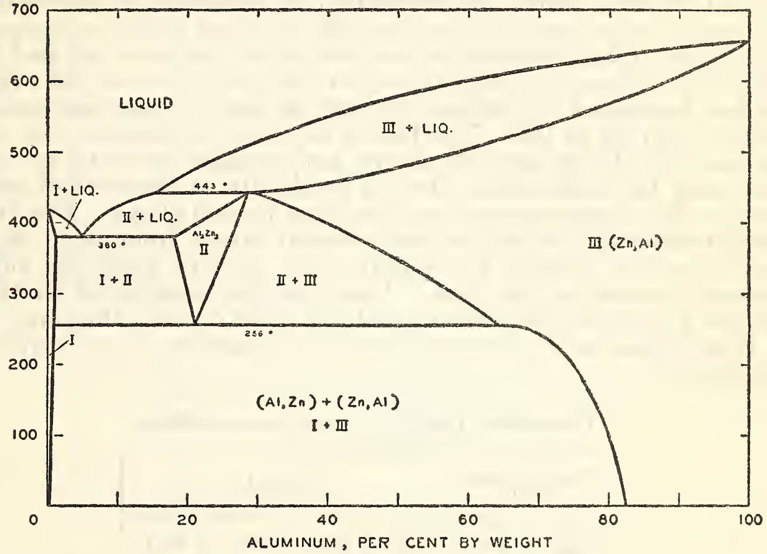

FIGURE 63.—*Constitutional diagram of the zinc-aluminum alloy system*

(a) ZINC-ALUMINUM

This binary system has received a great deal of attention and study. In spite of this fact, however, complete agreement has not been reached on all points. The constitutional diagram given in Figure 63 (2) represents in its most important features, the work of Hanson and Gayler (10). The results reported by Peirce (8) on the zinc-rich solid solution have been incorporated in the diagram. At normal room temperature, only two phases are found in the complete series of alloys. These are a solid solution of zinc in aluminum and one of aluminum in zinc.[7] Since the two metals differ in their crystal structure, zinc being of the close-packed hexagonal type and aluminum of the face centered cubic type, it is to be expected that the solubility of either metal in the other will be limited.

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[7] The method of representing the composition of a solid solution in the constitutional diagrams is that used in the International Critical Tables, for example (Zn,Al). The second metal is the "solvent" or the one present in the greater amount.

The spontaneous decomposition or eutectoic transformation, upon cooling, of the phase designated as II (frequently designated as β) is is of very great importance in determining the properties of the zinc-rich alloys. The formula, Al_2Zn_3, has been assigned to this phase, on the assumption that it is an intermetallic compound (5). Alloys quenched from above the temperature 256° C. retain this constituent, but upon aging at room temperature the decomposition ($II \rightarrow I + III$) occurs, this change being accompanied by evolution of heat and change of volume. This phenomenon is of far-reaching importance in a practical way as is discussed under the section on die-casting alloys. As Hanson and Gayler (10) have shown, this decomposition occurs with a very marked evolution of heat in alloys containing relatively large amounts of the constituent, II, and the specimen may become uncomfortably warm to the hand. As shown by Phebus and Blake (6) X-ray crystal analyses confirm the microstructural evidence by showing that, at normal room temperatures the fully annealed alloys contain only two phases; a face centered-cubic crystal structure ($a = 4.043$ to 4.034 A) in alloys whose zinc content ranges from 0 to 20 per cent and a close-packed hexagonal crystalline structure in alloys whose zinc content ranges from 95 to 100. The failure to detect evidence of the solid solution (Zn,Al) in zinc-rich alloys, for example, above 95 per cent zinc, may be attributed to the low sensitivity of the method rather than to the complete absence of this phase in such alloys. The intermediate alloys, in which the zinc content ranges from 20 to 95 per cent, give two distinct X-ray diffraction patterns which are superimposed the one on the other. These are characteristic of the close-packed hexagonal and the face centered cubic crystal structure.

Information on the density of the zinc-aluminum alloys is given in Table 55.

TABLE 55.—*Density of zinc-aluminum alloys*

Nominal composition		Density [1]			
Aluminum	Zinc	20° C.	700° C.	800° C.	900° C.
Per cent	*Per cent*	*g/cm³*	*g/cm³*	*g/cm³*	*g/cm³*
0	100	7.136 7.14	6.34 ----------	---------- ----------	---------- ----------
7	93	[2] 6.36	5.59	5.52	5.45
10	90	6.178 6.087	---------- ----------	---------- ----------	---------- ----------
20	80	5.228 5.280	---------- ----------	---------- ----------	---------- ----------
29	71	[2] 4.73	4.23	4.18	4.14
30	70	4.670 4.678	---------- ----------	---------- ----------	---------- ----------
40	60	4.160 4.168	---------- ----------	---------- ----------	---------- ----------
47	53	[2] 3.87	3.57	3.52	3.47
50	50	3.752	----------	----------	----------
50	50	3.785	----------	----------	----------

[1] Data for density at high temperature from (9).
[2] From reference (9), others from Shepherd (24).

In Table 56 from Isihara (11) are summarized data on the hardness of zinc-rich alloys of this series in the annealed and the quenched condition.

TABLE 56.—*Scleroscope hardness of zinc-aluminum alloys* (*11*)

Treatment	Hardness number of alloys with varying Al content					
	5 per cent aluminum	10 per cent aluminum	22 per cent aluminum	40 per cent aluminum	50 per cent aluminum	59 per cent aluminum
Annealed	14.4	14.3	23.5	19.3	19.3	19.2
Quenched, 240°	14.9	14.7	22.0	21.9	19.5	19.0
Quenched, 260°	18.0	29.2	34.4	28.1	26.1	19.5
Quenched, 265°	17.8	30.0	35.2	29.0	25.9	24.8
Quenched, 270°	19.7	----------	35.6	27.8	26.2	24.5
Quenched, 300°	----------	----------	35.7	29.5	26.3	24.3
Quenched, 330°	20.0	33.4	----------	----------	----------	24.5
Quenched, 350°	----------	33.7	----------	27.1	26.1	----------
Quenched, 370°	20.2	----------	25.8	29.8	27.0	25.0
Quenched, 400°	----------	15.3	22.4	21.7	19.5	25.0

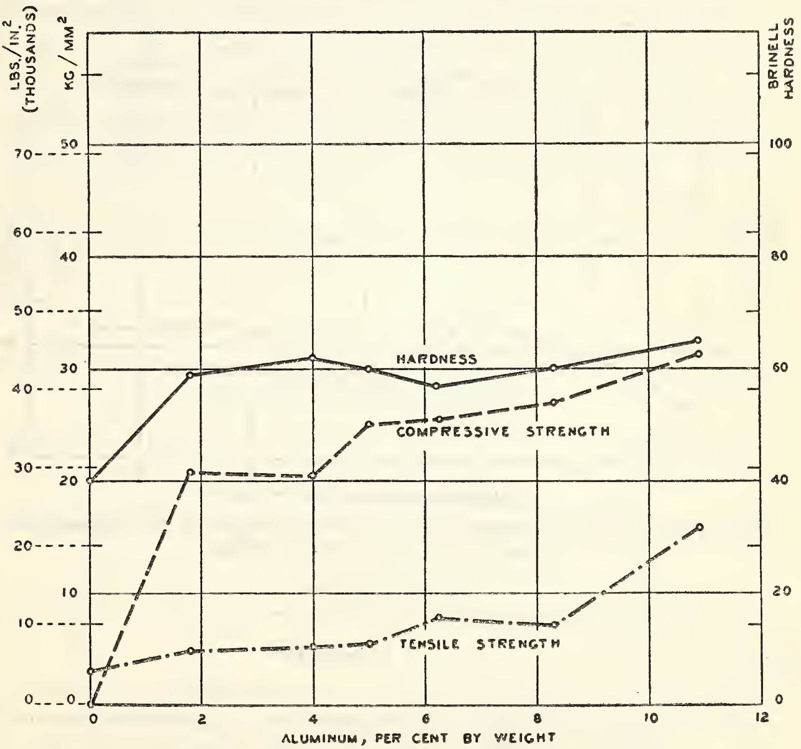


FIGURE 64.—*Hardness and strength of zinc-rich alloys of the zinc-aluminum alloy system*

The marked increase produced by quenching from 260° C. is to be attributed to the suppression of the decomposition of the constituent, II, ordinarily occurring slightly below this temperature and its retention in considerable amounts in the alloy at room temperature.

In Figure 64 are summarized data on the hardness and strength of the zinc-rich alloys (15) in the cast state. These alloys, with addition of copper, form the basis of most of the zinc-base die casting alloys

(p. 182). Figures 65 and 66 show the effect of additions of 2 and 6 per cent copper, respectively, to the zinc-aluminum alloys. The effect of a copper addition of 4 per cent was reported as only slightly greater than that of an addition of 2 per cent and the two properties of an alloy containing 8 per cent copper were only slightly higher than those given for the alloy containing 6 per cent copper.

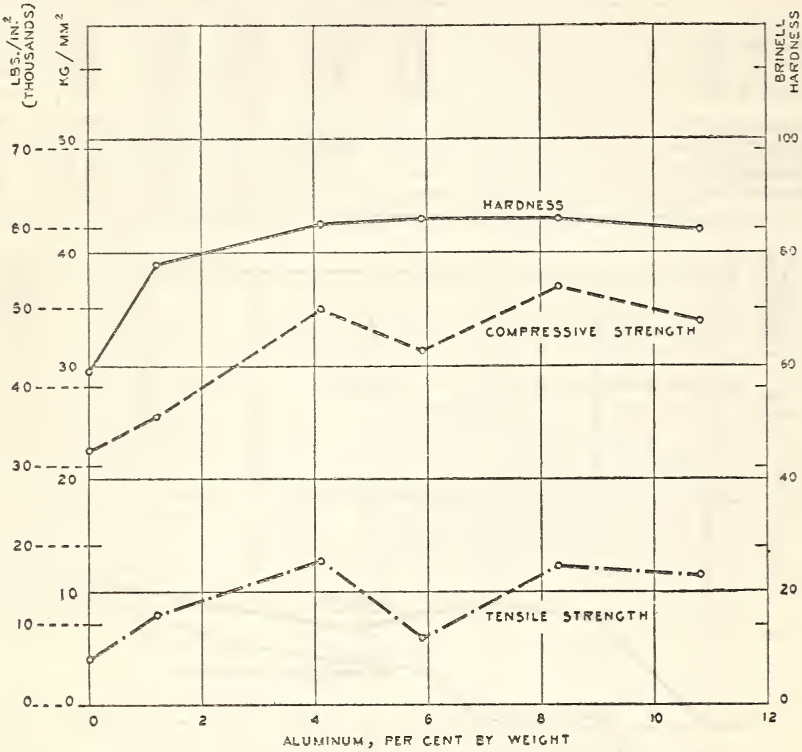


FIGURE 65.—*Effect of an addition of 2 per cent of copper on the hardness and strength of the zinc-aluminum alloys*

Zinc-aluminum

Text reference	Year	Name and title
1	1930	Fraenkel, W., Wachsmith, E., Kinetic measurement of a transformation reaction in the solid state. Z. Metallkunde, **22**, pp. 162–167.
2	1930	Anderson, E. A., Constitution of zinc-aluminum alloys, National Metals Handbook, Am. Soc. Steel Treat., p. 810.
3	1927	Fraenkel, W., Spanner, J., Transformations of zinc-aluminum alloys in the solid state (Influence of small additions of other metals on the velocity of transformation). Z. Metallkunde, **19**, pp. 58–60; J. Inst. Metals, **37**, p. 478.
4	1927	Isore, J., Die pressing of aluminum-zinc alloys. Aciers Speciaux, **2**, pp. 582–587.
5	1926	Isihara, T., A further investigation on the equilibrium diagram of the aluminum-zinc system. Sci. Rep. Tohoku Imp. Univ., **15**, pp. 209–224; Chem. Abst., **20**, p. 2813; J. Inst. Metals, **26**, p. 345.
6	1925	Phebus, W. C., Blake, F. C., The X-ray analysis of certain alloys. Phys. Rev., **25**, p. 107.
7	1924	Tanabe, T., Studies in the aluminum-zinc system. J. Inst. Metals, **32**, pp. 415–452.
8	1923	Peirce, W. M., Studies on the constitution of binary zinc-base alloys. Am. Inst. Mining Met. Eng., **68**, pp. 767–792.
9	1922	Bornemann, K., Sauerwald, F., Density measurements of metals and alloys at high temperatures, with special reference to the molten state, II. Z. Metallkunde, **14**, pp. 254–258.
10	1922	Hanson, D., Gayler, M. L. V., A further study of the alloys of aluminum and zinc. J. Inst. Metals, **27**, pp. 267–294; Chem. Abst., **6**, p. 1733.

Zinc-aluminum—Continued

Text reference	Year	Name and title
11	1922	Isihara, I., Relation between the equilibrium diagram and the hardness in binary alloys. Sci. Rept. Tohoku Imp. Univ., **11,** pp. 207–222.
12	1921	Houghton, J. C., Zinc and zinc-rich alloys. Metal Ind. (London), **18,** pp. 4–7.
13	1921	Schulze, A., The thermal expansion of aluminum zinc alloys. Physik. Z., **22,** pp. 403–406; Chem. Abst., **15,** p. 3608; J. Inst. Metals, **30,** 1923, p. 473.
14	1920	Von Schwarz, M., Alloys of zinc and aluminum. Z. Metallkunde, **12,** p. 6; J. Inst. Metals, **25,** p. 405.
15	1919	Schulz, E. H., Wachlert, M., Study of the copper-aluminum-zinc alloys of high zinc content. Metall. Erz., **16,** pp. 195–201.
16	1917	Escard, J., Alloys of zinc and aluminum. L'Ind. Chim., **4,** pp. 772–773; Chem. Abst., **12,** 1918, p. 1044.
17	1917	Ludwik, P., The hardness of the most important alloys for technical purposes. Z. Ver. deut. Ing., **61,** (1) pp. 549–554; Z. Anorg. Chem., **94,** 1916, p. 161–192; Stahl Eisen, **40,** 1920, pp. 1547–1551.
18	1917	Fedorov, A. S., The conversion of aluminum-zinc alloys into a crystalline form. J. Russ. Phys. Chem. Soc., **49,** pp. 394–407; Chem. Abst., **18,** p. 1457.
19	1917	Vogel, O., Bauer, O., Alloys of aluminum and zinc. Intern. Z. Metallog., **8,** pp. 101–178; Rev. Metal, **22,** pp. 148–151; Chem. Abst., **12,** 1918, p. 577.
20	1915	Bauer, O., Vogel, O., Aluminum-zinc alloys. Mitt. Kgl. Materialprufungsamt., **33,** pp. 146–198; J. Soc. Chem. Ind., **35,** pp. 543–544; Chem. Abst., **10,** p. 2195.
21	1912	Smirnoff, V., The thermal expansion of alloys of aluminum and zinc. Compt. Rend., **155,** pp. 351–352; J. Chem. Soc., **102a,** II, p. 896.
22	1910–11	Rosenhain, W., Archbutt, S. L., The constitution of the alloys of aluminum and zinc. Proc. Roy. Soc. (London), **85,** A, No. 580, pp. 389–392.
23	1910	McEwen, D., Turner, T., Shrinkage of antimony-lead alloys and of aluminum-zinc alloys during and after solidification. J. Inst. Metals, **4,** pp. 128–162; Met. Ind., **9,** pp. 69–71; Chem. Abst., **5,** 1911, p. 1735.
24	1905	Shepherd, E. S., Aluminum-zinc alloys, J. Phys. Chem., **9,** pp. 504–512; J. Chem. Soc., **88a,** II, p. 588.

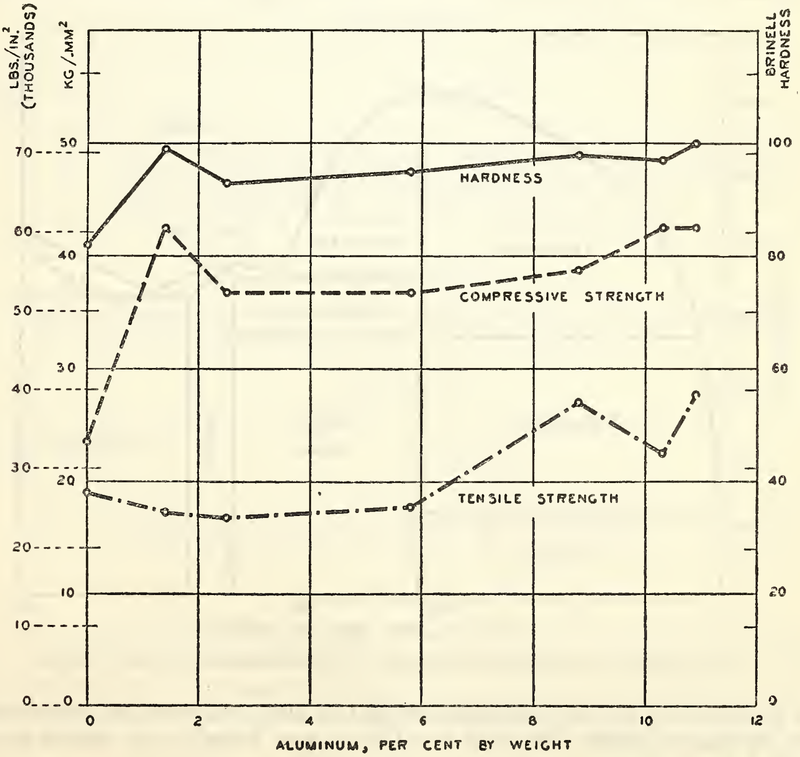


FIGURE 66.—*Effect of an addition of 6 per cent of copper on the hardness and strength of the zinc-aluminum alloys*

(b) ZINC-ANTIMONY

The two metals alloy in all proportions. The constitutional diagram worked out by Zemcznznyi (8) is given in Figure 67. The properties of a number of zinc-antimony alloys in the liquid state, especially the specific volume and shrinkage, have been studied by Sauerwald (4). The shrinkage in cooling, expressed as per cent of volume, at 800° C., of the alloy containing 55 per cent of antimony was stated to be only one-quarter that of zinc, whereas the shrinkage of antimony under the same conditions was found to be about one-third that of zinc.

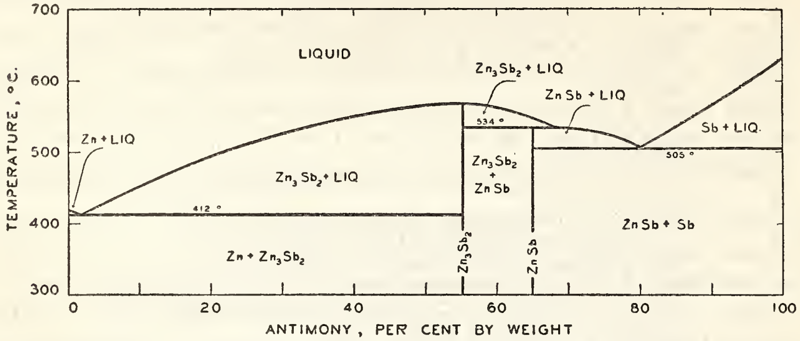


FIGURE 67.—*Constitutional diagram of the zinc-antimony series of alloys*

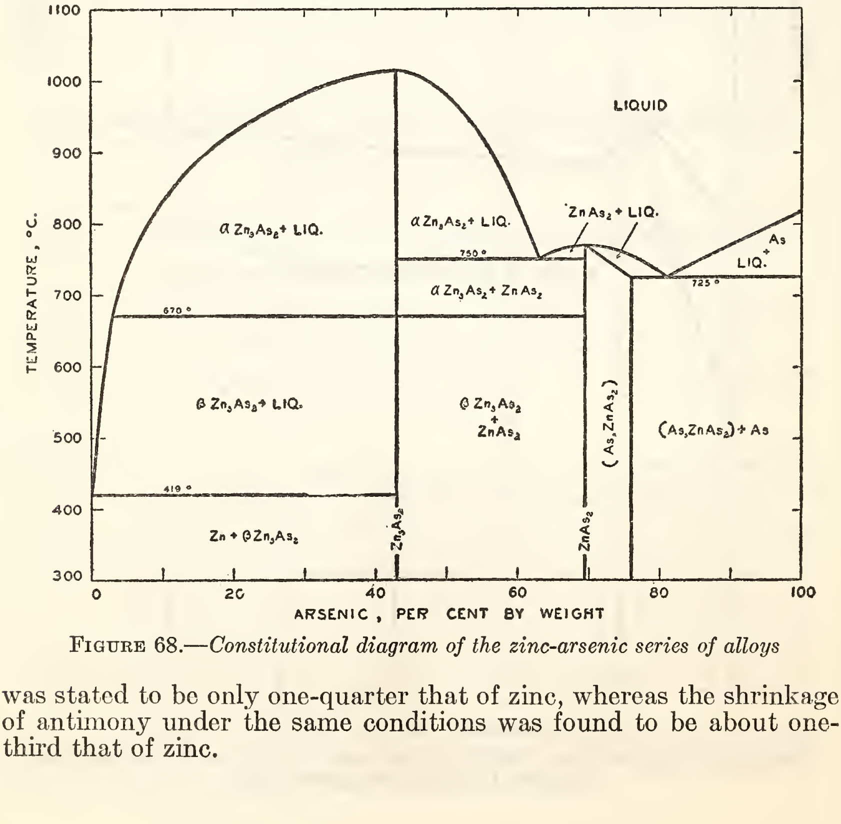


FIGURE 68.—*Constitutional diagram of the zinc-arsenic series of alloys*

Zinc-antimony

Text reference	Year	Name and title
1	1927	Endo, H., On the magnetic susceptibility of some binary alloys at high temperatures and their equilibrium diagrams. Sci. Rept. Tohoku Imp. Univ., **16**, I, pp. 201–234.
2	1927	Takei, T., Equilibrium diagram of the zinc-antimony system. Sci. Repts. Tohoku Imp. Univ., **16**, pp. 1031–1056.
3	1922	Kurnakoff, N. S., Achnasaroff, A. N., On the influence of the velocity of cooling on the hardness and microstructure of eutectic mixtures. Z. Anorg. Chem., **125**, pp. 185–200.
4	1922	Sauerwald, F., Density measurements of metals and alloys at high temperatures, with special reference to the liquid state. IV. Measurements by the displacement method. The systems Sb-Zn and Al-Sb, the metals Ag and Mg, Z. Metallkunde, **14**, p. 457–461; J. Inst. Metals, **29**, 1923, p. 625.
5	1917	Ludwik, P., The hardness of the most important alloys for technical purposes. Z. Ver. deut. Ing., **61**, 1917, pp. 549–554; Z. Anorg. Chem., **94**, 1916, pp. 161–192; Stahl Eisen, **40**, 1920, pp. 1547–1551.
6	1911	Arnemann, P. T., The metallographic examination of zinc and of rich zinc alloys with metals often contained in crude zinc. Metallurgie, **7**, pp. 201–211.
7	1909	Curry, B. E., Some zinc alloys. J. Phys. Chem., **13**, pp. 589–605; Chem. Abst., **4**, 1910, p. 1154.
8	1906	Zemcznznyi, S. F., Alloys of zinc and antimony. Chem. Zentr., I, p. 536; J. Chem. Soc., **90a**, II, p. 448; Zeit. Anorg. Chem., **49**, p. 384–399; J. Chem. Soc., **90a**, II, p. 549.
9	1905	Monkemeyer, K., Alloys of zinc and antimony. Z. Anorg. Chem., **43**, pp. 182–196; J. Chem. Soc., **88a**, II, p. 171.

(c) ZINC-ARSENIC

The constitutional diagram for this series, given in Figure 68, is based on the work of Heike (2).

Zinc-arsenic

Text reference	Year	Name and title
1	1928	Natta, G., Passerini, L., On the arsenides of magnesium and zinc. Gazz. Chim. Ital., **58**, pp. 541–550; Chem. Zentr., **99**, (II) pp. 2110–2111; J. Inst. Metals, **41**, p. 506.
2	1921	Heike, W., The solidification of the zinc-arsenic alloys. Z. Anorg. Chem., **118**, pp. 264–268; J. Inst. Metals, **29**, 1923, p. 671; Chem. Abst., **16**, 1922.
3	1906	Friedrich, K., Leroux, A., Zinc und Arsen. Metallurgie, **3**, p. 477–479.

(d) ZINC-BARIUM

Alloys of barium and zinc of low barium content have been prepared but a diagram of this alloy system is not available.

Zinc-barium

Text reference	Year	Name and title
	1922	Goldschmidt, V. M., The preparation of barium alloys. Norg. Geol. Undersokelse Staten Raastofkomite Publication No. 7; Chem. Abst., **17**, 1923, p. 2393.

(e) ZINC-BISMUTH

The constitutional diagram given for the alloy system in Figure 69, is that of the International Critical Tables (vol. 2, p. 428), the diagram being the one used by Mathewson (2) and represents the work of several earlier workers. A slight modification has been made to agree with the results on the solid solubility of zinc in bismuth as determined by Endo (1). The alloys are of very minor importance as judged by their practical or industrial uses.

Zinc-bismuth

Text reference	Year	Name and title
1	1925	Endo, H., On the relation between the equilibrium diagram and the magnetic susceptibility in binary alloys. Sci. Rep. Tohoku Imp. Univ. **14**, pp. 479–512.
2	1914	Mathewson, C. H., Scott, W. M., The constitution of bismuth-cadmium-zinc alloys. Z. Metallkunde, **5**, pp. 1–56.
3	1909	Curry, B. E., Some zinc alloys. J. Phys. Chem., **13**, p. 589.

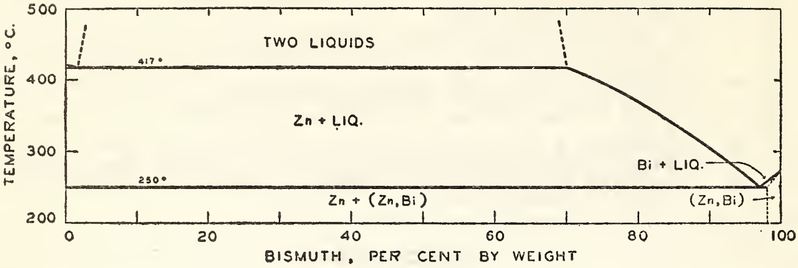


FIGURE 69.—*Constitutional diagram of the zinc-bismuth series*

(f) ZINC-CADMIUM

The constitutional diagram of the zinc-cadmium alloys is a simple eutectiferous one. The eutectic consists of the two solid solutions (Zn, Cd) and (Cd, Zn) and contains 82.5 per cent of cadmium. According to Peirce (9), somewhat less than 1 per cent of zinc is soluble in cadmium at room temperature, and between 1.5 and 2.0 per cent near the eutectic temperature (264.5° C.). Cadmium is soluble in zinc to the extent of 1 per cent at room temperature and 2 to 2.25 per cent near the eutectic temperature. The constitutional diagram is given in Figure 70 (1). In the constitutional diagram given by Jenkins, certain features based upon the allotropy of zinc were included. These have not been embodied in the diagram of Figure 70.

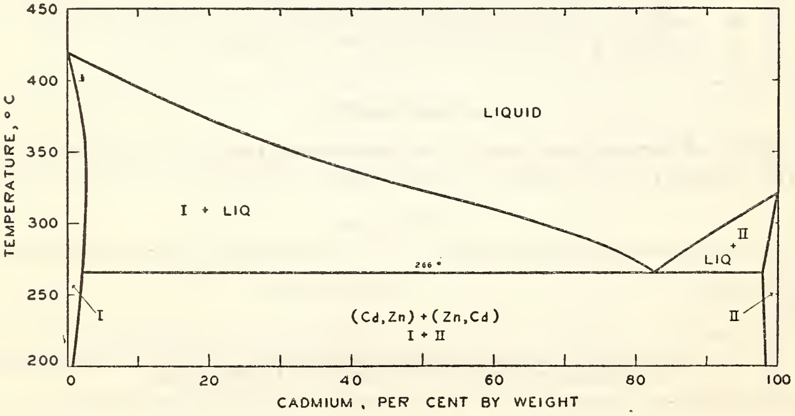


FIGURE 70.—*Constitutional diagram of the zinc-cadmium alloys*

A summary of the behavior of the various alloys with respect to their solution potential is given in Figure 71 (11).

Results of hardness tests of the zinc-cadmium series of alloys have been reported by Kurnakoff and Achasarov (10). These are given in Figure 72, together with comparison data obtained by earlier workers. It will be noted that by annealing the cast alloys, the marked peak in the hardness curve coinciding with the eutectic composition can be greatly reduced.

According to Grube and Burkhardt (4), the zinc-rich alloys containing 2 per cent cadmium can be strengthened and hardened by heat treatment; that is, by aging the quenched alloy at room temperature. An increase in tensile strength from 14.3 kg/mm^2 to 19.2 kg/mm^2, of elongation from 5.7 to 11.4 per cent, and of Brinell hardness (2.5 mm ball, 187 kg load, 60 seconds) from 57 to 64 was reported to occur in 15 days. By aging at a higher temperature, 70° C., the time required for corresponding results was shortened to 34 hours. Further heating resulted in softening of the alloy.

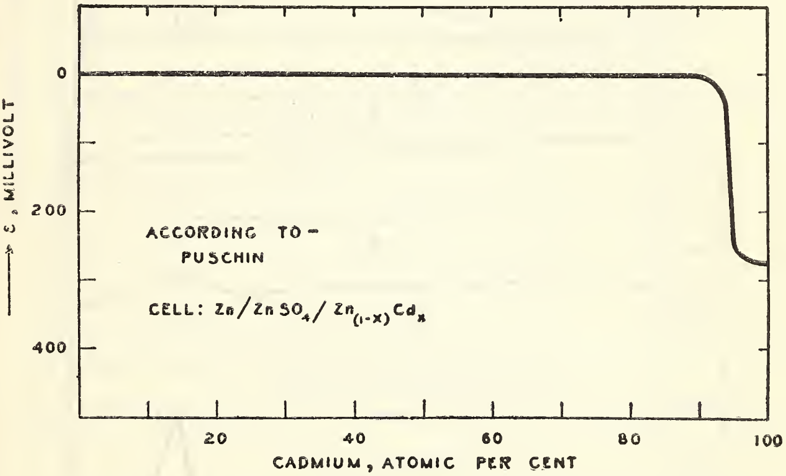


FIGURE 71.—*Relative solution potentials of the zinc-cadmium alloys*

One of the most extensive published investigations of the alloys of this system is that of Jenkins (5). Figure 73 gives the hardness of cast specimens of the zinc-rich alloys. It will be noted that Jenkins reported a decrease in hardness upon aging. This should not be confused with the hardening upon aging previously discussed. In that case, a preliminary quenching of the alloy was necessary in order for the hardening effect upon aging to occur. This is in accord with the usually accepted explanation of "precipitation hardening." Figures 74 and 75, from Jenkins, show the effect of rolling and annealing upon the tensile strength and elongation of the zinc-rich alloys of cadmium.

Budgeon (7) has stated that some of the zinc-cadmium alloys are useful as solders, the alloy containing 40 to 45 per cent of cadmium being mentioned as being particularly useful for aluminum bronze. The shearing stress of representative zinc-cadmium alloys used as

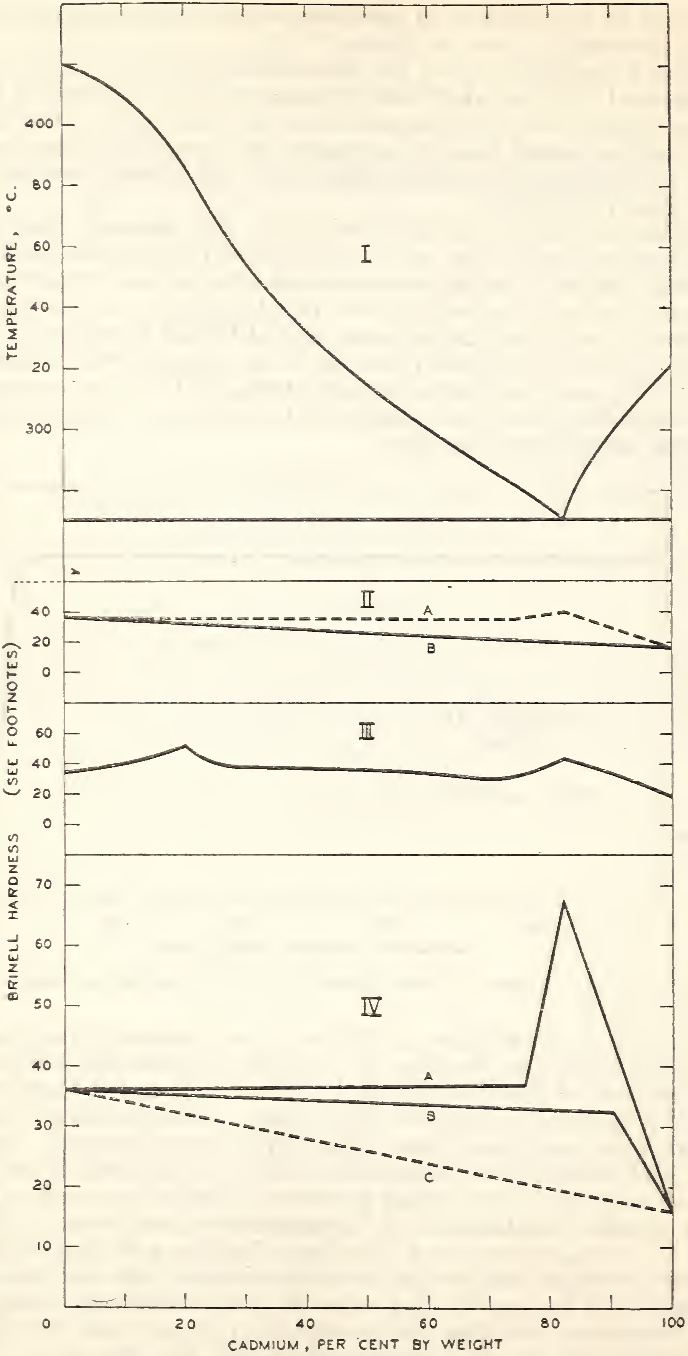


Figure 72.—*Hardness of the cast zinc-cadmium alloys*

solders has been reported by Deeley (6). The results are given in Figure 76.

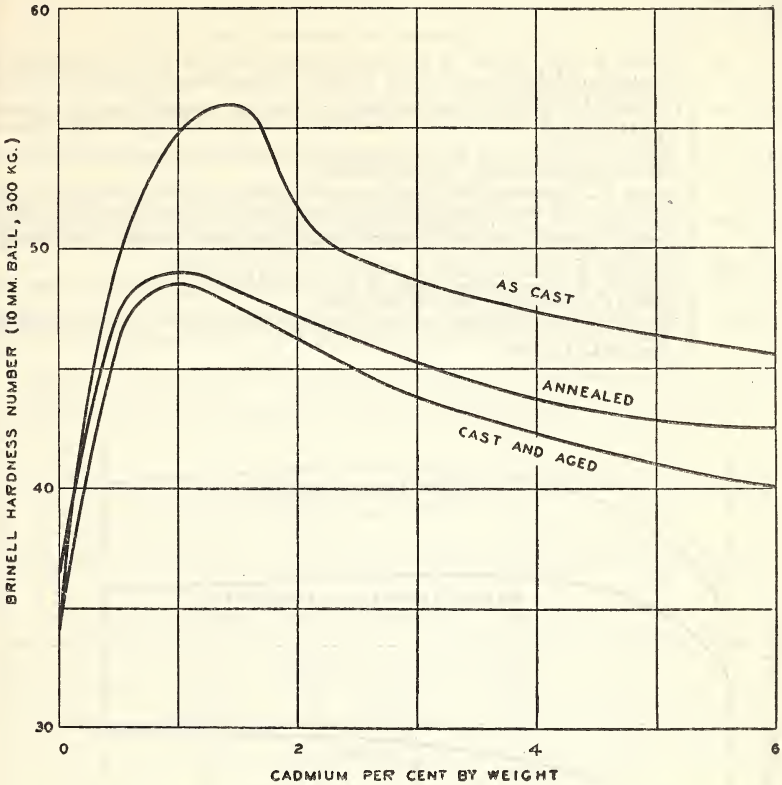


FIGURE 73.—*Hardness of cast zinc-rich alloys of the zinc-cadmium series*

Zinc-cadmium

Text reference	Year	Name and title
1	1930	Peirce, W. M., Constitution of zinc-cadmium alloys, National Metals Handbook, Am. Soc. Steel Treat, pp. 813–814.
2	1930	Stockdale, D., A note on the constitution of the cadmium-zinc alloys, J. Inst. Met., **44**, preprint.
3	1930	Straumanis, M., The decrease of solution speed of zinc by alloying with cadmium, Z. Phys. Chem., **148A**, pp. 112–124.
4	1929	Grube, J., Burkhardt, A., Die elektrische leitfahigkeit, die korrosion und die vergutbarkeit der kadmium-zink legierungen, Z. Metallkunde, **21**, pp. 231–234.
5	1926	Jenkins, C. H. M., Constitution and physical properties of alloys of cadmium and zinc, J. Inst. Metals, **36**, pp. 63–97; Engineering, **122**, p. 614.
6	1925	Deeley, R. B., Zinc cadmium alloys. A note on their shear strengths as solders, J. Inst. Metals, **34**, pp. 193–198; Metal Ind., (London) **27**, p. 234.
7	1924	Budgen, N. F., Cadmium. Its metallurgy, properties, and uses, C. Griffin & Co., publisher.
8	1924	Cook, M., The cadmium-lead-zinc system, J. Inst. Metals, **31**, pp. 297–313.
9	1923	Peirce, W. M., Studies on the constitution of binary zinc-base alloys, Trans. Am. Inst. Min. Met. Eng., **68**, pp. 767–795.
10	1922	Kurnakov, N. S., Achnasarov, A. N., The influence of the rate of cooling on the hardness and microstructure of eutectic mixtures, Z. Anorg. Chem., **125**, pp. 185–206.
11	1921	Guertler, W., Metallographie, Bd. 2, Tl. 1, Abs. 3 (Elektrochemische Metallkunde, R. Kremann) publ. Gebruder Borntraeger, Berlin.

Zinc-cadmium—Continued

Text reference	Year	Name and title
12	1916	Ludwik, P., The hardness of the most important alloys for technical purposes, Ver. deut. Ing., **61(1)**, 1917, pp. 549–554; Z. Anorg. Chem., **94**, pp. 161–192; Stahl Eisen, **40**, 1920, pp. 1547–1551.
13	1914	Glassunov, A., Matweew, M., Hardness and electrical conductivity of zinc-cadmium alloys, Intern. Z. Metallog., **5**, pp. 113–122; Chem. Abst., **8**, 1914, p. 1405; Z. Metallkunde, **5**, pp. 113–122.
14	1914	Mathewson, C. H., Scott, W. M., The constitution of bismuth-cadmium-zinc alloys, Int. Z. Metallographie, **5**, pp. 1–57 (in English).
15	1913	Lorenz, R., Plumbridge, D., Über die binaren systeme zink-zinn, zink-cadmium, zinn-cadmium, und das ternare system zinc-zinn-cadmium, Z. Anorg. Chem., **83**, pp. 228–242.
16	1910	Arnemann, P. T., Die metallographische untersuchung von zink und zinkreichen legierungen des zinkes mit den im rohzink haufiger enthaltenen metallen, Metallurgie, **7**, pp. 201–210.
17	1909	Currey, B. E., Some zinc alloys, J. Phys. Chem., **13**, pp. 589–605.
18	1907	Hindrichs, G., Zinc-cadmium alloys, Z. Anorg. Chem., **55**, pp. 415–418; J. Chem. Soc., **92a**, II, p. 953; Chem. Abst., **2**, 1908, p. 395.
19	1907	Shaposhnikov, A., Sacharov, M., Hardness and microstructure of alloys of cadmium and zinc, J. Russ. Phys. Chem. Soc., **39**, pp. 907–914; Chem. Abst., **2**, 1908, p. 65; J. Chem. Soc., **92a**, II, p. 869.

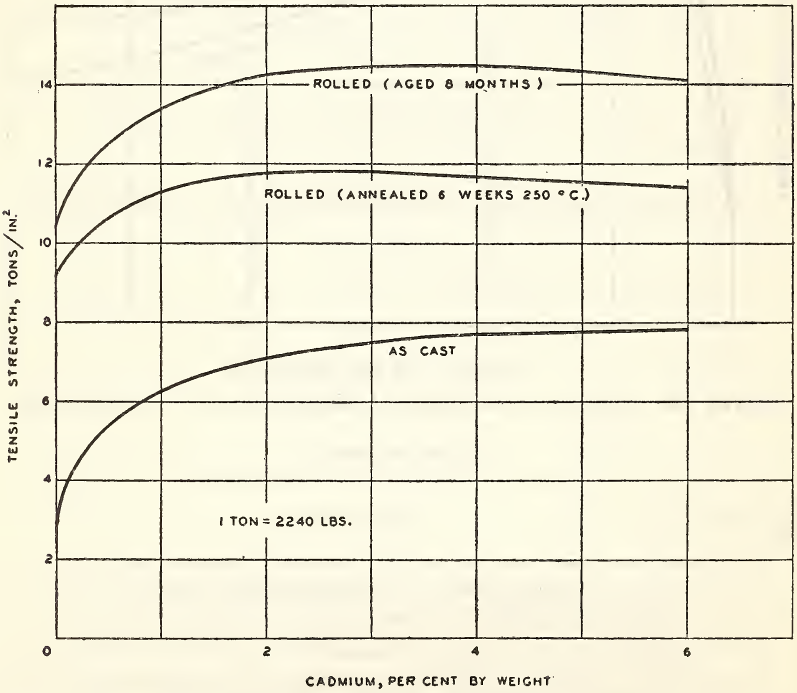


FIGURE 74.—*Tensile strength of zinc-rich alloys of the zinc-cadmium series, after rolling*

(g) ZINC-CALCIUM

According to Donski (1) on whose results the diagram in Figure 77 from the International Critical Tables (vol. 2, p. 429) is based, zinc and calcium alloy in all proportions. The liquidus curves have two maxima, 705° and 678° C., corresponding to the formation of two compounds, $CaZn_{10}$ and Ca_2Zn_3, respectively.

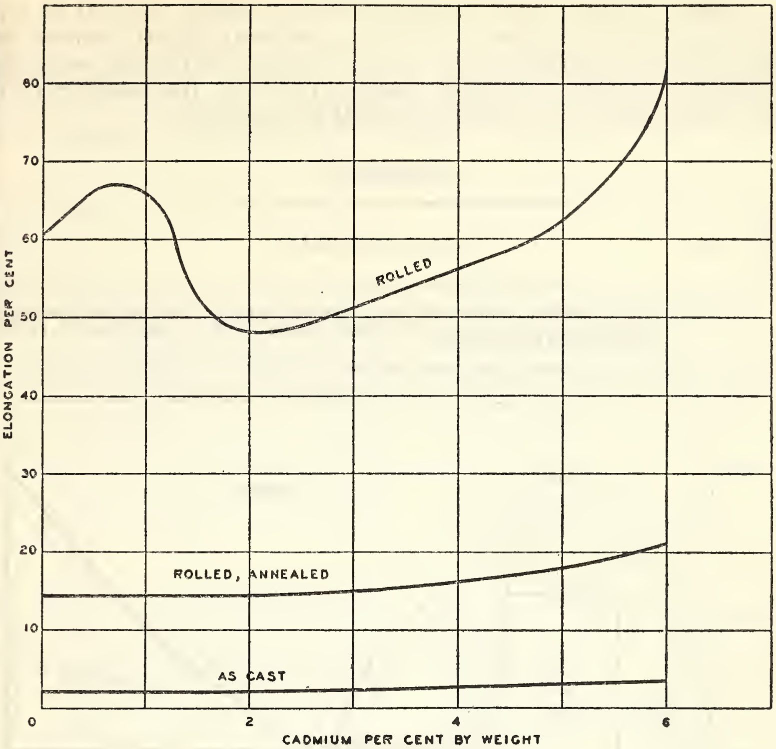


FIGURE 75.—*Elongation of zinc-rich alloys of the zinc-cadmium series, after rolling*

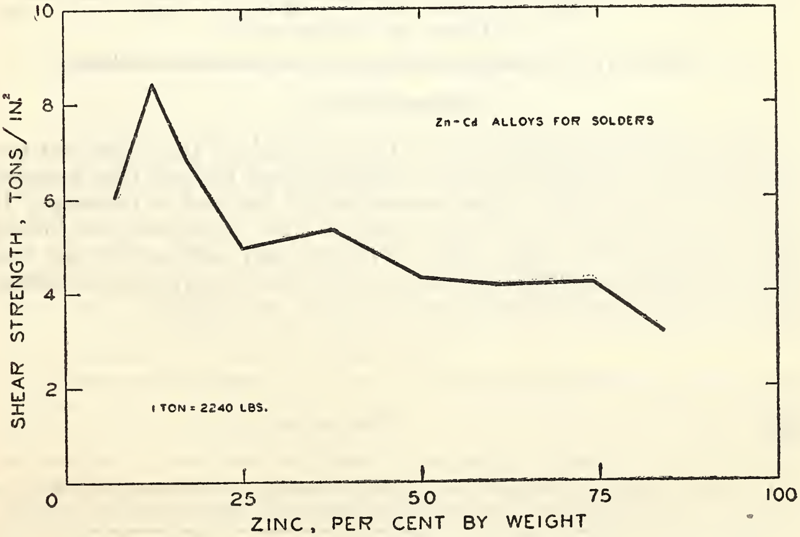


FIGURE 76.—*Shear strength of zinc-cadmium alloys proposed for use as solders*

Donski also states that the alloys with a calcium content of 6 per cent or less have the color of pure zinc, are only slightly harder than zinc and are not attacked by water. Alloys containing more than 6 per cent of calcium darken quickly in the air, the stability of the alloy decreasing as the calcium content is increased.

Zinc-calcium

Text reference	Year	Name and title
1	1908	Donski, L., Alloys of calcium with zinc, cadmium, aluminum, thallium, lead, tin, bismuth, antimony, and copper, Z. Anorg. Chem., **57**, pp. 185–219; Chem. Abst., **2**, p. 1819; J. Chem. Soc., **94**, (2), p. 278.

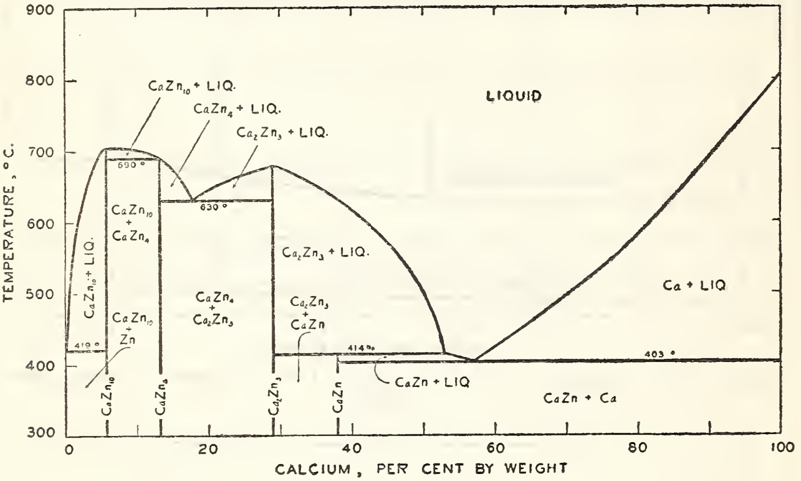


FIGURE 77.—*Constitutional diagram of the zinc-calcium alloys*

(h) ZINC-CERIUM

The constitutional diagram for the zinc-cerium alloys has not been determined. Clotofski (1) has reported upon the solution potential of alloys of this series. The cerium which he used in preparing the alloys contained 92.5 per cent cerium with impurities as follows: Iron, 1.46 per cent; silicon, 0.88 per cent; and carbon 0.35 per cent. The results of the potential measurements were interpreted as indicating the existence of the compounds, Ce_4Zn and Ce_2Zn.

Zinc-cerium

Text reference	Year	Name and title
1	1920	Clotofski, F., Compound formation and the electromotive behavior of cerium in its alloys with iron and zinc, Z. Anorg. Chem., **114**, pp. 1-23; Chem. Abst., ,**15**, 1921, p. 2770.

(i) ZINC-COBALT

Of the zinc-cobalt series of alloys, only the zinc-rich alloys have been studied. The constitutional diagram as given in Figure 78, based on the work of Lewkonja (3), is very similar to the corresponding portion of the diagram of the zinc-nickel system.

Zinc-cobalt

Text reference	Year	Name and title
1	1923	Peirce, W. M., Studies on the constitution of the binary zinc-base alloys, Trans. Am. Inst. Min. Engr. **68**, pp. 767–795.
2	1911	Ducelliez, F., Alloys of cobalt and zinc, Bull. Soc. Chim. de France, **9**, 4th ser., pp. 1017–1023; Chem. Abst., **6**, 1912, p. 473.
3	1908	Lewkonja, K., Alloys of cobalt with tin, antimony, lead, bismuth, thallium, zinc, cadmium, chromium, and silicon, Z. Anorg. Chem., **59**, pp. 293–345; Chem. Abst., **2**, p. 3328.

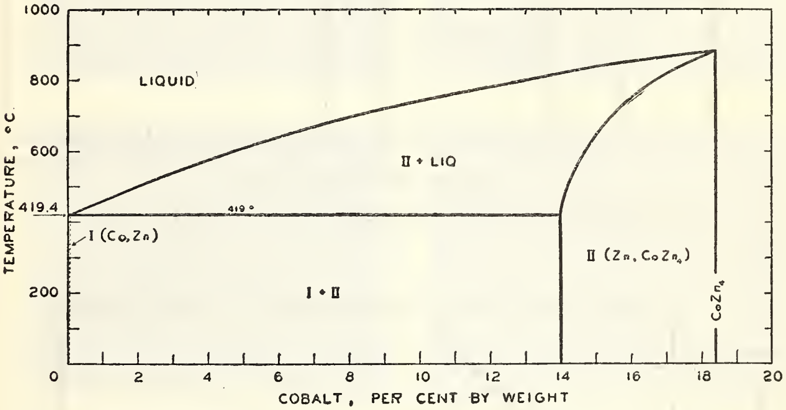


FIGURE 78.—*Portion of the constitutional diagram of the zinc-cobalt alloys*

(j) ZINC-COPPER

As judged by the amount of zinc used, the copper-zinc series is the most important of all the zinc alloys. In 1929 (Table 10), 28.5 per cent of the zinc sold was used in making alloys of this class. This was for the manufacture of brass or copper-rich alloys, however. The zinc-rich alloys are used very little. The copper-rich alloys or brasses have been extensively studied. Any discussion of them would be a very lengthy one. No attempt will be made to discuss them in this circular, the résumé given here being confined to the zinc-rich alloys of the series.

In Figure 79 (3) is given the constitutional diagram of this binary system and in Figure 80 typical micrographs showing how the microstructure changes as the composition is varied from pure copper to zinc by the addition of zinc in increasing proportions.

Supplementary data on the structural characteristics of the various phases of the system as determined by X-ray examinations are given in Figure 81, from The International Critical Tables (vol. 1, p. 350) as based upon the work of Owen and Preston (12).

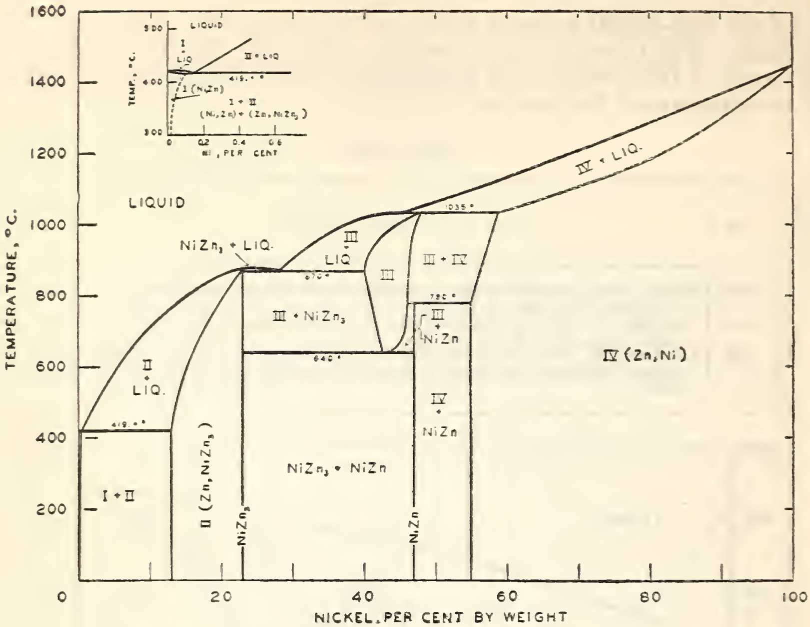


FIGURE 79.—*Constitutional diagram of the zinc-copper alloys*

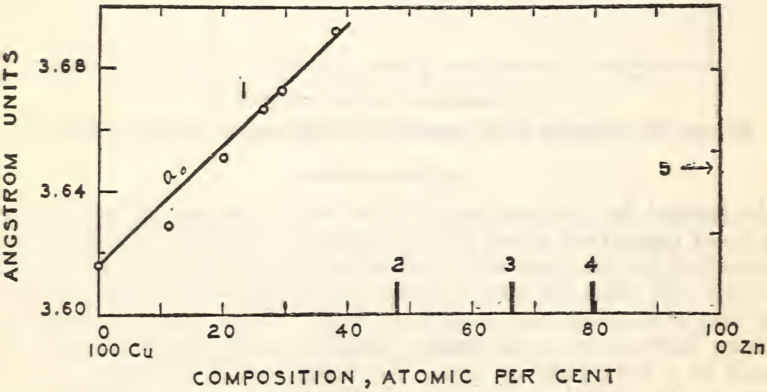
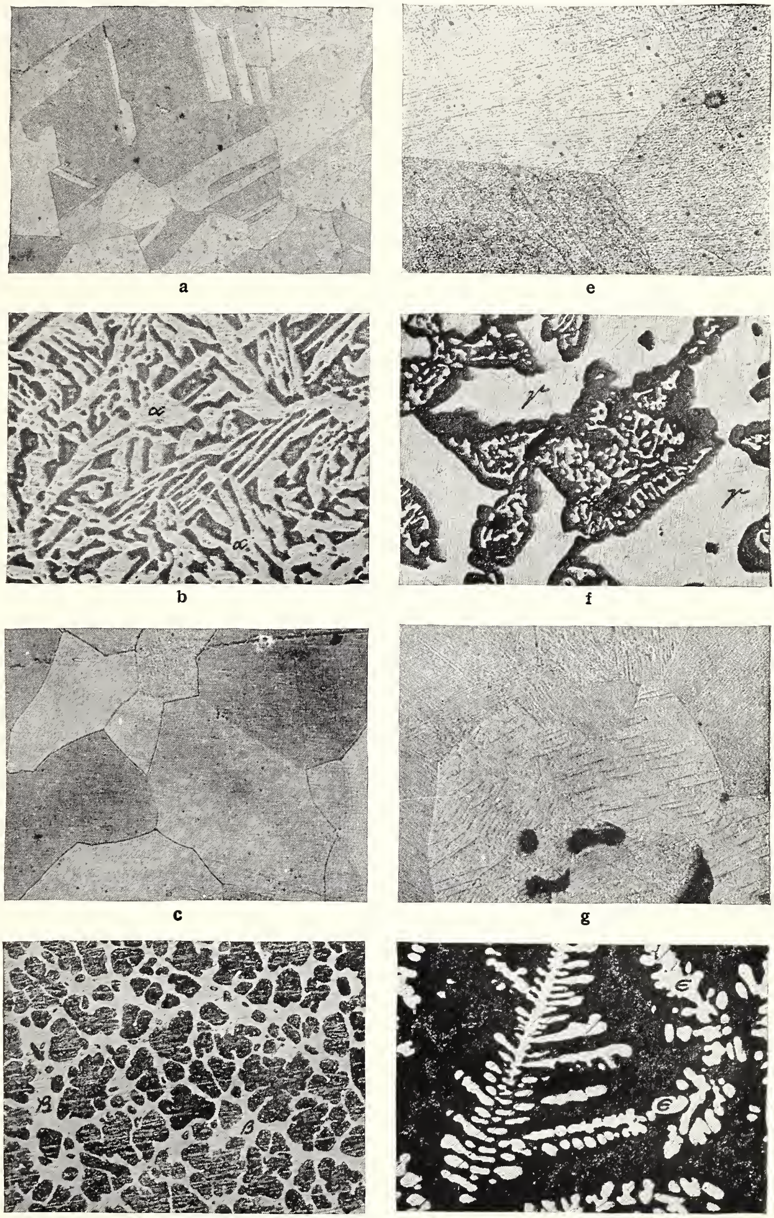


FIGURE 81.—*Summary of structural characteristics of zinc-copper alloys determined by X-ray examinations*

1. The α-brasses have the copper structure. The value of the a varies as shown in the diagram (face-centered cubic structure). 2. β-brass gives the pattern of a body-centered cube containing 2 molecules of CuZn and having a=2.95A. No difference was detected in samples quenched from the β and β' regions. 3. γ-brass gives a pattern attributed to a rhombohedral arrangement having a=4.14A and c/a=0.649. Westgren and Phragmen (S) concluded, from a similarity in the powder and Laue spectograms for copper-aluminum alloys with 16 and 25 per cent aluminum and for copper-zinc alloys with 65 and 67 per cent zinc, that zinc-copper alloys with 62, 65, and 67 per cent zinc have a face-centered cubic structure. 4. ϵ-brass gives a pattern which has been interpreted as hexagonal with a_0=2.72A and c_0/a_0=1.58. 5. Zinc structure: hexagonal close-packed arrangement of atoms.



a e b f c g d h

FIGURE 80.—*Representative microstructures of the various phases of the zinc-copper series of alloys,* × *100*

Note the alternation of alloys of simple and of duplex structure as the composition is varied. The alloys *d* to *h*, inclusive, are of very little use industrially. The compositions given are only approximate. *a*, α brass, 90 per cent copper, annealed after cold work, etched with acidified aqueous solution of ferric chloride; *b*, α-β brass, 60 per cent copper, hot-rolled, yellow matrix of beta containing reddish figures of alpha; etched with a dilute solution of sulphuric acid containing potassium dichromate; *c*, β brass, 55 per cent copper, cast, golden yellow in color, etched with an ammoniacal solution of copper ammonium chloride; *d*, β-γ brass, 46 per cent copper, cast, yellow matrix of beta containing silvery gray crystallites of gamma; etched with aqueous solution of ammonium persulphate; *e*, γ brass, 40 per cent copper, cast; silvery gray in color, hard and brittle; etched as in *d*; *f*, γ-ε brass, 28 per cent copper, cast; matrix of γ containing the eutectoid of γ and ε; etched as in *d*; *g*, ε brass, 15 per cent copper, cast, slightly purple when etched; etching reagent, ammonium hydroxide and ammonium persulphate; *h*, ε-η brass, 5 per cent copper, zinc-rich matrix of η containing bright unetched crystallites of ε; etched as in *d*.

Additional data on the alloy system are given in Figure 82, from Guertler (19) which summarizes observations made on the "solution potential" of representative alloys of this system.

Determinations of the density of copper-zinc alloys, in which the copper content ranged from 6.25 to 93.5 per cent, have been made by Bamford (17). Figure 83 summarizes the density at room temperature of these alloys in the chill-cast and sand-cast condition. There will be noted, especially in the curve summarizing the results for the sand-cast alloys, variations corresponding to phase changes in the system. The theoretical curve given was based upon the composition of the various alloys, and did not take into account the changes in the crystalline condition of the various phases, as given in Figure 81.

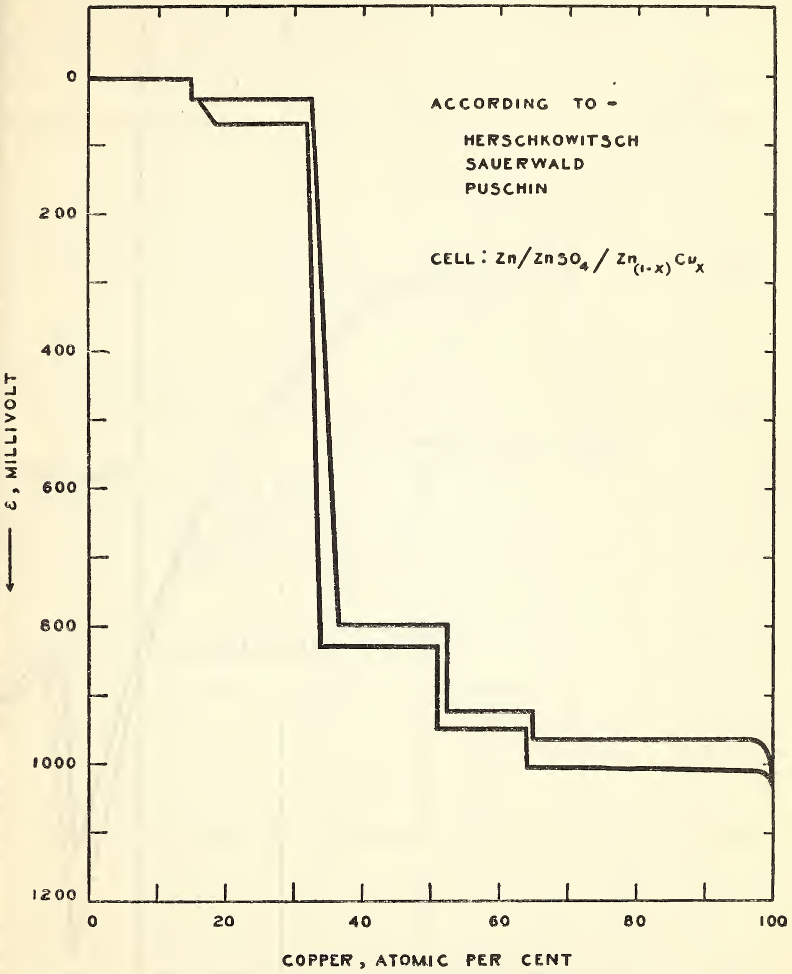


FIGURE 82.—*Relative solution potentials of the various phases in the zinc-copper series of alloys*

Johnson and Jones (16) have reported upon the relative shrinkage of alloys covering the entire copper-zinc system. Their results are summarized in Figure 84. It will be noted that for the zinc-rich alloys there was good agreement with the results reported for density. (Fig. 83.)

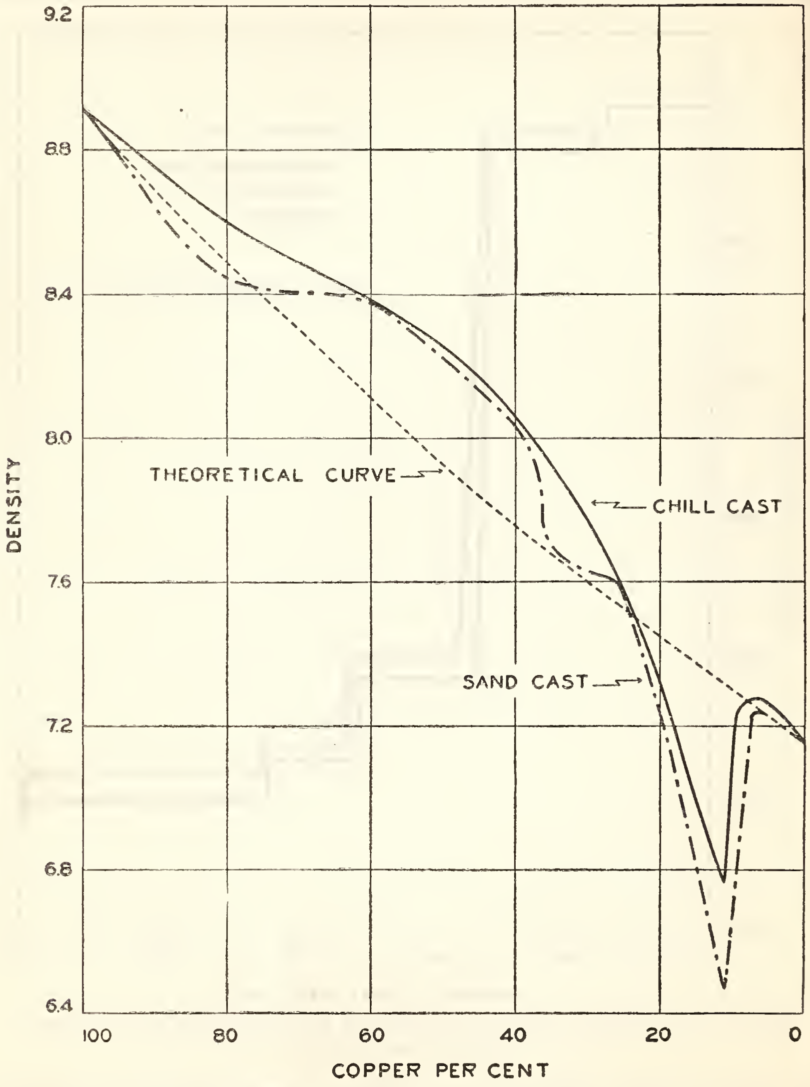


Figure 83.—*Density of zinc-copper alloys of different compositions*

On account of the very limited number of industrial uses of these zinc-rich alloys, their various properties have not been very extensively or systematically studied. Iokike (11) has reported upon the expansivity, hardness, and some other properties of the alloys containing 13 to 15 per cent of copper, which have been claimed to expand upon freezing. The behavior of the alloys of low copper content when mechanically worked has been studied by Rosenhain, Haughton, and Bingham (20). These results are summarized in Figure 85. The ability of the alloys to withstand cold rolling decreased very rapidly as the copper content was increased above 1 per cent (approximately) to 10 per cent. All of the alloys (containing copper up to 10 per cent) could be reduced over 70 per cent in thickness by hot rolling. Excellent mechanical properties were claimed for the alloy containing 1 per cent of copper.

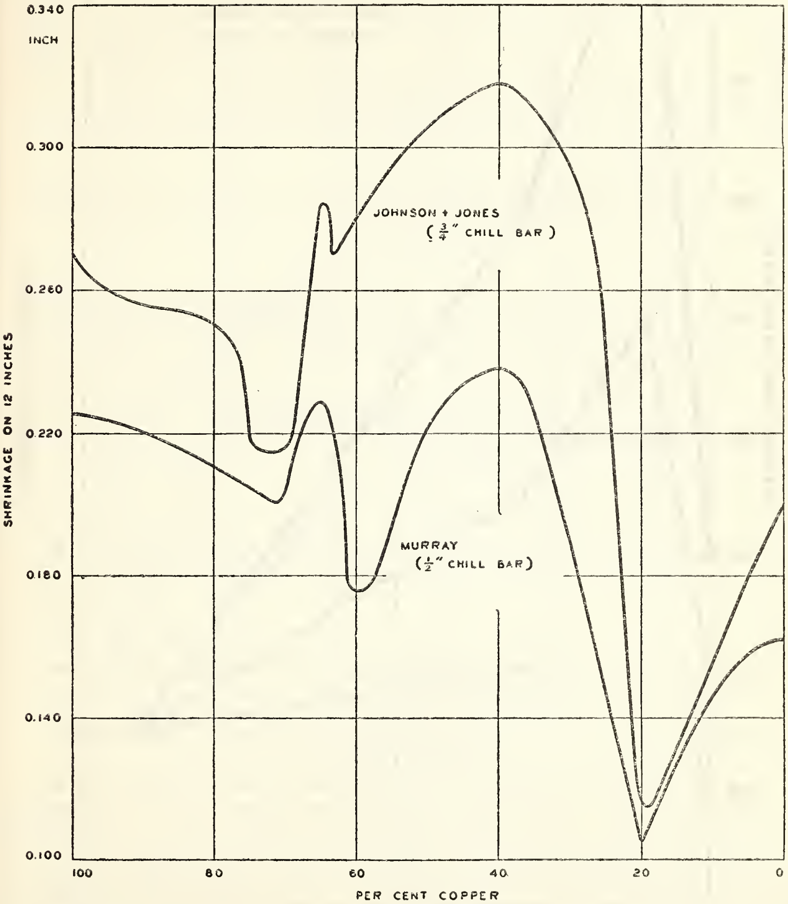


FIGURE 84.—*Relative shrinkage of zinc-copper alloys of different compositions on casting*

The effect of successive additions of copper may be summarized briefly as follows: The breaking stress of the hot-rolled alloy was nearly doubled (approximately 22,400 lbs./in.^{2} to 44,800 lbs./in.^{2}) by the addition of 1 per cent; a further addition of 2 per cent copper resulted in no marked change, further additions up to 9 per cent increased the breaking stress uniformly up to approximately 30 tons/in.^{2} The elongation was increased from 25 to 40 per cent, approximately, by the first addition of 1 per cent copper; further additions of copper reduced the elongation progressively to 0 per cent in the alloy containing 9 per cent copper.

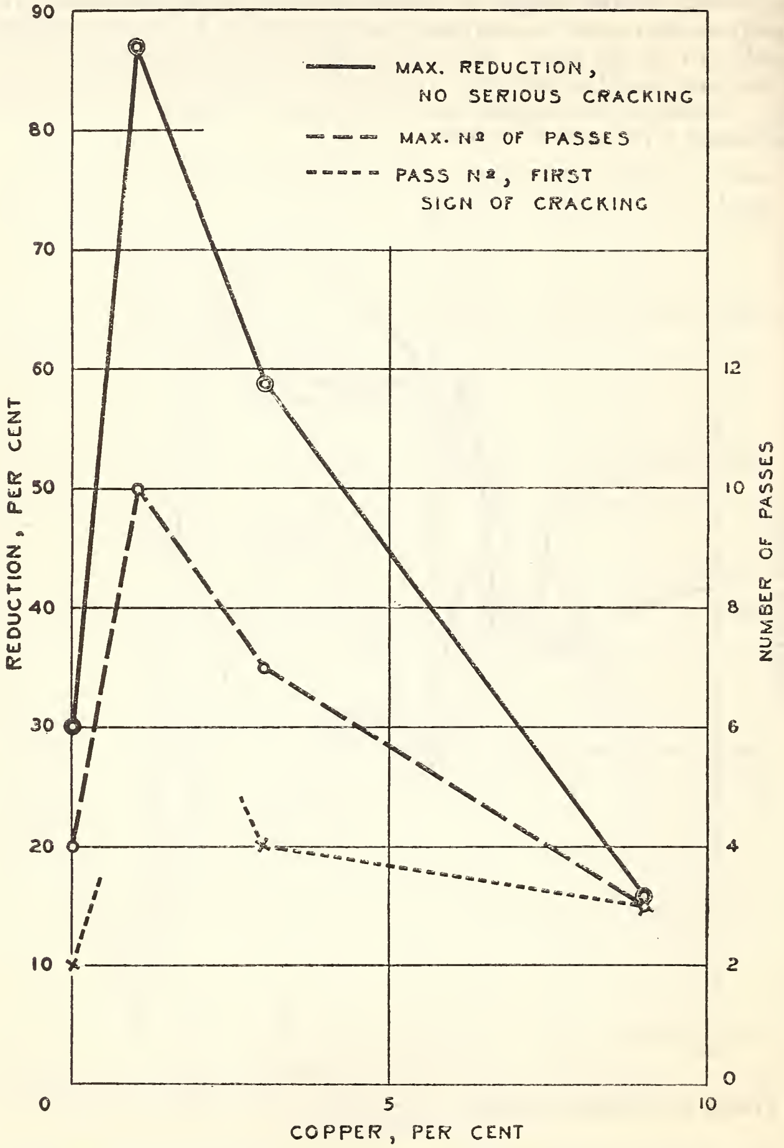


FIGURE 85.—*Behavior of zinc-copper alloys, low in copper, when worked mechanically by rolling*

Results obtained by Schulz and Wachlert (23) on the same class of alloys in the cast condition are summarized in Figure 86. It may be pointed out that the marked effect noted by Rosenhain of small percentages of copper on the tensile strength is not apparent in the cast material.

Guillet and Bernard (22) have also reported on the tensile properties of alloys of this class.

One of the leading American zinc companies has recently developed commercially as a sheet material an alloy of zinc which, in addition to copper, contains a small percentage of cadmium. As in the case of zinc-base die-casting alloys (p. 182) a small amount of magnesium is used, and its presence is claimed to be decidedly advantageous. The approximate composition of this alloy is copper, 1 per cent; cadmium, 0.8 per cent; magnesium, 0.1 per cent; zinc, remainder. (Table 59.) It is stronger and stiffer than zinc. Hence, when it is used for roofing, it is not necessary that the purlins or supports be spaced so close together as for unalloyed zinc. For example, a spacing of 51 inches has been given as suitable for 14-gage corrugated sheet (0.036) inch thick, whereas, for the corresponding sheet of zinc, a spacing of 35½ inches is recommended for supporting the same load.

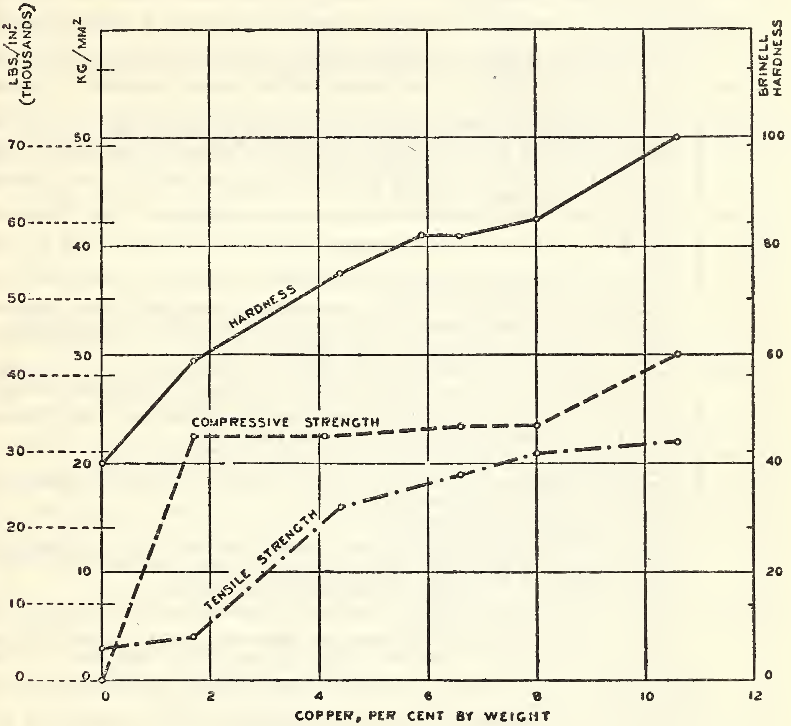


FIGURE 86.—*Tensile and compression properties of cast zinc-copper alloys low in copper*

Zinc-copper

Text reference	Year	Name and title
1	1930	Elam, C. F., The diffusion of zinc in copper crystals, J. Inst. Metals, **43**, p. 17.
2	1930	Hansen, M., Uber den vergutungsvorgang in zink-kupferlegierungen, Z. Metallkunde, **22**, pp. 149–154.
3	1930	Phillips, A., Constitution of copper-zinc alloys, National Metals Handbook, Am. Soc. Steel Treating, p. 703.
4	1928	Kohler, W., Diffusion of zinc in copper and in copper-zinc mixed crystals at 350°. Diffusion in the solid state, Zentr. Hutten. u. Walzwerke, **31**, pp. 650–657; Chem. Abst., **23**, 1929, p. 1328.
5	1927	Bauer, O., Hansen, M., Der aufbau der kupfer-zinklegierungen, Z. Metallkunde, **19**, pp. 423–434.
6	1927	Endo, H., On the magnetic susceptibility of some binary alloys at high temperatures and their equilibrium diagrams, Sci. Rept. Tohoku Imp. Univ., **16**, I, pp. 201–234.
7	1927	Jitsuka, D., Nachprufung des zustandschaubildes des systems kupfer-zink, Z. Metallkunde, **19**, pp. 396–403.
8	1926	Crepaz, E., The constitution of binary alloys of copper and zinc, Ann. Scuola Ing. Padova, **2**, pp. 49–54; Chem. Abst., **20**, p. 2971; J. Inst. Metals, **37**, 1927, p. 462.
9	1925	Jitsuka, D., Revision of the equilibrium diagram of the copper-zinc system, Mem. Coll. Sci. Kyoto Imp. Univ. (A), **8**, No. 3, pp. 179–197.
10	1925	Westgren, A., Phragmen, G., X-ray analysis of copper-zinc, silver-zinc, and gold-zinc alloys, Phil. Mag., **50** (VI), p. 311.
11	1924	Iokike, K., On the copper-zinc alloys which expand on solidification, J. Inst. Metals, **31**, pp. 225–251.
12	1923	Owen, E. A., Preston, G. D., X-ray analysis of copper-zinc alloys, Proc. Phys. Soc., **36**, p. 49.
13	1923	Pierce, W. M., Studies on the constitution of binary zinc-base alloys, Trans. Am. Inst. Mining Met. Eng., **68**, pp. 767–795.
14	1922	Bornemann, K., Sauerwald, F., Density measurements of metals and alloys at high temperatures with special reference to the molten state, Z. Metallkunde, **14**, pp. 254–258.
15	1922	Guillet, L., Ballay, M., Vapor pressures of some copper-zinc alloys in the solid state, Compt. Rendu., **175**, pp. 1057–1058; Chem. Abst., **17**, 1923, p. 907.
16	1922	Johnson, F., Jones, W. G., New forms of apparatus for determining the linear shrinkage and for bottom-pouring of cast metals and alloys, accompanied by data on the shrinkage and hardness of cast copper-zinc alloys, J. Inst. Metals, **28**, pp. 299–326.
17	1921	Bamford, T. G., Density of copper-zinc alloys, J. Inst. Metals, **26**, pp. 155–166; Engineering, **112**, pp. 385–387, 585–587; Chem. Abst., **16**, 1922, p. 220.
18	1921	Edwards, C. A., Herbert, A. M., Plastic deformation of some copper alloys at elevated temperatures, J. Inst. Metals, **25**, pp. 175–199; Chem. Abst., **15**, p. 1685.
19	1921	Guertler, W., Metallographie, Bd., 2, Tl. 1, Abs. 3 (Elektrochemische Metallkunde, R. Kremann), publ. Gebruder Borntraeger, Berlin.
20	1920	Rosenhain, W., Haughton, J. L., Bingham, K. E., Zinc alloys with aluminum and copper, J. Inst. Metals, **23**, pp. 261–324.
21	1920	Weiss, H., The constituents formed by the diffusion of zinc and copper at a temperature when both metals and their alloys are in the solid state, Compt. Rendu., **171**, pp. 108–111; J. Inst. Metals, **30**, 1923, p. 438; Chem. Abst., **16**, 1922, p. 550.
22	1919	Guillet, L., Bernard, V., Zinc alloys instead of copper, Iron Age, **103**, p. 175.
23	1919	Schulz, E. H., Wachlert, M., Study of the copper-aluminum-zinc alloys of high zinc content, Metall Erz, **16**, pp. 195–201.
24	1917	Ludwik, P., Hardness of the most important alloys for technical purposes, Zeit. Ver. deut. Ing., **61**, p. 549; Z. Anorg. Chem., **94**, 1916, pp. 161–162; Stahl Eisen, **40**, 1920, p. 1547–1551.
25	1915	Bromewski, W., The structure of copper-zinc and copper-tin alloy, Rev. Metal., **12**, pp. 961–989.
26	1913	Pushin, N. A., Rzazhsky, V. N., Electrical conductivity of alloys of copper and zinc, Z. Anorg. Chem., **82**, pp. 50–62; Chem. Abst., **7**, p. 2920.
27	1911	Carpenter, H. C. H., Edwards, C. A., A new critical point in copper-zinc alloys: Its interpretation and influence on their properties, J. Inst. Metals, **5**, pp. 127–157.
28	1910	Arnemann, P. T., The metallographic examination of zinc and of rich zinc alloys with metals often contained in crude zinc, Metallurgie, **7**, pp. 201–211.

(k) ZINC-GOLD

As is shown by Figure 87, gold (like silver and copper) alloys readily with zinc; the constitutional diagrams for the three binary systems having many points of similarity. The diagram given in Figure 86, from the International Critical Tables (vol. 2, p. 426), is the work of Saldau (4), who has studied these alloys extensively. A comparison of the diagram in Figure 88 (5), showing the relative solution potentials of the various different phases of the system, with Figure 112, serves to emphasize the similarity in the alloy systems of zinc with gold and with silver as do likewise the data from the International Critical Tables (vol. 2) on the crystal structure summarized in Tables 57 and 58.

TABLE 57.—*Crystal structure of zinc-gold alloys*

Phase	Zinc content[1]	Symmetry	Unit cell				Reference
			a	c	c/a	Number of atoms	
	Per cent		*A*	*A*			
IV (β)	30.2	Cubic	3.146			2	(3).
			3.19				(1).
III (γ)	36.9	do	9.268			52.97	
	41.1	do	9.223			51.96	
(γ′) (AuZn^3?)	50.2	do	7.880			32.	(3).
II (δ)	67.5	Hexagonal	2.809	4.377	1.558	2	
	72.3	do	2.809	4.369	1.555	2	
I (η)	95.0	do	2.674	4.887	1.828	2	

[1] The percentage of zinc for the various phases as given by Westgren and Phrágmen do not agree in all cases with the corresponding phases in the constitutional diagram as determined in the ordinary way. The phase δ is designated as ε by Westgren and Phrágmen; γ′ corresponds to γ_2 of Figure 86.

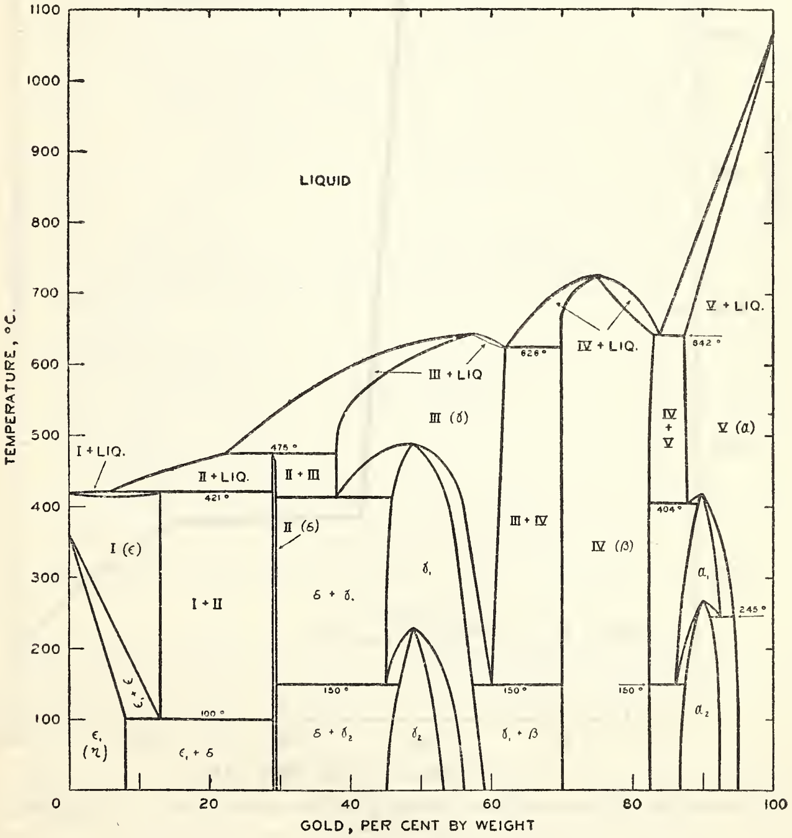


FIGURE 87.—*Constitutional diagram of the gold-zinc series of alloys*

In his determination of the constitutional diagram of this alloy series, Saldau (4) made extensive use of the method of electrical resistivity. This reference should be consulted for information along this line.

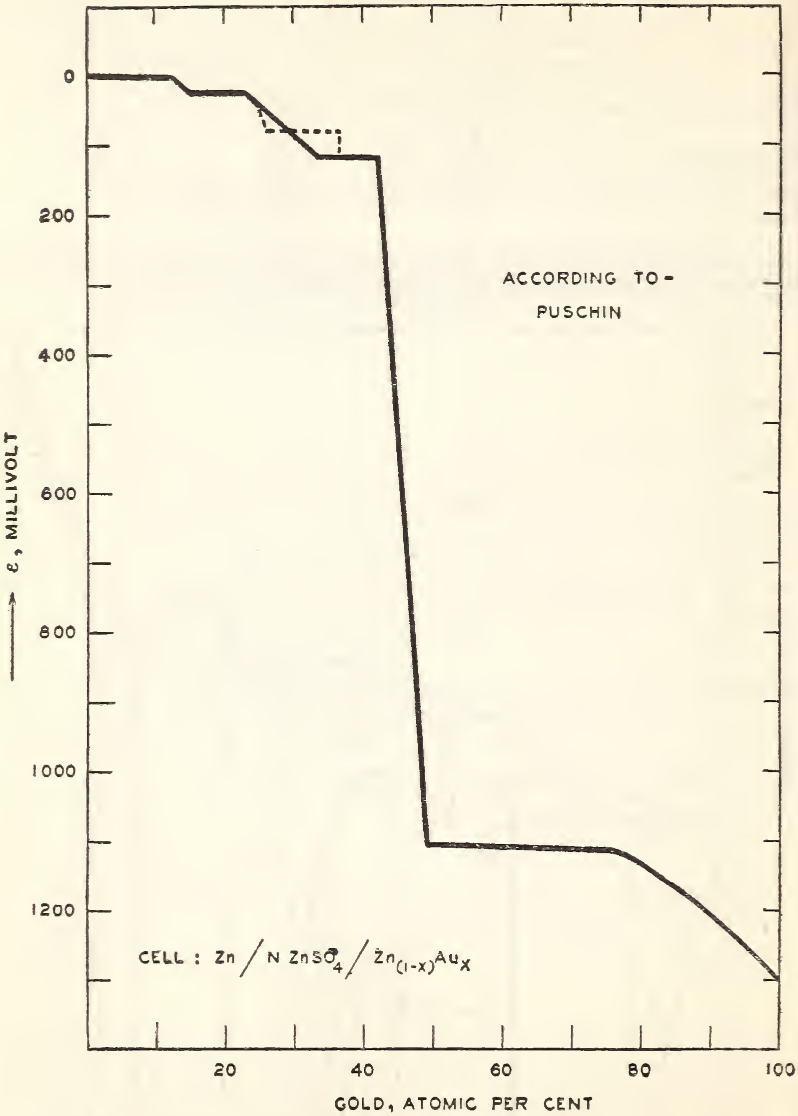


FIGURE 88.—*Relative solution potential of the various phases in the zinc-gold alloys*

Zinc-gold

Text reference	Year	Name and title
1	1926	Owen, E. A., Preston, G. D., Atomic structure of AgMg and AuZn alloys, Phil. Mag., 2 (VII), pp. 1266–1270.
2	1925	Schulze, A., Gold zinklegierungen, Z. Metallkunde, **17,** p. 65.
3	1925	Westgren, A., Phragmen, G., X-ray analysis of copper-zinc, zinc, silver-zinc, and gold-zinc alloys, Phil. Mag., **50** (VI), p. 311; also Kolloid, **36A,** p. 86.
4	1924	Saldau, P., Gleichgewicht im system gold-zink, Z. Anorg. Chem., **141,** pp. 325–362; J. Inst. Metals, **30,** p. 351.
5	1921	Guertler, W., Metallographie, Bd., 2, Tl., 1, Abs. 3, Elektrochemische Metallkunde, R. Kremann, publ. Gebruder Borntraeger, Berlin.
6	1917–18	Saldau, P. Y., Determination of electrical conductivity at high temperatures and its application to the study of alloys, J. Russ. Phys. Chem. Soc., **49,** pp. 149–546; J. Inst. Metals, **30,** 1923, p. 495.
7	1906	Vogel, R., Gold-zinc alloys, Z. Anorg. Chem., **48,** p. 319–332; J. Chem. Soc., **90a** (2), p. 287.

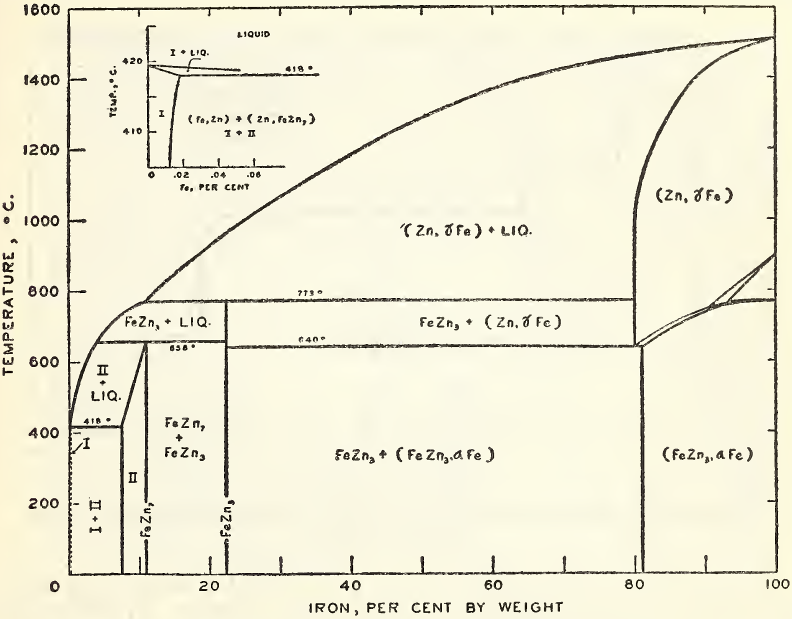


FIGURE 89.—*Constitutional diagram of the zinc-iron series of alloys*

(1) ZINC-IRON

Zinc alloys readily with iron. Although the alloys find almost no application commercially, the fact that alloying readily occurs is of great importance since it constitutes the fundamental principle underlying the galvanizing industry.

The constitutional diagram of the binary system in Figure 89 summarizes the work of a number of investigators (1). The portion of the diagram showing the constitution of alloys with an iron content from 0 to about 20 per cent has been carefully studied. The remainder of the diagram is still open to question on many points. Zinc-iron alloys containing more than about 25 per cent zinc must be made in a closed retort under pressure. Attempts to make such alloys under normal atmospheric pressure have failed.

The existence of two phases, showing the characteristics of intermetallic compounds, in zinc-rich alloys (that is, alloys containing less than approximately 20 per cent iron) is well established. One of these is referred to as $FeZn_7$, which corresponds to an iron content of 10.9 per cent, although the field in the diagram extends from 7.3 to 11 per cent (approximately) of iron. To the other crystalline phase, usually referred to as $FeZn_3$ and corresponding to about 22.2 per cent iron, the formula Fe_3Zn_{10} has recently been assigned on the basis of X-ray studies as given below. The limit of solid solubility of iron in zinc has been determined by Peirce (6) as 0.02 per cent.

Figure 90 summarizes data given by Guertler (8) on the relative solution potentials of the zinc-iron alloys. As would be predicted, each of these alloys was found to be intermediate between zinc and iron in its behavior.

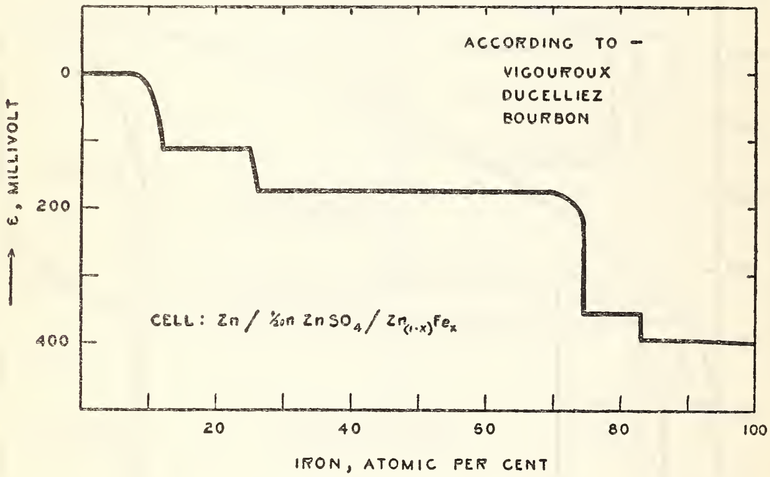


FIGURE 90.—*Relative solution potentials of the various phases in the zinc-iron alloys*

Information on these alloys from X-ray crystal analysis is available from two investigations. Osawa and Ogawa (3) determined that the crystal forms of binary alloys of zinc and iron have a close similarity to the zinc-silver, zinc-copper and zinc-gold systems. For example, the α-phase (face-centered cubic), β-phase (body-centered cubic) and ϵ-phase (hexagonal) of the zinc-copper system correspond with the iron-rich phase ($FeZn_3$, Fe), the phase $FeZn_3$, and the compound $FeZn_7$, respectively, of the zinc-iron system. They reported for $FeZn_7$ $a=2.778$ A and the axial ratio, $c/a=1.607$.

Later, Stillwell and Clark (2) in a study made of hot-dipped galvanized coatings, classified three phases—a phase, "A," having a hexagonal close-packed lattice with $a=3.17$ A and $c/a=1.58$; a phase, "B," having a hexagonal close-packed lattice with $a=2.602$ A and $c/a=1.885$; and a phase, "C," having a body-centered cubic lattice with $a=3.10$ A. They concluded that the phase, A, is isomorphous with $FeZn_7$ and is a solid solution of zinc in $FeZn_7$, by reason of the fact that the atomic radius of iron is 1.26 A and that of zinc 1.37 A and the lattice should, therefore, expand when zinc is dissolved in

FIGURE 91.—*Microstructure of zinc containing 1 per cent of iron,* × *100*

The crystals are those of $FeZn_7$ (micrograph from The New Jersey Zinc Co.). Etching reagent: 100 ml water, 20 g chromic acid, 1.5 sodium sulphate.

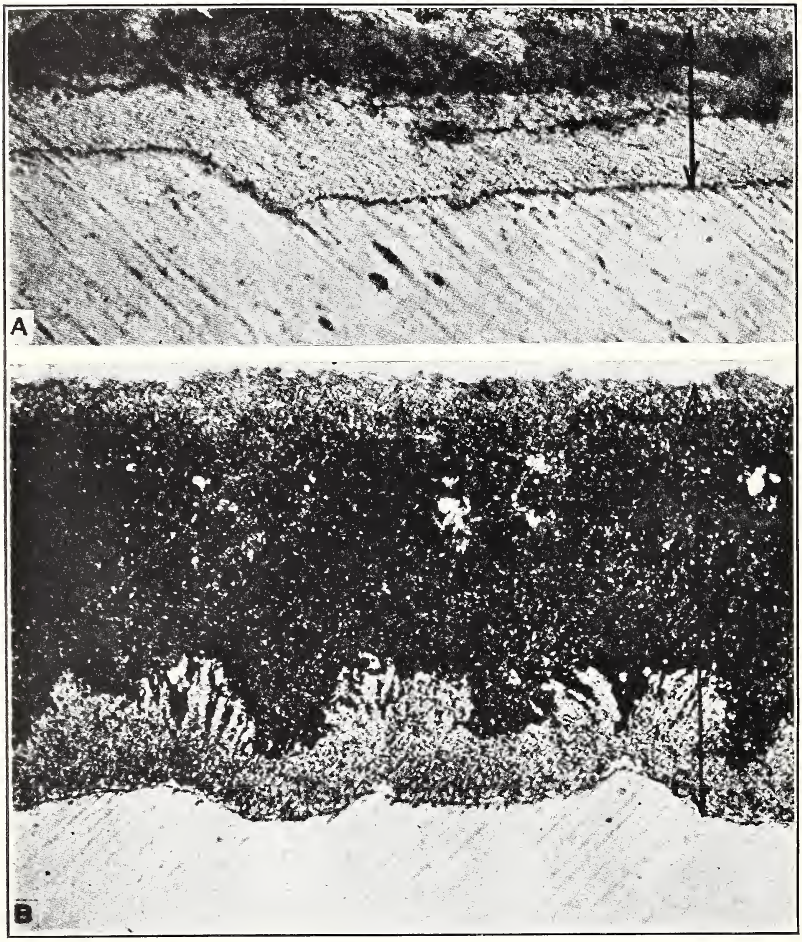


FIGURE 92.—*Microstructure of zinc coatings produced in the commercial galvanizing of sheet steel,* × *500*

The section shown is perpendicular to the surface of the sheet. Etching reagent, 1 per cent alcoholic solution of iodine. *A*, Thin coating; average weight, 1.37 ounces per square foot of sheet. The alloy layer constitutes the greater part of the coating. *B*, thick coating; average weight, 2.5 ounces per square foot of sheet. Note the well-developed alloy layer, $FeZn_7$, and the traces of layer another adjacent to the steel base (lower part of the figure).

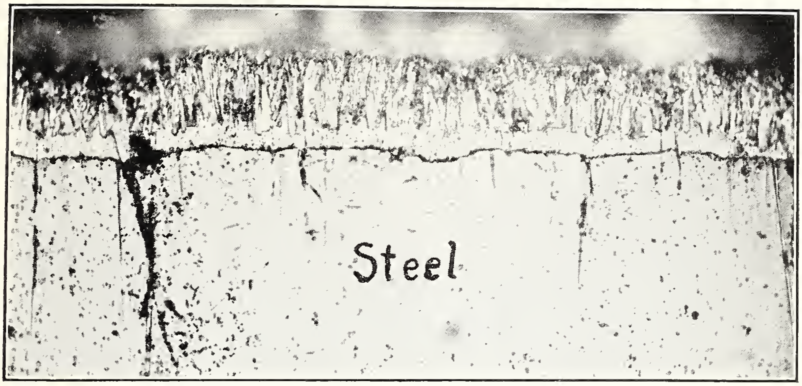


Figure 93.—*Microstructure of zinc alloyed with iron in the commercial galvanizing of wire,* × *500*

Much of the outer zinc-rich portion of the coating has been removed by "wiping" the wire.

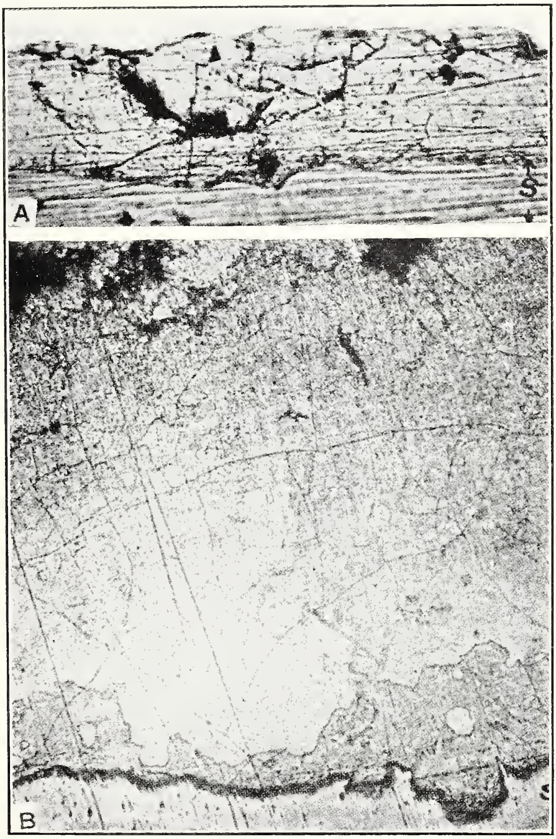


Figure 94.—*Microstructure of a "zinc" coating produced by alloying with iron in the sherardizing (cementation) of steel*

A, Cross section perpendicular to face of steel sheet; weight of coating, 0.9 ounce per square foot. The fissured appearance is characteristic of these coatings. × 350, etched as in Figure 91; *B*, oblique section of a sherardized coating, × 100. Note the evidence of a second alloy layer adjacent to the steel base (lower part of the figure).

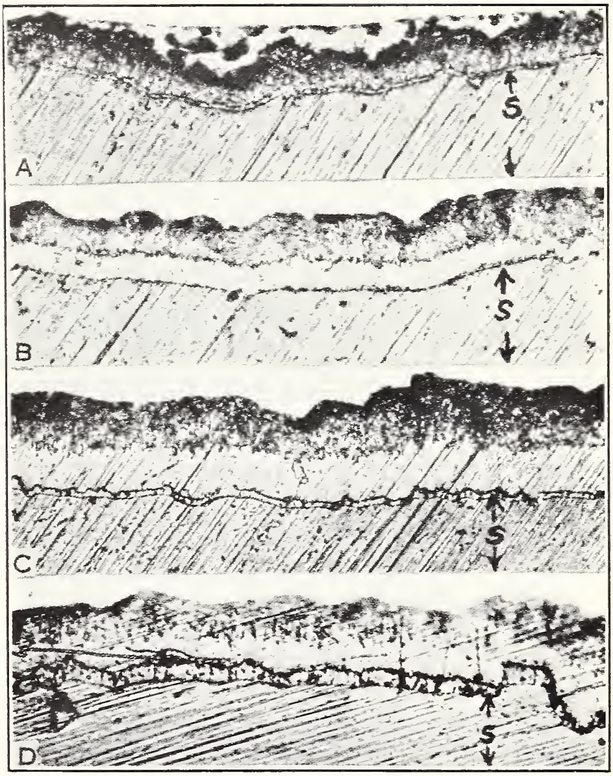


FIGURE 95.—*Effect of annealing on the microstructure of galvanized coatings,* × *350*

Etched as in Figure 91. *A*, Commercial hot-dipped zinc coating on an iron sheet which is indicated by *S*; weight of coating, 1.25 ounces per square foot; *B*, same as *A* after heating 2 hours at 350° C. Note how prominent the alloy layer is. *C*, same as *A*, after heating 4 hours at 350° C. Note how the thickness of the second alloy layer has increased; *D*, same as *A* after heating 5 hours at 350° C. The coating consists essentially of two alloy layers; the outer one corresponds rather closely to FeZn, in composition; the inner one, to $FeZn_3$.

$FeZn_7$. They further concluded that the phase, B, is likewise, isomorphous with pure zinc, which they stated has $a = 2.665$ A and $c/a = 1.865$. They offered no explanation for the presence of the phase, C. Figure 91 shows the microstructure of a zinc-iron alloy containing 1 per cent iron, an amount amply sufficient to give rise to the phase, $FeZn_7$. This phase is hard and very brittle. The volume change during the solidification of this phase has been reported to be rather unusual (1) in that an expansion occurs during freezing. The solidified mass consists of crystallites which show very little cohesion for one another. The presence of this constituent in zinc very seriously affects its ductility. Likewise alloys containing the phase, $FeZn_3$, are very brittle. Little is known concerning the physical properties of the iron-rich alloys of zinc.

As stated above, the ease with which alloying between zinc and iron occurs makes possible the galvanizing of steel and iron. In Figures 92 and 93 is shown the microstructure of zinc coatings on steel and in Figure 94, a coating consisting essentially of only the "alloy layer" made by the cementation process (sherardizing) (5). By suitable heat treatment it is possible to intensify the alloying effect in a galvanized coating as is shown in Figure 95.

One of the chief uses to which zinc-iron alloys can be applied, aside from their incidental occurrence in galvanized steel, is in the preparation of iron-bearing brasses, such as delta metal.

Zinc-iron

Text reference	Year	Name and title
1	1930	Marshall, L. H., Peirce, W. M., Constitution of zinc-iron alloys, National Metals Handbook, Om. Soc. Steel Treat., pp. 815–817.
2	1930	Stillwell, C. W., Clark, G. L., X-ray examination of commercial galvanized iron by a modified reflection method, J. Ind. Eng. Chem., Anal. ed., **2**, p. 266.
3	1929	Ozawa, A., Ogawa, Y., X-ray investigation of iron and zinc alloys, Sci. Repts. Tohoku Imp. Univ., June, p. 165.
4	1928–29	Ogawa, Y., Murakami, T., The equilibrium diagram of the iron-zinc system, Tech. Reports, Tohoku Imp. Univ., **8**, pp. 53–69.
5	1927	Rawdon, H. S., Protective metallic coatings, Monograph No. 40, Am. Chemical Society, Chemical Catalog Co., New York, publishers.
6	1923	Peirce, W. M., Studies on the constitution of binary zinc-base alloys, Trans. Am. Inst. Mining Met. Eng., **68**, pp. 767–791.
7	1922	Protective metallic coatings for the rust proofing of iron and steel, B. S. Circular No. 80.
8	1921	Guertler, W., Metallographie, Bd. 2. Tl. 1, Abs. 3. (Elektrochemische Metallkunde, R. Kremann) pub. Gebruder Borntraeger, Berlin.
9	1918	Smith, E. A., Zinc industry, Longmans, Green & Co., London.
10	1913	Raydt, U., Tamman, G., The structure and properties of zinc-iron alloys molten under pressure, Z. Anorg. Chem., **83**, pp. 257–266.
11	1910	Arnemann, P. T., The metallographic examination of zinc and of rich zinc alloys with metals often contained in crude zinc, Metallurgie, **7**, pp. 201–211.
12	1907	Von Vegesack, A., The alloys of zinc and thallium and of zinc and iron, Z. Anorg. Chem., **52**, pp. 30–40.

(m) ZINC-LEAD

In the liquid state, each of the two metals will dissolve a limited amount of the other metal, as is shown in Figure 96 (4). In the solid state, however, the two metals are insoluble in each other. The microstructure of zinc containing small amounts of lead has been given in Figures 22 and 23, and the effect of such a structural condition has been mentioned in the discussion of impurities in zinc.

The relative solution potentials of the zinc-lead alloys are given in Figure 97 (6).

Zinc-lead

Text reference	Year	Name and title
1	1926	Kremann, R., Troster, A., Electrolytic conduction in molten alloys XVII. Electrolysis of alloys of zinc with lead, bismuth, and cadmium, of antimony with lead and bismuth and of cadmium with lead and bismuth. XVIII. Summary of the results of this series of papers, Monatsh., **47,** pp. 285–293, 295–306; Chem. Abst., **21,** 1927, p. 3809.
2	1926	Von Zur Muhlen, L., Neuere untersuchungen Russicher blei-zinklagerstatten, Metall. Erz., **23,** pp. 551–554.
3	1924	Cook, M., The cadmium-lead-zinc system, J. Inst. Metals, **31,** pp. 297–313.
4	1923	Peirce, W. M., Studies on the constitution of binary zinc-base alloys, Trans. Am. Inst. Mining Met. Eng., **68,** pp. 767–791; also National Metals Handbook, Am. Soc. Steel Treat., 1930, p. 818.
5	1922	Goebel, J., Binary lead alloys, Z. Metallkunde, **14,** pp. 357–366, 388–394, 425–432, 449–456; Chem. Abst., **17,** 1923, p. 52.
6	1921	Guertler, W., Metallographie, Bd. 2, Tl. 1, Abs. 3. (Elektrochemische Metallkunde, R. Kremann) pub. Gebruder Borntraeger, Berlin.
7	1920	Ludwik, P., The hardness of the most important alloys for technical purposes, Z. Ver. deut. Ing., **61,** 1917, p. 549; Z. Anorg. Chem., **94,** 1916, pp. 161–192; Stahl Eisen, **40,** pp. 1547–1551.
8	1910	Arnemann, P. T., The metallographic examination of zinc and of rich zinc alloys with metals often contained in crude zinc. Metallurgie, **7,** pp. 201–211.
9	1910	Bruni, G., Sandonnini, C., Quercigh, E., Uber die ternaren legierungen von magnesium, zink und cadmium, Z. Anorg. Chem., **68,** pp. 73–90.
10	1910	Bornemann, K., Muller, P., The electrical conductivity of metallic alloys in the fluid condition, Metallurgie, **7,** pp. 396–402; Chem. Zentr. (2), p. 434; Chem. Abst., **5,** 1911, p. 859.
11	1909	Curry, B. E., Some zinc alloys, J. Phys. Chem., **13,** pp. 589–605.

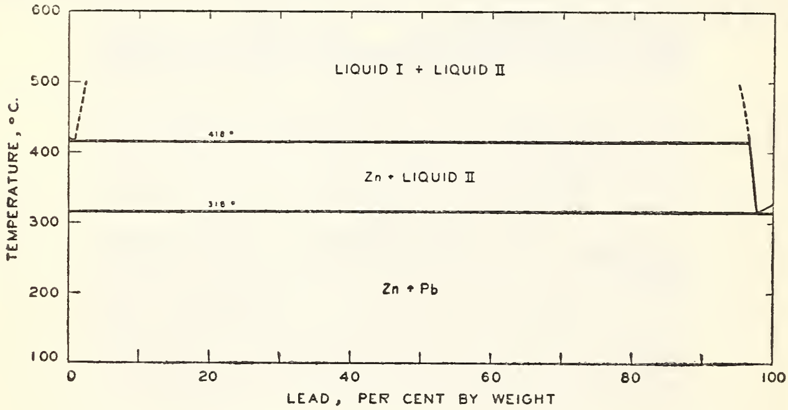


FIGURE 96.—*Constitutional diagram of the zinc-lead series of alloys*

(n) ZINC-MAGNESIUM

An intermetallic compound, $MgZn_2$ (84.5 per cent zinc, melting point 590° C.) is a prominent feature of the constitutional diagram of the zinc-magnesium alloys. The liquidus is characterized by two eutectics, between the compound and the solid solution of each of the two constituent metals. The diagram is rather complicated, however, by a number of peritectic reactions as will be seen from the diagram in Figure 98 (1, 5).

The results of studies on the solution potential of these alloys have been reported by Kremann (9). The data reported throw very little, if any, light on the constitutional diagram.

Friauf (7) has studied the compound, $MgZn_2$, magnesium zincide, by X-ray methods and reported that the crystal is hexagonal with $a = 5.15$ A, $c = 8.48$ A, $c/a = 1.64$ and a least distance of 3.15, 2.52, and

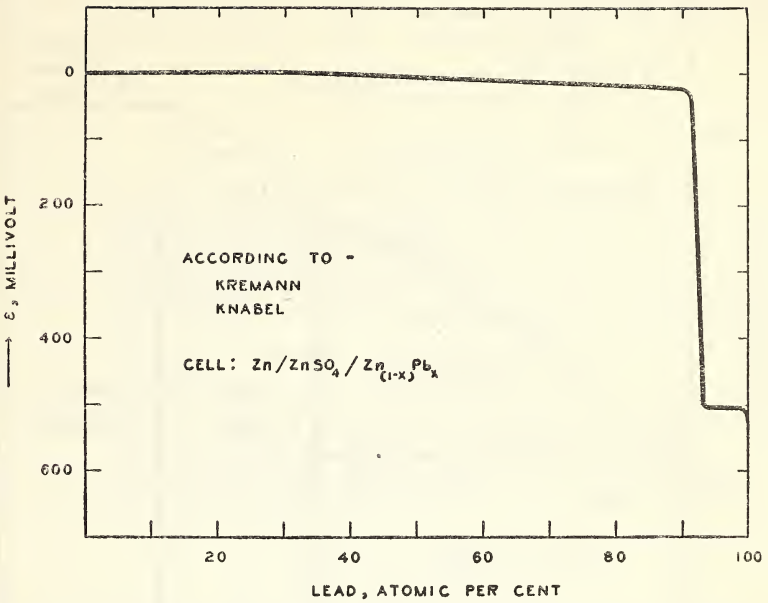


Figure 97.—*Relative solution potentials of zinc-lead alloys of different compositions*

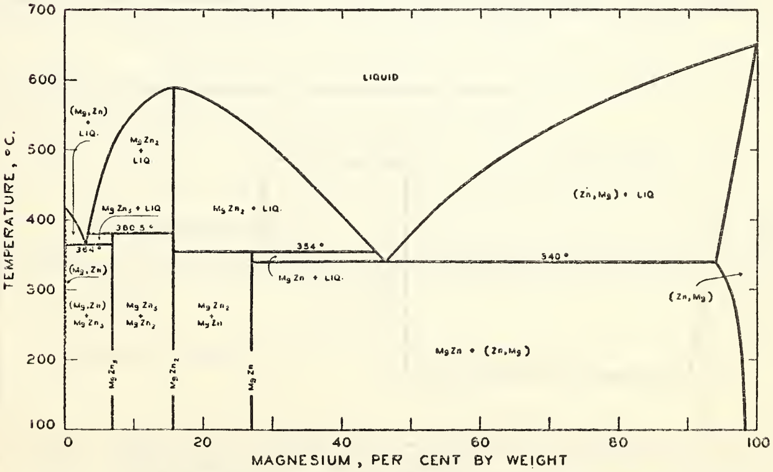


Figure 98.—*Constitutional diagram of the zinc-magnesium series of alloys*

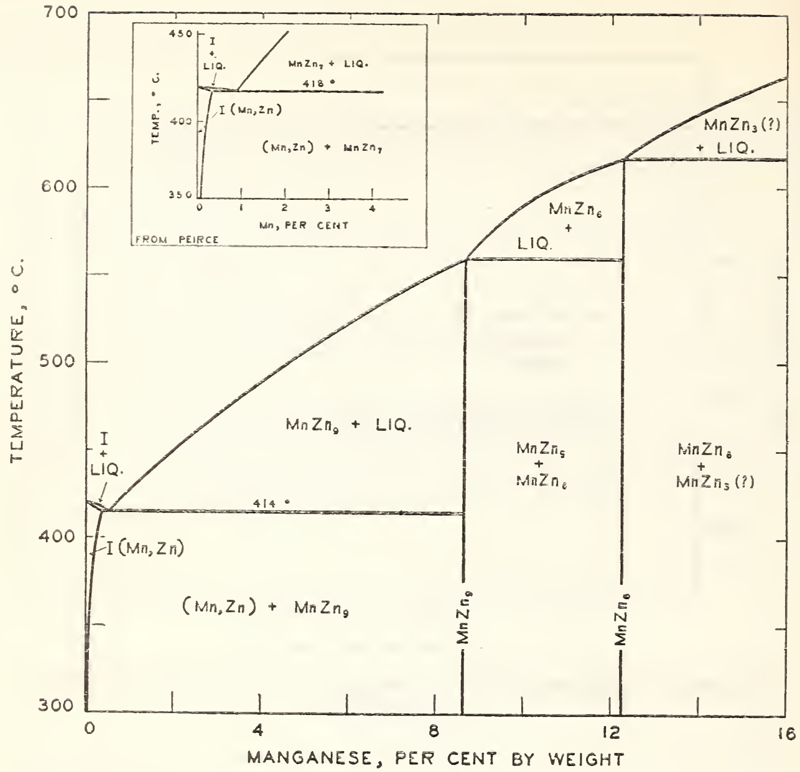


Figure 99.—*Constitutional diagram of the zinc-manganese series of alloys*

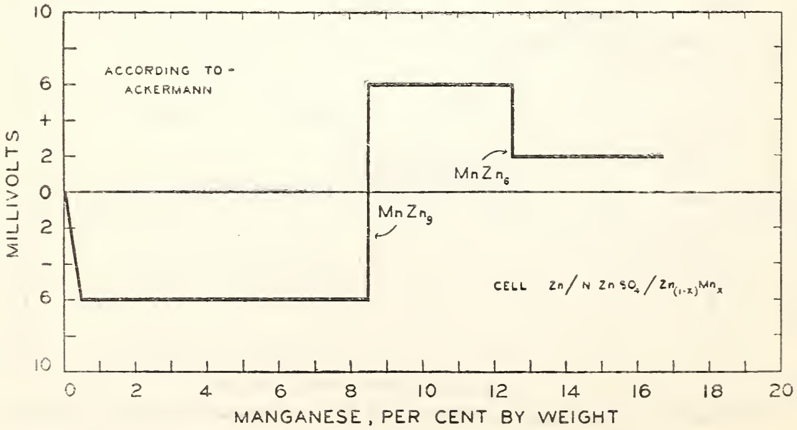


Figure 100.—*Relative solution potentials of the different phases in the zinc-manganese series*

3.02 A between two magnesium atoms, two zinc atoms, and a magnesium and a zinc atom, respectively.

Some information on the properties of the zinc-rich alloys of magnesium has already been given in discussing the effects of magnesium on the properties of zinc (p. 38).

Zinc-magnesium

Text reference	Year	Name and title
1	1930	Anderson, E. A., Edmunds, G., Constitution of zinc-magnesium alloys, National Metals Handbook, Am. Soc. Steel Treat., p. 820.
2	1930	Gann, J. A., Winston, A. W., Constitution of magnesium-zinc alloys, National Metals Handbook, Am. Soc. Steel Treat., pp. 743–745.
3	1930	Wassermann, G., Molecular or atomic solid solution of a metallic compound in the matrix, Z. Metallkunde, **22,** pp. 158–160.
4	1929	Grube, G., Burkhardt, A., The electrical conductivity, the thermal expansion and the hardness of magnesium-zinc alloys, Z. Elektrochem., **35,** pp. 315–332; Chem. Abst., **23,** p. 4862.
5	1929	Hume-Rothey, W., Rounsefell, E. O., The system magnesium-zinc, J. Inst. Metals, **41,** pp. 119–138.
6	1928	Chadwick, R., The constitution of the alloys of magnesium and zinc, J. Inst. Metals, **39,** pp. 285–298.
7	1927	Friauf, J. B., The crystal structure of magnesium dizincide, Phys. Rev., **29** (2), pp. 34–40.
8	1923	Peirce, W. M., Studies on the constitution of zinc base binary systems, Trans. Am. Inst. Mining Met. Eng., **68,** pp. 767–791.
9	1921	Guertler, W., Metallographie, Bd. 2, Tl. 1, Abs. 3. (Elektrochemische Metallkunde, R. Kremann) publ. Gebruder Borntraeger, Berlin.
10	1912	Bruni, G., Sandonnini, C., Quercigh, E., Ternary alloys of magnesium, zink, and cadmium, Z. Anorg. Chem., **78,** pp. 273–297.

(o) ZINC-MANGANESE

The most recent study of the constitutional diagram for this system is that of Ackermann (1) which modifies considerably the diagram based on the earlier work of Siebe (3) and of Parravano and Perret (4). The diagram given in Figure 99 has been slightly modified with respect to the limit of solubility of manganese in zinc to agree with the results reported by Peirce's work (2). Figure 100 summarizes the electrode potentials of zinc-manganese alloys, as determined by Ackermann. The diagram is of interest in that it confirms the existence of the compounds of zinc and manganese shown in the constitutional diagram and determined by other means.

Manganese has a marked hardening effect upon cast zinc as is shown by Figure 101. Alloys whose manganese content is not greater than 4 per cent will withstand severe compressive stresses either static or impact, without cracking, as is shown by the results summarized in Figure 102 (1). Information on the behavior of these alloys when subjected to rolling or other forms of mechanical working is not available.

Zinc-manganese

Text reference	Year	Name and title
1	1927	Ackermann, C. L., The binary system manganese-zinc, Z. Metallkunde, **19,** pp. 200–204; Metallurgist (Sup. to the Engineer), **3,** p. 118.
2	1923	Peirce, W. M., Studies on the constitution of binary zinc-base alloys, Am. Inst. Mining Met. Eng., **68,** pp. 767–791.
3	1919	Siebe, P., Manganese-bismuth, manganese-zinc, and manganese-silver alloys, Z. Anorg. Chem., **108,** pp. 161–183; Chem. Abst., **14,** 1920, p. 2288.
4	1915	Parravano, N., Perret, U., The alloys of zinc and manganese, Gazz. Chim. Ital., **45,** I, pp. 1–6; Chem. Abst., **9,** p. 1454.
5	1912	Lones, T. E., Zinc and its alloys, Pitman.

(p) ZINC-MERCURY

The work of Pushin (12) forms the basis of the constitutional diagram given in Figure 103, which is that given in the International Critical Tables (vol. 2, p. 436). Although this work has been criticized on some points (2, 5), it undoubtedly has established the main facts concerning the constitution of the zinc-mercury alloys. The diagram is of the simple eutectic type. Liquid zinc and mercury are completely miscible, the liquidus forms a smooth curve from the freez-

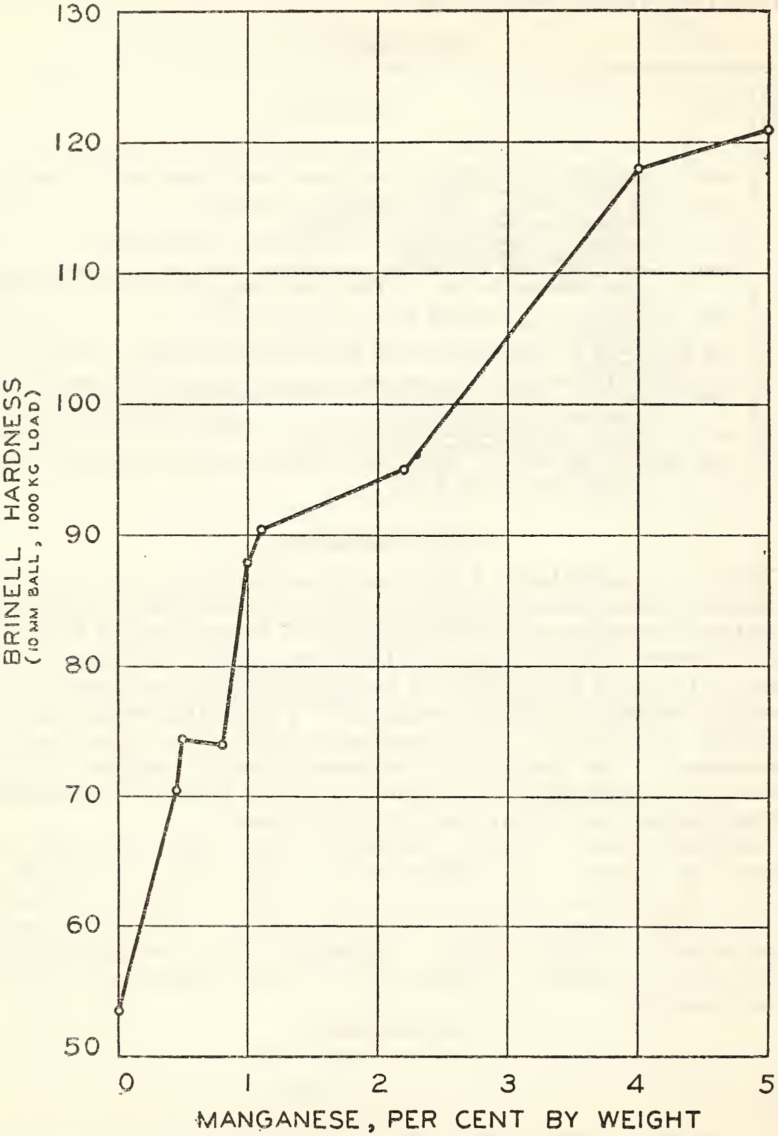


FIGURE 101.—*Brinell hardness of cast zinc-rich alloys of the zinc-manganese series*

ing point of zinc to the freezing point (−42° C.) of the zinc-mercury eutectic which contains 99 per cent zinc. Upon solidification of an alloy, zinc crystallizes continuously out of the melt as the temperature is lowered until the eutectic temperature is reached when the eutectic of mercury and zinc forms. There is no indication of solid solution of either metal in the other, according to Pushin.

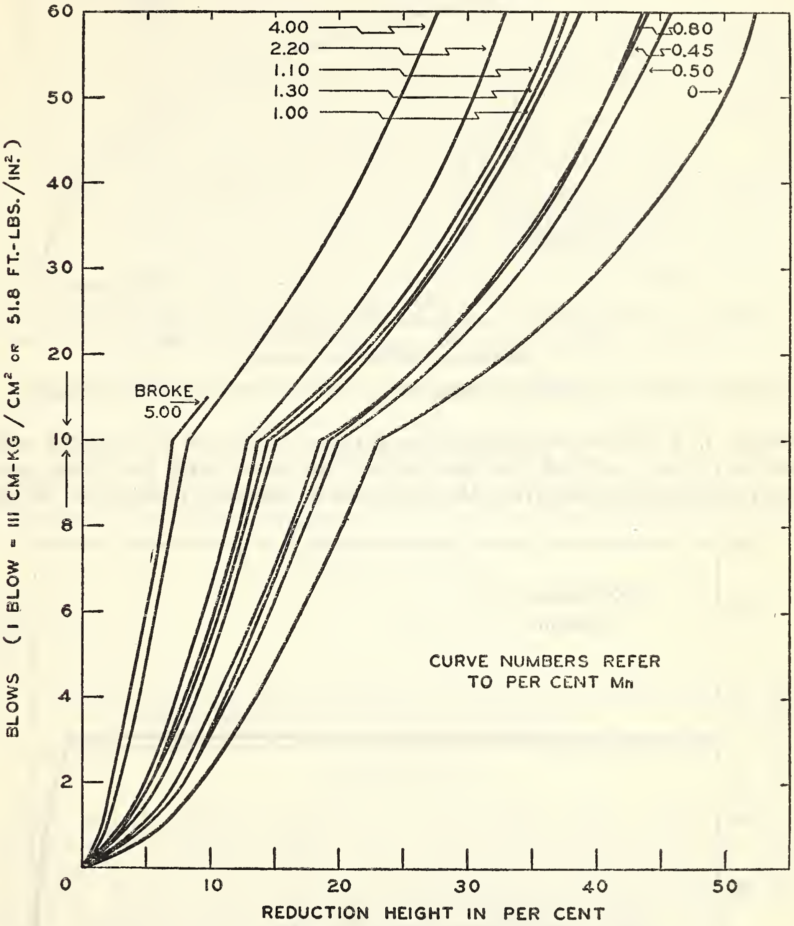


FIGURE 102.—*Behavior of cast zinc-rich alloys of the zinc-manganese series when hammered*

The data given in Figure 104 (4) on the relative solution potential of the various phases of the system are in accord with the main features of the constitutional diagram in Figure 103.

By means of a simple indentation method, the hardness of zinc amalgams with a mercury content of 0 to 90 per cent has been studied by Tammann and Mansuri (2). It was shown that equilibrium is not attained immediately after preparation of the alloy. Progressive increases in hardness were noted as the alloys were allowed to stand and these changes were measured over a period of 48 hours. According to these results, the hardness of zinc amalgams increases very rapidly with a decrease of mercury content from 90 to 50 per cent, the changes in hardness resulting from further decreases in mercury content were not marked, the maximum increase being less than one-tenth of that resulting from the decrease in mercury from 90 to 50 per cent. The small progressive increase ended in a maximum hardness for the alloy containing 25 per cent mercury. Further decreases in

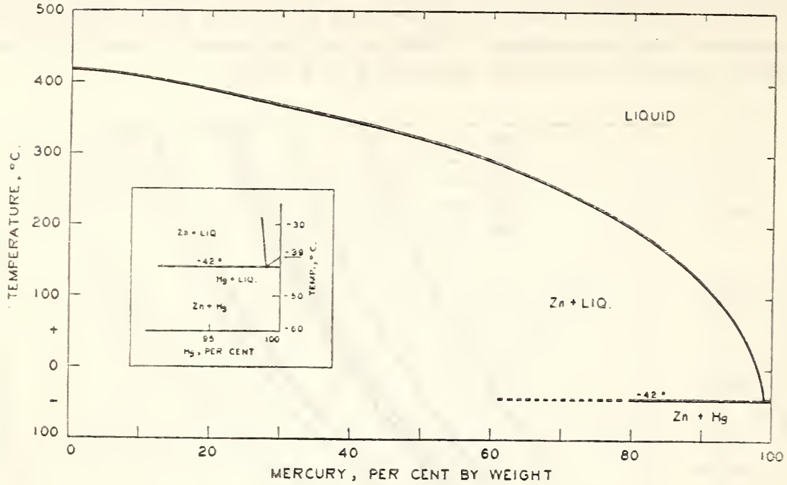


FIGURE 103.—*Constitutional diagram of the zinc-mercury series of alloy*

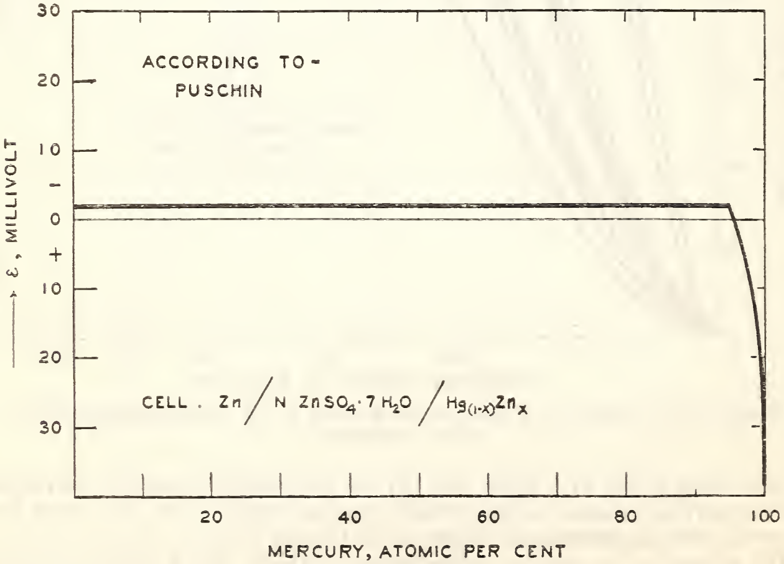


FIGURE 104.—*Relative solution potential of zinc-mercury alloys of different compositions*

mercury resulted in a slight progressive decrease in hardness to the hardness of zinc.

Zinc-mercury

Text reference	Year	Name and title
1	1928	Pearce, J. N., Eversole, J. F., A study of the potentials and activities of the metals in zinc-amalgam cells, J. Phys. Chem. (1), **32,** pp. 209–220.
2	1924	Tammann, G., Mansuri, Q. A., The hardness of amalgams of Sn, Pb, Zn, Cd, and Cu as well as of the ternary amalgam Ag, Sn, Hg, Z. Anorg. Chem., **132,** pp. 65–76; Chem. Abst., **18,** 1924, p. 1931.
3	1923	Martinen, J., Tiihonen, J. R., Determination of the specific heats of zinc and tin amalgams, Soc. Sci. Fennica Commentationes Physico-Math., **1,** No. 11, 11 pp., Chem. Abst., **17,** 1923, p. 1182.
4	1921	Guertler, W., Metallographie, Bd. 2, Tl. 1, Abs. 3, publ. Gebruder Borntraeger, Berlin. Electrochemische Metallkunde, R. Kremann.
5	1910	Cohen, E., Inouye, K., Zinc amalgams, Z. Phys. Chem., **71,** pp. 625–635.
6	1910	Cohen, E., Van Ginneken, P. J. H., Zinc amalgams and the Clark element, Z. Physik. Chem., **75,** pp. 437–502; J. Chem. Soc., **100,** II, 1911, p. 14; Chem. Abst., **5,** 1911, p. 1014.
7	1910	Crenshaw, J. L., Reduction of zinc by mercury and the electromotive force of zinc amalgams, J. Phys. Chem., **14,** p. 158–183; J. Chem. Soc., **98a** (2), p. 258.
8	1910	Richards, T. W., Garrod-Thomas, R. N., Electrochemical investigation of fluid amalgams of zinc, cadmium, lead, copper, and lithium, II, Z. Physik. Chem., **72,** pp. 165–201; J. Chem. Soc., **98a,** II, p. 384.
9	1909	Cohen, E., Inouye, K., Zinc amalgams, Chem. Weekblad., **6,** pp. 921–930; J. Chem. Soc., **98a,** II, 1910, p. 37; Chem. Abst., **4,** 1910, p. 1255.
10	1909	Cohen, E., Tombrock, W., Electromotive force of zinc amalgams, Proc. K. Wetenschaffen, Amsterdam, **12,** pp. 98–104.
11	1907	Richards, R. W., Forbes, G. S., Changes of energy accompanying the dilution of zinc and cadmium amalgams, Zeit. Physikal. Chem., **58,** pp. 683–752; J. Chem. Soc., **92a,** II, p. 424.
12	1903	Pushin, N. A., Über die legierungen des quecksilbers, Zeit. Anorg. Chem., **36,** pp. 201–254.

(q) ZINC-MOLYBDENUM

The zinc-molybdenum alloys are technically unimportant. A diagram of this alloy system was not found in the technical literature.

Zinc-molybdenum

Text reference	Year	Name and title
	1924	Powell, P., Molybdenum, its alloys and its applicability as an alloying constituent, Brass World, **20,** pp. 117–123; J. Inst. Metals, **33,** p. 357; 1925.

(r) ZINC-NICKEL

The constitutional diagram of this system (fig. 105) from the International Critical Tables (Vol. 2, p. 439) is based upon the work of Tafel (5) and of Voss (6). The results of Peirce's study (3) of the zinc-rich alloys, particularly the determination of the limit of solubility of nickel in zinc, have been incorporated in Figure 105.

Alloys of this system may be prepared by the simultaneous electrodeposition of the two metals from a solution containing ions of both metals. Schock and Hirsch (7) reported that alloys with nickel contents varying from 20 to 90 per cent (approximately) were obtained. The yield was low, however, in many cases and it was necessary to use solutions of different compositions in order to vary the nickel content of the deposited alloy. This subject has recently been studied by Cocks (2).

A misunderstanding may sometimes arise in practice concerning the practical uses of zinc-nickel alloys. The alloys themselves are of very little use. However, nickel-plated sheet zinc, which is generally referred to as "nickel-zinc," is used considerably in the manufacture of small stamped parts (1).

Zinc-nickel

Text reference	Year	Name and title
1	1928	Anderson, S. E., Pressing, bending, and forming of nickel-zinc sheets, Metal Stampings, **1**, p. 369.
2	1928	Cocks, H. C., The effect of superposed alternating current on the deposition of zinc-nickel alloys, Trans. Faraday Soc., **24**, pp. 348-358.
3	1923	Peirce, W. M., Studies on the constitution of binary zinc-base alloys, Trans. Am. Inst. Mining Met. Eng., **68**, pp. 767-791.
4	1911	Vigouroux, E., Bourbon, A., New studies of the alloys of nickel and zinc, Bull. Soc. Chim., **9**, pp. 873-879.
5	1908	Tafel, V. E., Constitution of zinc-copper-nickel alloys, also the binary systems copper-nickel, zinc-copper, zinc-nickel, Metallurgie, **5**, pp. 413-430.
6	1908	Voss, G., Alloys of nickel with tin, lead, thallium, bismuth, chromium, magnesium, zinc, and cadmium, Z. Anorg. Chem., **57**, pp. 34-71; Chem. Abst., **2**, p. 1549.
7	1907	Schock, E. D., Hirsch, A., Electrolytic deposition of nickel-zinc alloys, Trans. Am. Electrochem. Soc., **11** pp. 135-152; Chem. Abst., **1**, p. 2996.
8	1907	Tafel, V. E., Alloys of zinc and nickel, Metallurgie, **4**, p. 781-785; J. Chem. Soc., **94a**, II, 1908, p. 105.

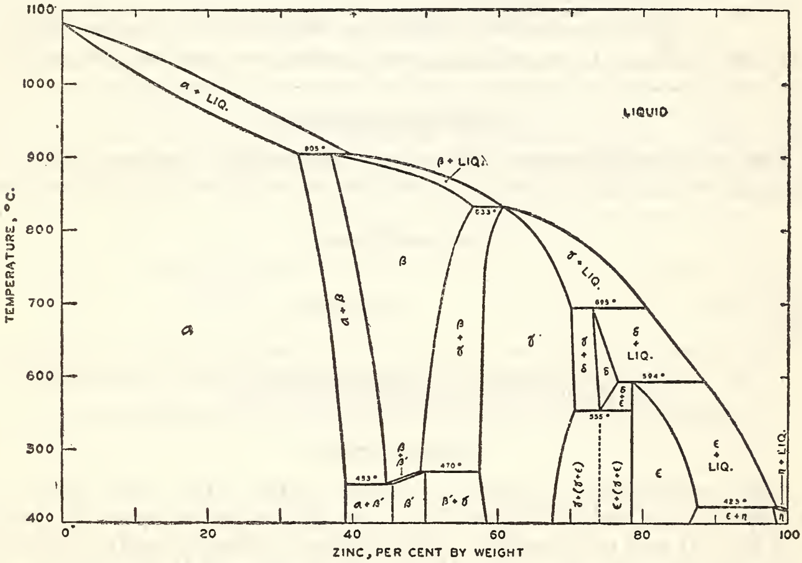


Figure 105.—*Constitutional diagram of the zinc-nickel series of alloys*

(s) ZINC-POTASSIUM, ZINC-SODIUM

These two alloy systems are very similar and may be considered together. The fact that sodium will unite with zinc was known soon after the metal sodium had been isolated from its compounds. Mathewson (3) has cited the work of Gay Lussac and Thenard who, in 1811, described the alloy containing 80 per cent of zinc and 20 per cent of sodium. The constitutional diagram of the zinc-sodium given in Figure 106 is from the work of Mathewson (3) and that of the zinc-potassium series given in Figure 107 is based on the work of Smith (5). As these figures show, neither zinc nor sodium is soluble in the other in the solid state. Liquid zinc will dissolve nearly 4 per cent of sodium at 557° C. Above this temperature, alloys containing more than this amount of sodium consist of two immiscible layers.

The constitutional diagram of the potassium series of alloys shows that zinc will dissolve about 2 per cent of potassium at 580° C. and potassium about 4 per cent of zinc at the same temperature. Otherwise, the diagrams do not differ greatly.

The information in diagram in Figure 108 on the potentials of the zinc-sodium alloys when immersed in a liquid is in fair agreement wtih the constitutional diagram. There is evidence, however, of certain features in the constitution of the zinc-rich alloys which are still obscure. The corresponding diagram for the zinc-potassium alloys (fig. 109), emphasizes this even more strongly for the zinc-potassium series.

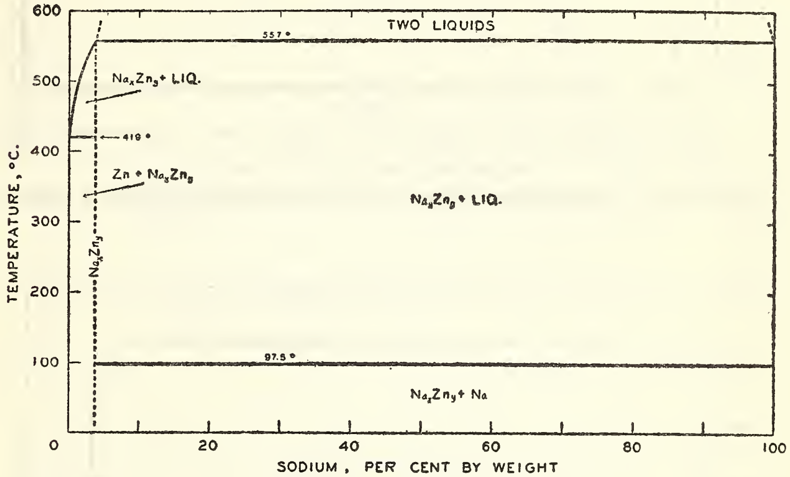


FIGURE 106.—*Constitutional diagram of the zinc-sodium series of alloys*

Zinc-sodium

Text reference	Year	Name and title
1	1920	Kremann, R., Von Reminghaus, P., Das elektromotorische verhalten einiger binarer metallegierungen, VI. Das elektromotorische verhalten des legierungen von natrium mit blei, thallium, zink und kadmium, Z. Metallkunde, **12**, p. 273–287.
2	1919	Goudriaan, D. F., Zincates of sodium, Proc. Acad. Sci. Amsterdam, **22**, pp. 179–189; Chem. Abst., **14**, 1920, p. 664.
3	1906	Mathewson, C. H., Sodium-aluminum, sodium-magnesium and sodium-zinc alloys, Z. Anorg. Chem., **48**, pp. 191–200; J. Chem. Soc., **90a** (2), p. 165.

Zinc-potassium

4	1920	Kremann, R., Mehr, A., Das elektromotorische verhalten einiger binarer metallegierungen. XIV. Das elektromotorische verhalten der legierungen des kaliums mit quecksilver, kadmium und zinc, Z. Metallkunde, **12**, pp. 444–455.
5	1907	Smith, D. P., The alloys of potassium with aluminum, magnesium, zinc, cadmium, bismuth, tin, and lead, Z. Anorg. Chem., **56**, pp. 109–142; Chem. Abst., **2**, 1908, p. 787; J. Chem. Soc., **92a**, (2), 1908, p. 949.

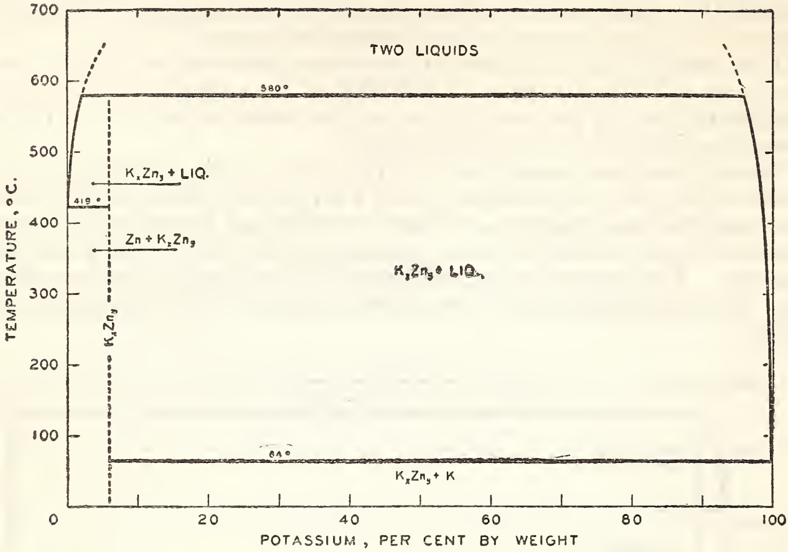


FIGURE 107.—*Constitutional diagram of the zinc-potassium series of alloys*

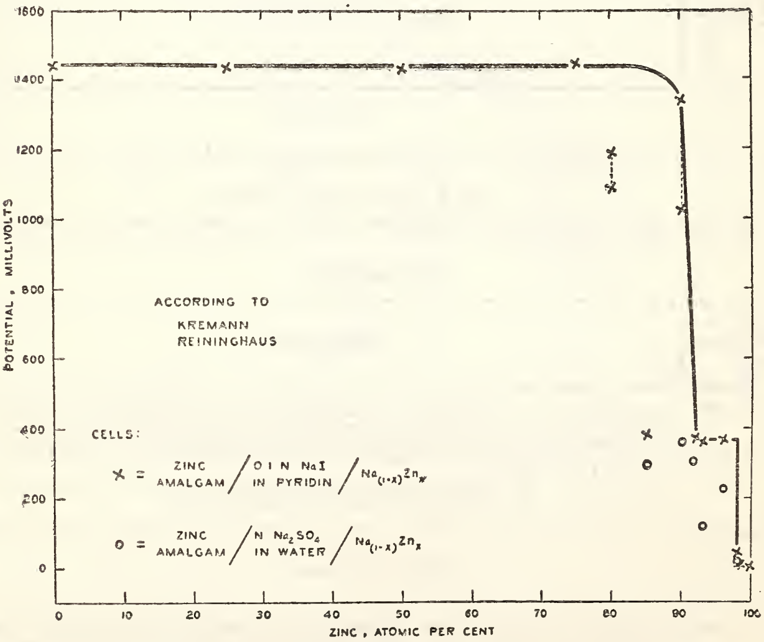


FIGURE 108.—*Relative solution potentials of zinc-sodium alloys of different compositions*

(t) ZINC-SELENIUM, ZINC-TELLURIUM

In Figure 110 is given the diagram summarizing existing knowledge (2) on the constitution of the zinc-selenium series of alloys. It will be noted that selenium is only slightly soluble in the liquid zinc; the two metals form immiscible layers.

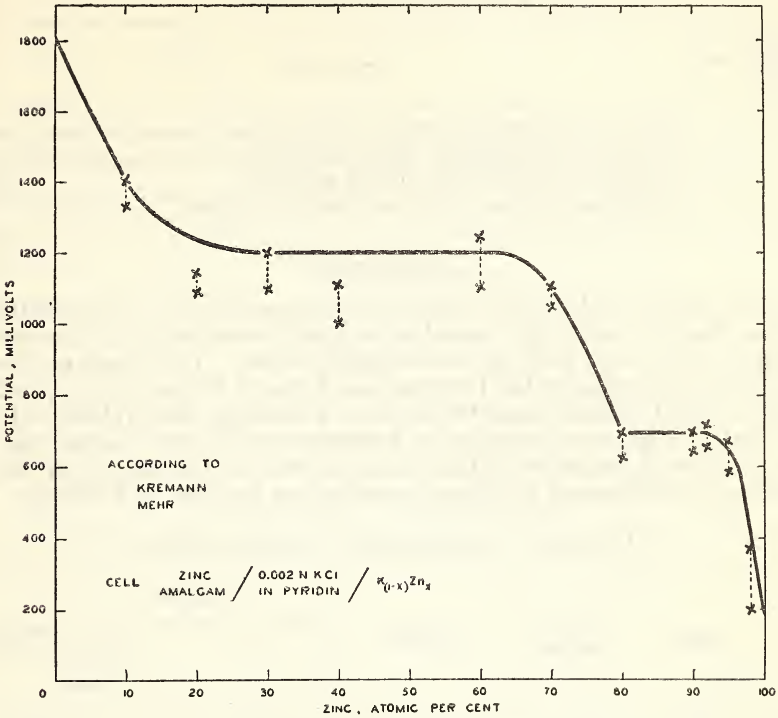


FIGURE 109.—*Relative solution potentials of zinc-potassium alloys of different compositions*

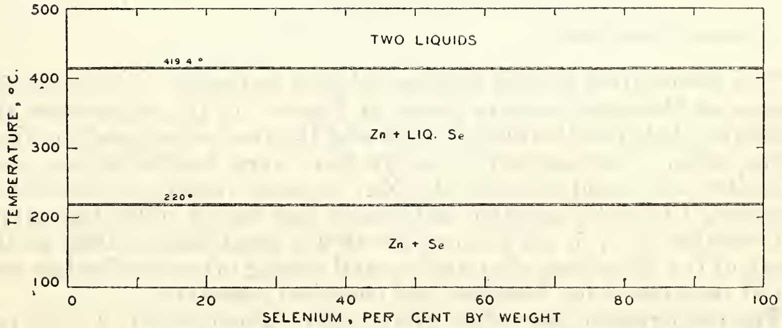


FIGURE 110.—*Constitutional diagram of the zinc-selenium series of alloys*

The constitutional diagram for the zinc-tellurium system, based on data from Kobayashi (3), is given in Figure 111. This diagram is very incomplete in many respects. Both of these diagrams are from the International Critical Tables (vol 2, p. 441). Neither of these alloy series is of practical importance.

Zinc-selenium, zinc-tellurium

Text reference	Year	Name and title
1	1921	Ransom, J. H., Thieme, C. O., Note on alloying tellurium with some white metals, Chem. Met. Eng., **25**, pp. 102–103; Chem. Abst., **15**, p. 3815.
2	1916–17	Chikashige, M., Kurosawa, R., Metallographic study of the zinc-selenium system, Mem. College of Science, Kyoto Imp. Univ., **2**, pp. 245–248.
3	1912	Kobayashi, M., Alloys of tellurium with zinc, Eng. Kyoto Imp. Univ., **3**, pp. 217–220; Chem. Abst., **6**, p. 213; J. Chem. Soc., **100** (2), 1911, p. 1089.

(u) ZINC-SILVER

Zinc alloys readily with silver in all proportions. The constitutional diagram strikingly resembles in many respects that of the zinc-copper alloys and that of the zinc-gold series. The diagram given in Figure 112 is that of the International Critical Tables (vol. 2, p. 423) and is based largely upon the work of Carpenter and Whitely (11). Information as summarized in the International Critical Tables (vol.1) on the crystal structure of the various phases in the zinc-silver alloy system as determined by X-ray examination is given in Table 58.

TABLE 58.—*Crystal structure of zinc-silver alloys*

Phase	Zinc[1] content	Symmetry	Unit cell				Reference
			a	*c*	*c/a*	Number of atoms	
	Per cent		*A*	*A*			
VI (α)	0–27	Cubic	4.06– 4.005				(8).
V (β)	38.25	do	3.156			2	(7).
IV (γ)	50.3	do	9.327			52.37	
III (δ)	60.5	Hexagonal	2.818	4.456	1.581	2	
	78.1	do	2.815	4.382	1.557	2	
I (η)		Hexagonal, close packed with zinclike structure					

[1] See footnote, Table 57, p. 155.

The information on the relative solution potential of the different phases of this alloy system given in Figure 113 (9) emphasizes the similarity between this alloy system and the zinc-copper and the zinc-silver series. The zinc-silver alloys have very few industrial uses. The silver-rich solid solution (Ag, Zn) responds readily to mechanical working, it is both malleable and ductile and can be rolled like silver.

Petrenko (2, 3, 5, 10, 12) has devoted a great deal of time to the study of the zinc-silver alloy system and among other studies has surveyed the system for hardness and electrical resistivity.

The properties of zinc-silver alloys with a zinc content, 0 to 25 per cent, have been studied by this bureau as part of the investigation of tarnish-resisting silver alloys (4). The study was limited to alloys of the solid solution (Zn, Ag). Of the binary alloys of silver studied those of zinc and of cadmium were found to be the most resistant to

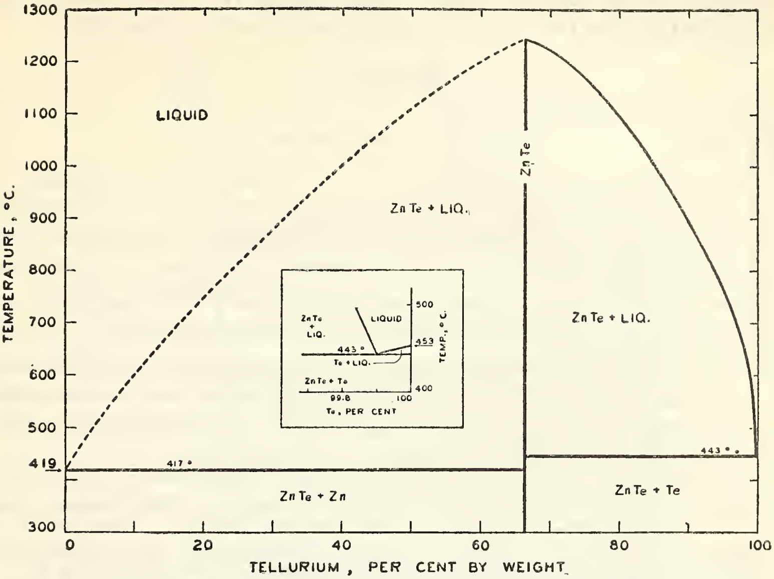


FIGURE 111.—*Constitutional diagram of the zinc-tellurium series of alloys*

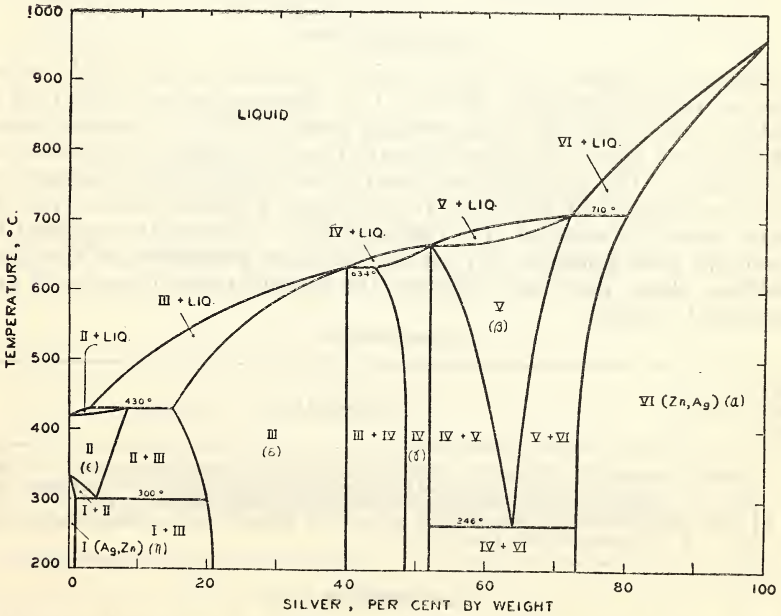


FIGURE 112.—*Constitutional diagram of the zinc-silver series of alloys*

tarnish. The tensile properties, however, were the lowest of all the workable binary alloys. Saeftel and Sachs (6) have studied the mechanical properties of alloys of this system more extensively.

Zinc-silver

Text reference	Year	Name and title
1	1930	Guillet, L., Cournot, J., Influence des traitements thermiques sur certains alliages argent-zinc et argent-cadmium, Rev. Metal, **27,** pp. 1–7.
2	1929	Petrenko, B. G., The formation of the β-phase of silver-zinc alloys. Zeit. f Anorg. Chem., **184,** pp. 369–375.
2a	1929–30	Petrenko, G. I., B. G., Structure of the γ-phase in the alloys silver-zinc, Z. Anorg. Chem. **185,** pp, 96–100.
3	1927	Petrenko, G. I., The changes of silver-zinc alloys in the crystalline condition, Z. Anorg. Chem., **165,** pp. 297–304; Chem. Abst., **21,** p. 3878.
4	1927	Jordan, L., Grenell, L. H., Herschman, H. K., Tarnish resisting silver alloys. B. S. Tech. Paper No. 348.
5	1925	Petrenko, G. I., The electrical conductivity of silver-zinc alloys in the quenched condition, Z. Anorg. Chem., **149,** pp. 395–400; J. Inst. Metals, **36,** 1926, p. 450.
6	1925	Saeftel, F., Sachs, G., Festigkeitseigenschaften und struktur einiger mischkristallreihen, Z. Metallkunde, **17,** pp. 155–161; 258–264; 294–298.
7	1925	Westgren, A., Phragmen, G., X-ray analysis of copper-zinc, silver-zinc and gold-zinc alloys, Phil. Mag., **50** (VI), p. 311.
8	1922	Bain, E. C., Nature of solid solutions. Chem. Met. Eng., **28,** pp. 21–24.
9	1921	Guertler, W., Metallographie, Bd. 2, Tl. 1, Abs. 3, Elektrochemische Metallkunde, R. Kremann. Publ. Gebruder Borntraeger, Berlin.
10	1914	Petrenko, G. I., Hardness of the systems (*a*) silver-zinc and (*b*) silver-aluminum, J. Russ. Phys. Chem. Soc., **46,** p. 176; J. Soc. Chem. Ind., **33,** p. 1211. Chem. Abst., **9,** 1915 p. 777.
11	1912–13	Carpenter, H. C. H., Whitely, W., The silver zinc equilibrium. With an appendix on the copper-zinc, silver-zinc and silver-cadmium equilibria, Z. Metallkunde, **3**, p. 145.
12	1912	Petrenko, G. I., Transformations in the silver-zinc alloys in crystallized state, Chem. Ztg., **36,** p. 220; Chem. Abst., **7,** 1913, p. 2184.
13	1909	Pushin, N., Maksimenko, M., The electrical conductivity of the alloys of silver and zinc in relation to their thermo-electric power, J. Russ. Phys. Chem. Soc., **41,** pp. 500–524; Chem. Zentr. (2), p. 682; Chem. Abst., **5**, 1911, p. 819; J. Chem. Soc., **96a,** (2), p. 539

(v) ZINC-THALLIUM

Zinc and thallium are only partially miscible in the liquid state. Zinc, at its melting point (419.47° C.), dissolves about 2 per cent of thallium and thallium, at its melting point (302°C.), dissolves about 5 per cent of zinc. In the solid state the two metals are insoluble in each other. The principal features of the constitutional diagram are given in Figure 114 from the International Critical Tables (vol. 2), based upon the work of von Vegesack (2). The results reported by Kremann and Lobinger (1) on the solution potentials of the zinc-thallium alloys have not changed the constitutional diagram in any important respect.

Zinc-thallium

Text reference	Year	Name and title
1	1920	Kremann, R., Lobinger, A., Electromotive properties of certain binary alloys. IV. Electromotive behavior of alloys of thallium with zinc, lead, bismuth, tin, antimony, cadmium, Z. Metallkunde, **12,** pp. 246–256; J. Inst. Metals, **25,** 1921, p. 410.
2	1907	Von Vegesack, A., Zinc-thallium and zinc-iron alloys, Z. Anorg. Chem., **52,** pp. 30–40; J. Chem. Soc., **92**a, II, p. 170.

(w) ZINC-TIN

The two metals are completely miscible in the liquid state, but insoluble in the solid. The constitutional diagram, Figure 115 (1), is of the typical eutectic type, the eutectic containing 92.1 per cent

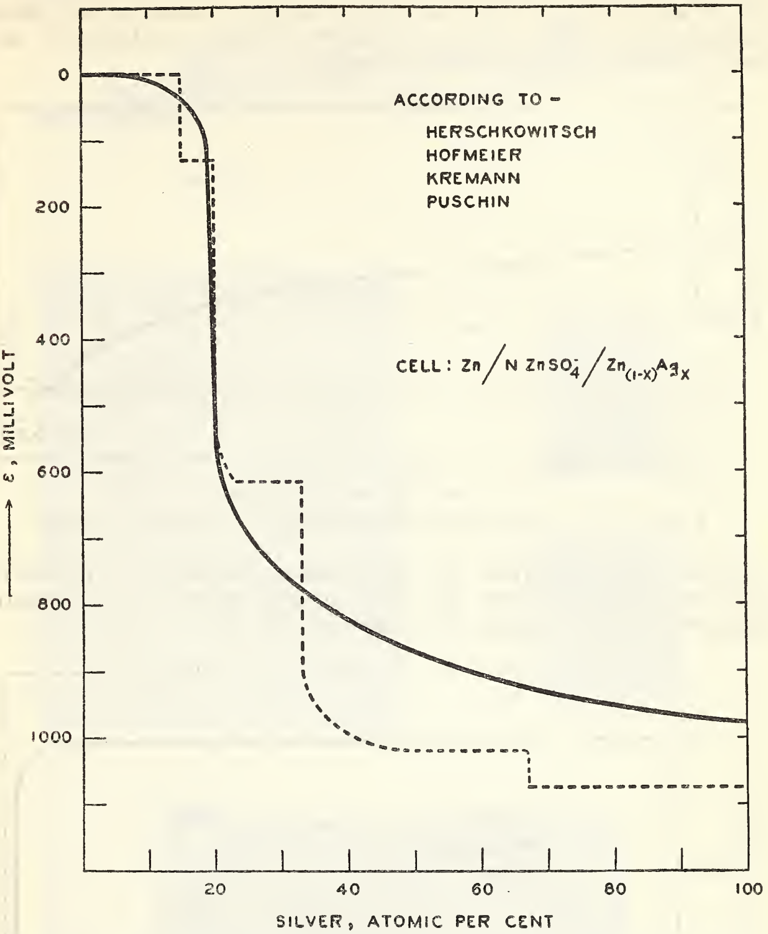


FIGURE 113.—*Relative solution potentials of the various phases in the zinc-silver series of alloys*

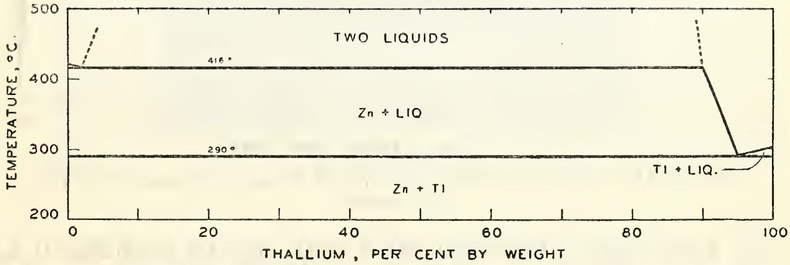


FIGURE 114.—*Constitutional diagram of the zinc-thallium series of alloys*

of tin and melting at a temperature of 198° C. All available evidence goes to show that the solid solubility of either metal in the other is extremely slight. According to Peirce (5), the solubility of tin in zinc is less than 0.05 per cent by weight.

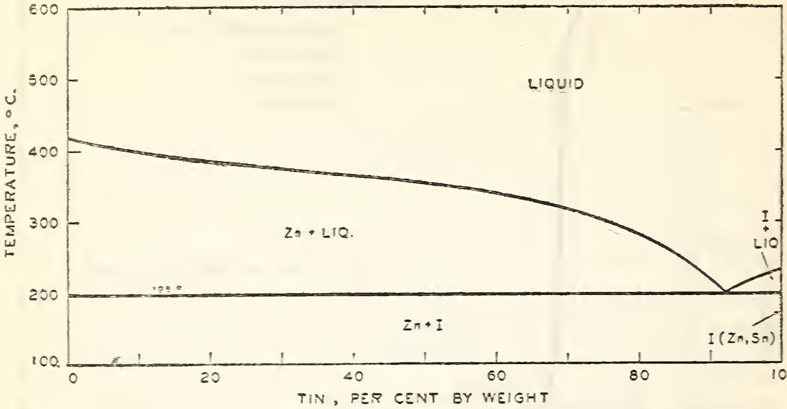


FIGURE 115.—*Constitutional diagram of the zinc-tin series of alloys*

Figure 116 summarizes the information available (7) on the relative solution potentials of the alloys of this system, the composition being progressively varied from pure zinc to tin.

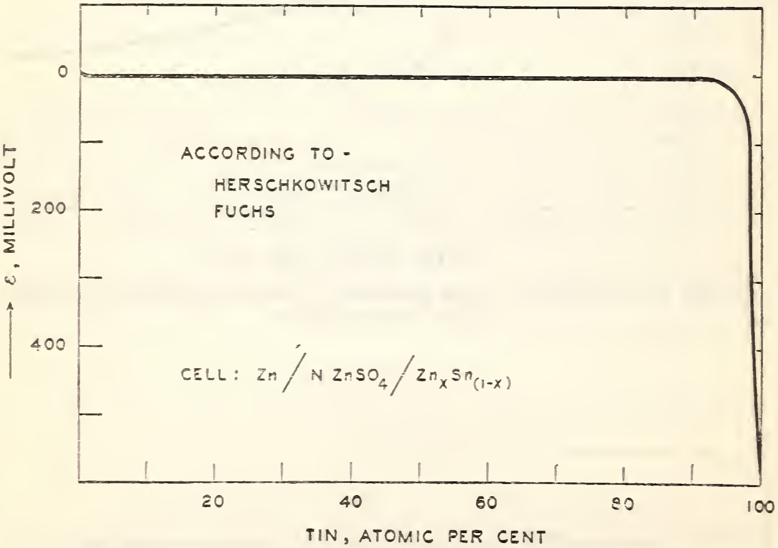


FIGURE 116.—*Relative solution potentials of the various phases of the zinc-tin series*

Tin has a very detrimental effect upon zinc by rendering it hot-short and brittle by reason of its low melting point together with its pronounced tendency to form enveloping films around the zinc grains.

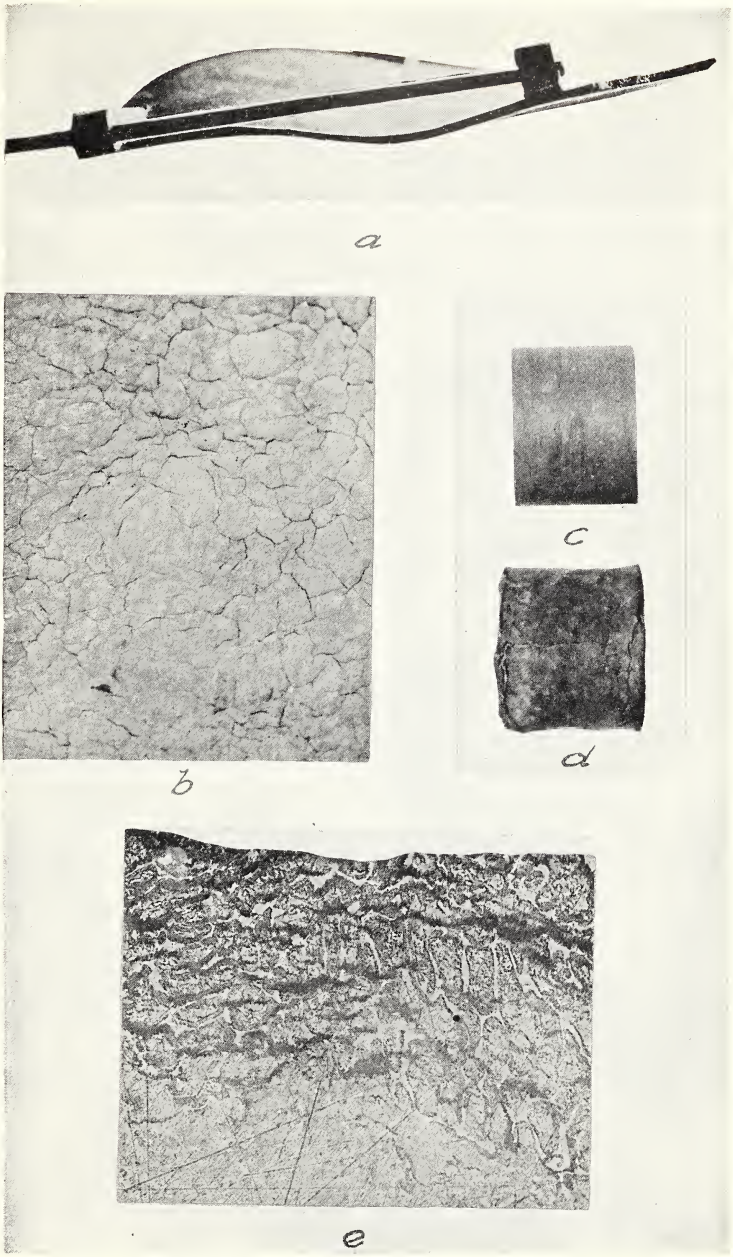


FIGURE 117.—*Appearance of a zinc alloy of high aluminum*

a, Fuse box cover (approximate composition: Aluminum, 15 per cent; lead, 0.4 per cent; zinc, remainder) which was used in a tropical climate and warped in service. × ¼; *b*, surface of specimen, showing "alligator cracks." × 1; *c*, cylinder of an alloy (composition, copper, 1.4 per cent; aluminum, 15.2 per cent, zinc, 83.4 per cent) exposed to "dry heat" (100° C.) for six days. The dimensions of the specimen remained unchanged. × 1½; *d*, specimen similar to *c* exposed to "moist heat" (100° C.) for six days. The specimen expanded and cracked. × 1½; *e*, cross section of specimen similar to *d*, showing the "expansion cracks" which formed in the metal near the surface by the action of heat and moisture. Most of these occur in the eutectic; the specimen was unetched. × 100.

Zinc-tin

Text reference	Year	Name and title
1	1930	Peirce, W. M., Constitution of zinc-tin alloys, National Metals Handbook, Am. Soc. Steel Treat., p. 822.
2	1929	Vondracek, R., The velocity of dissolution of zinc-tin alloys in acids, Collection I, No. 12, Des Travaux Chim. de Tschecoslavaquie.
3	1928	Swartz, C. E., Krauskopf, F. C., Formation and decomposition of zinc ferrite, Am. Inst. Mining Met. Eng. **76,** pp. 465–493.
4	1925	Endo, H., On the relation between the equilibrium diagram and the magnetic susceptibility in binary alloys, Sci. Rpts. Tohoku Univ., **14,** pp. 479–512.
5	1923	Peirce, W. M., Studies on the constitution of zinc-base binary alloys, Trans. Am. Inst. Min. Met. Eng., **68,** p. 767.
6	1923	Crepaz, E., The ternary system Al–Zn–Sn. I. The binary systems Sn–Zn and Al–Sn, Giornale die Chimica Industriale e Applicata, **5,** p. 115.
7	1921	Guertler, W., Metallographie, Bd. 2, Tl. 1, Abs., 3, Elektrochemische Metallkunde, R. Kremann, publ. Gebruder Borntraeger, Berlin.
8	1919–20	Fuchs, P., Über die galvanischen spannungen der legierungen von zink und cadmium mit zinn, blei und wismut, Z. Anorg. Chem., **109,** pp. 80–88.
9	1919	Gieren, P., Beitrag zur kenntnis der gegossenen zinklegierungen unter besonderer berucksichtigung ihrer verwertung als lagermetall, Z. Metallkunde, **11,** pp. 14–22.
10	1918	Smith, E. A., Zinc industry, Longmans, Green & Co., London.
11	1917	Ludwik, P., The hardness of the most important alloys for technical purposes, Z. Ver. deut. Ing., **61,** p. 549; Z. Anorg. Chem., **94,** pp. 161–162; Stahl Eisen, **40,** pp. 1547–1551.
12	1913	Mazzotto, D., Thermische untersuchungen uber der umsetzung der leichflussigen legierungen im festen zustande, Z. Metallkunde, **4,** pp. 273–296.
13	1913–14	Lorenz, R., Plumbridge, D,, The binary systems: zinc-tin, zinc-cadmium, tin-cadmium, and the ternary system zinc-tin-cadmium, Z. Anorg. Chem., **82,** p. 228; **85,** pp. 435–436.
14	1911	Arnemann, P. T., The metallographic examination of zinc and of zinc alloys with metals often contained in crude zinc, Metallurgie, **7,** pp. 201–211.

2. TERNARY SYSTEMS

The most important of the ternary systems containing zinc, from the industrial standpoint, is the zinc-aluminum-copper series of alloys. The zinc-rich alloys of this series form the basis of the zinc-base die-casting alloys.

The most extensive work on the constitution of this alloy system is that of Rosenhain, Houghton, and Bingham (4). The space diagram has been constructed and reference should be made to this publication for details as these diagrams are far too complicated to lend themselves to a brief discussion or abstract. The mechanical properties of the zinc-rich alloys of this series have been studied by Schulz and Waehlert (5). A résumé of the results of this work has been given in the discussion of the zinc-aluminum binary alloys.

The use of certain alloys of this series as pyrophoric alloys has been discussed by Czochralski and Lohrke (3). The nominal composition of such alloys is aluminum, 3 per cent; copper, 6 per cent; zinc, remainder.

Zinc-aluminum-copper

Text reference	Year	Name and title
1	1927	Nishimura, H., An investigation on the alloy system Al–Cu–Zn, Suiyokai-Shi, **5,** (4), pp. 372–385; J. Inst. Metals, **40,** 1928, pp. 497–498.
2	1921	Hansel, Veredelungversuche mit inlandischen metallen. Presszink und zinklegierungen, Z. Metallkunde, **13,** pp. 209–219.
3	1920	Czochralski, J., Lohrke, E., Pyrophoric zinc alloys and their utilization, Z. Metallkunde, **12,** pp. 145–149.
4	1920	Rosenhain, W., Houghton, J. L., Bingham, K. E., Zinc alloys with aluminum and copper, J. Inst, Metals, **23,** pp. 261–324.
5	1919	Schulz, E. H., Waehlert, M., A study of copper-aluminum-zinc alloys high in zinc, Metall Erz, **16,** pp. 170–176, 195–201.

3. COMMERCIAL ALLOYS

(a) LIST OF ALLOYS

In Table 59 are listed alloys containing zinc as the major constituent, together with commercial designations of the alloys. The extensive list of alloys published by Campbell (1) has been used as a basis in compiling the list given here.

TABLE 59.—*Commercial alloys containing zinc as the major constituent*

(50 per cent or more of zinc)

Alloy	Zn	Cu	Al	Cd	Sn	Pb	Other elements	Reference[1]
Al solder	52		17.5		30		0.5 Ni	
Al solder (Mourey)	80	8	12					
Do	94	2	4					
Al solder	57			43				
Al solder (Bourbouse)	81.82		18.18					
Antifriction	82	5			6.5	6.5		(2).
American metal	Bal.	4.5			6.5	1.5		(7).
Anti-attrition	Bal.	2			38			(7).
Do	Bal.	4			11			(7).
Ava metal	Bal.	2	2					(7).
Babbitt	69	5			19	5	3 Sb	
Battery plates	63.4	3.2			21.3	12		
Bearings (hard)	90	7			1.5		1.5 Sb	
Bearings	88	8			2		2 Sb	
Do	85	5			10			
Do	77	5.5			17.5			
Bearings (English)	67.7	7.4			14.9			
Bearings	66.5	0.55	20		22.7	.25		
Do	85	5					10 Sb	(3).
Do	66.5	4.2			29.3			(3).
Do	55	0.55	20		22.7	1.25		
Biddery	90.2	6.3			.8	2.6		
Biddery (Heine's)	84.3	11.4			1.4	2.9		
Birmingham platina	79.4	20.25					0.33 Fe	
Bourbouse Al solder	81.82		18.18					
Button	80	20						
Die casting (N. J. Zinc Co.)	92.9	3	4				0.1 Mg	
Dunnlevic and Jones	52	1.6			46		0.4 Sb	
Dunnlevic and Jones (antifriction)	85	5					10 Sb	
Dunnlevic and Jones (Russian)	80	8					do	
Ehrhardt's	89	4			4	3		
Ehrhardt's (type)	89	3			6	2		
English white metal	76.2	5.6			17.5			
E Z L No. 1	Bal.	3.3			21.3	12		(7).
Do	Bal.	3.2	Trace.		21.3	19		(7).
E Z L No. 2	Bal.	3.2			19	16.6		(7).
Do	Bal.	3	Trace.		19	16.6		(7).
Erhard bronze	Bal.	8	3				Trace Fe	(7).
Do	Bal.	8.1	3.1		Trace.	1.9		(7).
Do	Bal.	9	1					(7).
Fenton's Alloy	80	6			14			
Do	80	8.5					14.5 Sb	
Do	79	6			14		1 Sb	(2).
Fletcher's alloy	66.5				33.5			(4).
Fuse alloy	Bal.	4.90	3.11			1.08	0.32 Fe	(5).
Do	Bal.	4.70	3.20			1.00	0.30 Fe	(5).
Glievor bearing	73.5	4.4		1.4	6.7	5	9 Sb	
Glyco white bronze ZD	Bal.	3.75			6.2	4.45		(7).
Goldschmidt Essen	Bal.	6–7	5–6					(7).
Goldschmidt white bronze	Bal.	5–6	2–3				1 Mn	(7).
Goldschmidt zinc alloy	Bal.	5.32	2.70		.33	2.55	0.10 Fe 0.92 Mn	(7).
Do	Bal.	5.32	2.70		.33	1.55	0.92 Mn 0.5 Sb 0.10 Fe	(7).

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[1] Alloys, for which no reference appears, are given in the list of alloys prepared by Campbell (1).

TABLE 59.—*Commercial alloys containing zinc as the major constituent*—Continued

Alloy	Zn	Cu	Al	Cd	Sn	Pb	Other elements	Reference
Goldschmidt zinc alloy	Bal.	5.32	2.70		0.39	1.55	0.92 Mn	(7).
Goldschmidt white bronze	Bal.	5.40	2.70		.40	1.52	do Trace Fe	(7).
Germania white bronze	Bal.	4–5			8	1–2		(7).
Glykometall	85.5	2.4	2		5	4.7		(7).
Hamilton metal	93.4	3.5				3.1	1.5 Sb, P 5 Sn	
Hartzink	91.9	.13				2.4	5.3 Fe	
Hammonia	Bal.	2–4			60			(7).
Hohenzollern	Bal.	4–5	2				1–2 Mn	(7).
Iridium	77.25	1.12			21.63		Trace Sb	
Do	83.00	1.25			15.75		Trace Sb	
Jaeger-Roth's alloy	Bal.	2.70	5.80			1.04	0.36 Fe	(5).
Kemler	76	9	15					
Krieg's metal	Bal.	4			3	2		(7).
Kneiss metal	50				25	25		
Leddell alloy	90	5	5					
Do	89	6	3		1		1 Sb	(2).
Do	88.5	4.5	2.5					(2).
Do	88	5			5.5		1.5 Sb	(2).
Do	87.5	6.5	6					(2).
L C bearing alloy	Bal.				12	1–2		(7).
Ledebur	85	5					10 Sb	
Do	77	5.5			17.5			
Do	76	5			17.5		1.5 Sb	(2).
Do	74	5	6		15			(2).
Do	74	11	3		12			(2).
Do	73	5	1		19		2 Sb	(2).
Lumen	86	10	4					
Do	85	10	5					
Do	85	5	5		5			(2).
Maass's alloy	Bal.	2.88	4.44			.90	0.20 Sb	(5).
Olpea white bronze	Bal.	3.5			6.5	2		(7).
Papenburger	Bal.	5–6	2–3					(7).
Do	Bal.	5.75	2.20		Trace.	3.75		(7).
Pierrot metal Beugnot	83.3	8.3			7.6	3	3.5 Sb	
Propeller bushing	69	5			19		7 Sb	
Pump cocks	72	7			21			
Richards	96		4					
Richardson's	80				20			(4).
Russian, packing	98.5				.98	.32	0.16 Fe	
Salge	85.5	4			9.9	1.1		
Do	84	4			9.9	1.1	1 Sb	(2).
Do	83	10	2		5			(2).
Saxonai bronze	Bal.		6–8		3–5	2.5		(7).
Schomberg bearing	59.4	0.38			39.8	0.21	0.55 Fe	
Schomberg	87	3			10			(2).
Schulz	91	6	3					
Silver metal	66.5						33.5 Ag	
Sorel's alloy	98	1					1Fe	
Do	88	10					10 Fe	
Spandau	Bal.	4–5	2.5/3.5					(7).
Spiauter (hard zinc)	90	2					8 Sb	
Tandem white bronze	Bal.	1.25			72.25			(7).
Tandem white bronze No. 2	Bal.	2			58.5			(7).
Tandem white bronze No. 3	Bal.	4–5			30	2		(7).
Tandem white bronze No. 4	Bal.	4–5			16			(7).
Do	Bal.	5.2	Trace.		15.4	1.8	Trace Sb Trace Fe	(7).
Tandem white bronze No. 5	Bal.	2–4			8			(7).
Tenax	Bal.	2.56	4.4			.12	0–0.35 Fe	(5).
Vaucher's alloy	75				18	4.5	2.5 Sb	
War bronze	Bal.	4.85	2.2		0.15	0.92		
Wilder's (coating)	84		.5		14	1.5		(6).
Zelco	83	2	15					
Zamak (die cast)	Bal.	2.5/3.5	3.5/4.5 Max.				0.2 Max Mg	
Zilloy (cold rolled)	Bal.	1					0.8 Cd 0.01 Mg	

Commercial alloys

Text reference	Year	Name and title
1	1930	Campbell, W., A list of alloys, Proc. Am. Soc. Test. Mtls., **30,** p. 336.
2	1926	Vickers, C., Question section, Foundry, **54,** p. 999.
3	1921	Schulte, W., Tenax-metall. Giesserei Ztg., **18,** pp. 258–260, 268–270, 278–280.
4	1919	Gieren, P., Beitrage zur kenntnis der gegossonen zinklegierungen unter besonderer berucksichtigung ihrer verwertung als lagermetall, Z. Metallkunde, **11,** pp. 14–22.
5	1912	Campbell, W., Notes on metallography of alloys. Trans. Am, Inst. Mining Met. Eng., **44,** pp. 825–850.
6	1911	Lake, E. E., Alloys used for die casting, Iron Age, **88,** pp. 532–535.
7	1902	Ingalls, W. R., Production and properties of zinc, Engng. & Min. J.

(b) ZINC-BASE ALLOYS FOR BEARINGS

Although some of the zinc-base alloys are used with success as bearing alloys, this does not constitute one of the important uses of zinc alloys. Practically all of the alloys used as bearing metals are based upon the zinc-tin series, with various hardening elements, and the zinc-aluminum-copper series. According to Thews (1), the zinc-base alloys qualify as bearing alloys almost exclusively by their high compressive strength, the antifrictional properties being less satisfactory than those of the more familiar and commonly used bearing alloys. Thews states that the zinc-base bearing alloys are employed, therefore, only for heavily loaded bearings where high compressive strength combined with low cost are the chief requirements. Final or categorical conclusions should be held in abeyance, however, since it would appear that the field has not been as systematically and thoroughly studied as its importance would justify.

It is well established, however, that alloys containing free zinc or zinc-rich solid solutions are not satisfactory for bearing metals on account of their tendency to adhere to steel under pressure at temperatures not much above normal room temperatures.

In Table 60, are summarized data, quoted by Thews (1) from earlier work by Charpy (10), on the compressive strength of typical bearing alloys of the zinc-antimony-tin series.

TABLE 60.—*Compressive strength of zinc-base bearing metals, Zn-Sb-Sn series (1)*

Nominal composition			Load corresponding to a compression of 0.2 mm [1]	Load corresponding to a compression of 7.5 mm [1]
Zn	Sb	Sn		
Per cent	*Per cent*	*Per cent*	*kg*	*kg*
100	----------	----------	500	4, 200
90	10	----------	2, 450	Broke at 5, 000
80	20	----------	3, 000	Broke at 4, 000
70	30	----------	4, 100	Broke at 4, 700
90	5	5	1, 100	3, 950
80	10	10	1, 350	4, 150
70	15	15	1, 800	5, 200
80	5	15	1, 120	3, 550
70	7. 5	22. 5	1, 225	3, 500
60	10	30	1, 240	3, 350
90	----------	10	750	3, 050
80	----------	20	850	2, 725
70	----------	30	850	2, 500
60	----------	40	575	2, 175

[1] Specimens 15 mm in height and 10 by 10 mm. in cross-section; chill cast.

A list of zinc-base bearing alloys which have appeared in the technical literature is given in Table 61 from Thews (1). Nearly all of these alloys are of foreign origin. An American alloy intended for this use, which has long been available commercially, has the nominal composition—zinc 86 per cent, copper 10 per cent, aluminum 4 per cent, and magnesium 0.1 per cent.

TABLE 61.—*Zinc-base bearing metals (1)*

Designation and use	Composition					
	Zn	Sn	Cu	Sb	Pb	Other elements
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Russian packing	98. 5	0. 98	--------	--------	0. 32	0. 16 Fe.
Hamilton metal	93. 4	--------	3. 5	1. 5	3. 1	
For heavy work	90. 0	1. 5	7. 0	1. 5	--------	
Leddel alloy	90. 0	--------	5. 0	--------	--------	5. 0 Al.
Russian State Railway	90. 0	1. 5	7. 0	1. 5	--------	
Cheap Krupp mill	90. 0	1. 5	7. 0	1. 5	--------	
Ehrhard's metal	89. 0	4. 0	4. 0	--------	3. 0	
Bearings for common work (Hiorns)	88. 0	2. 0	8. 0	2. 0	--------	
Cheap Krupp mills	88. 0	2. 0	8. 0	2. 0	--------	
Leddel's "Aluminum bearing"	87. 5	--------	6. 25	--------	--------	6. 25 Al.
Glyko metal	85. 5	5. 0	2. 4	4. 7	--------	2.0 Al.
Salge metal	85. 5	9. 9	4. 0	--------	1. 1	
Ledebur's B. M.	85. 0	--------	5. 0	10. 0	--------	
Dunlevic and Jones antifriction	85. 0	--------	5. 0	10. 0	--------	
Saxonia metal	84. 8	5. 3	6. 0	--------	3. 0	0.2 Al.
Ehrhard's B. M.	84. 4	0. 2	10. 9	--------	1. 2	2. 5 Al.
Sulzer's antifriction	83. 6	9. 9	4. 0	--------	1. 2	
Pierrot's B. M.	83. 3	7. 6	2. 3	3. 8	3. 0	
Iridium B. M.	83. 0	15. 75	1. 25	Trace.	--------	
Germania B. Bronze	80. 4	9. 6	4. 4	--------	4. 7	0. 8 Fe.
Fenton's B. M. (Schott)	80. 0	14. 5	5. 5	--------	--------	
F. Axle boxes and cars	--------	--------	--------	--------	--------	
Fenton's B. M.	80. 0	14. 0	6. 0	--------	--------	
Fenton's B. M. II	80. 0	--------	5. 5	14. 5	--------	
Dunlevic and Jones	80. 0	--------	8. 0	10. 0	--------	
"English" B. M.	80. 0	14. 5	5. 5	--------	--------	
Iridium II	77. 25	21. 63	1. 12	Trace.	--------	
Ledebur's B. M.	77. 0	17. 5	5. 5	--------	--------	
Krupp Mills II	76. 92	--------	--------	7. 70	15. 38	
Becker's alloy for rapidly revolving shafts	76. 14	17. 47	5. 60	--------	--------	
Russian B. M.	76. 14	17. 47	5. 60	--------	--------	
English B. M. for heavy loads	76. 14	17. 47	5. 60	--------	--------	
Glievor metal	73. 50	6. 9	4. 3	8. 9	4. 9	1. 4 Cd.
English babbitt	69. 0	19. 0	4. 0	3. 0	5. 0	
For propeller bushings	69. 0	26. 0	5. 0	--------	--------	
Tandem B. M.	66. 0	21. 5	7. 0	--------	4. 8	0. 4 Al.
Schomberg's B. M.	59. 4	39. 9	0. 38	--------	0. 21	0.15 Fe.
"Aluminum B. M."	54. 95	22. 7	0. 55	--------	1. 25	20.20 Al.
Railway axles	52. 0	46. 0	1. 6	0. 4	--------	
Dunlevic's B. M.	52. 0	46. 0	1. 6	0. 4	--------	
"German" B. M.	50. 0	25. 0	--------	--------	25. 0	
Kneiss B. M.	50. 0	25. 0	--------	--------	25. 0	
Automobile B. M. and similar purposes	47. 5	--------	--------	5. 0	--------	47. 5 Cd.
Siemens and Halske	47. 5	--------	--------	5. 0	--------	47. 5 Cd.
Wagner's B. M.	47. 0	38. 0	1. 0	6. 0	4. 0	
For heavy loads	47. 0	38. 0	1. 0	6. 0	4. 0	
Krupp Mills I	45. 5	--------	--------	9. 0	45. 5	
Kneiss B. M.	40. 0	15. 0	3. 0	--------	42. 0	
For ordinary mills	40. 0	15. 0	3. 0	--------	42. 0	
For propeller boxes	29. 0	14. 0	57. 0	--------	--------	
Russian B. M.	26. 5	72. 2	1. 3	--------	--------	
Dunlevic and Jones antifriction	20. 0	--------	--------	20. 0	60. 0	
Stephenson's alloy	19. 0	31. 0	19. 0	--------	--------	31.0 Fe.

Selected from a list of 50 zinc-base alloys discussed by Gieren for their possible usefulness in bearing, are the following (Table 62) mentioned by the author as being most promising on the basis of the properties determined in the laboratory.

TABLE 62.—*List of selected zinc-base bearing alloys* (9)

No.	Nominal composition				
	Sn	Pb	Cu	Al	Zn
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*
1	8	1 to 2	4 to 5	--------	Balance.
5	16	--------	4 to 5	--------	Do.
25	--------	--------	5 to 6	2 to 3	Do.
26	--------	--------	8	3	Do.
15	--------	--------	5	5	Do.
35	--------	--------	5 to 6	2 to 3	Do.

Zinc-base bearing metals

Text reference	Year	Name and title
1	1930	Thews, E. R., Metallurgy of white metal scrap and residues. D. van Nostrand Co. (Inc.)
2	1929	Roekaert, F., Antifriction alloys. Aciers Speciaux, **4**, pp. 371, 470–482, 583–589.
3	1920	Praetorius, Experiments with substitute bearing metals at the laboratory of the Air Service Arsenal in Vienna, Der Motorwagen, **23**, pp. 44–46.
4	1920	Schulz, E. H., Standardization of zinc and zinc alloys. Metall Erz., **17**, pp. 398–400.
5	1919	Jones, J. L., Lumen metal. Metal Ind., **17**, pp. 232, 283.
6	1919	Study of cast zinc alloys with special reference to their use as bearing metals. Chem.-Zentralblatt, **90**, pp. 964–965.
7	1917	Holder, G. C., Antifriction metal, Metal Ind., **15**, pp. 153–155.
8	1916	Forg, R., Studies on bearing metals. Int. Zts. Metallog., **8**, pp. 68–94.
9	1911	Gieren, P., Contribution on cast-zinc alloys with special reference to their use as bearing metals. Z. Metallkunde, **11**, p. 14.
10	1899	Charpy, G., Study of white alloys called antifriction, Metallographist, **2**, pp. 9–55.

(c) ZINC-BASE ALLOYS FOR DIE CASTING

Of the various die-casting alloys, only those in which zinc is the major constituent, will be considered in this section. The characteristics which any successful die-casting alloy must possess have been well summarized by Peirce (5). It is necessary to use a metal (iron) container for melting and holding the alloy and all of the parts, including the dies, with which the molten alloy comes in contact are of steel or iron. It follows, therefore, that the alloy used must have only a slight solvent, or alloying, attack on these metal parts, otherwise it would quickly become contaminated to such an extent by the iron dissolved as to render it unsatisfactory for most uses. The alloy must possess a high degree of fluidity in order to ensure that a sound casting, the surface of which is an exact replica of that of the die, will be produced. Since the casting is made in a permanent or metal mold, the shrinkage stresses are high. This necessitates the use of an alloy which is reasonably free from "hot-shortness." In addition, of course, the tensile properties of the cast metal and, in particular, the resistance to impact, should be as high as in consistent with alloys of this kind. Finally, stability of the alloy under service conditions, to ensure permanence of dimensions and form, is of very great importance.

It is this latter feature that contributed more than any other to the disfavor with which die castings were formerly regarded by many. Figure 117 illustrates the general character and magnitude of the change which has been observed in zinc-base die castings of certain composition. Early failures of this kind have also been described by Williams (19). This unsatisfactory behavior of certain zinc-base die-casting alloys was thoroughly studied by Brauer and Peirce (15). The stability of a great many different compositions was determined in the laboratory, the specimens being subjected to the action of steam at 100° C. The alloys were essentially of the zinc-aluminum series to which various other elements had been added. The authors concluded that the corrosion and swelling of zinc-aluminum alloys is decidedly accelerated by the small amounts of lead and cadmium which occur frequently in zinc. Tin had a similar effect, whereas copper had a marked retarding effect. The effect of nickel and manganese was not pronounced, but they appeared to accelerate the attack, although later Peirce and Anderson (10) have reported that the opposite may be true. It also appeared that the percentage of aluminum in such alloys should not exceed about 5 per cent. In particular, the work emphasized the necessity of using zinc of known purity and pointed to the advantage to be gained by using high-grade zinc.

Any discussion of the present-day die-casting alloys must be largely based upon several current extensive investigations of these materials which are being sponsored by various technical societies. The American Society for Testing Materials has in progress a very extensive investigation of die-cast alloys (6), the initial part of the program consisting in the determination of the properties and composition of die-cast alloys supplied by cooperating producers. The compositions of the alloys given in Table 68, although prepared especially for this investigation, may be accepted as being typical of current American practice. Zinc-base alloys used for die-casting purposes in general commercial use consist essentially either of zinc hardened with copper and tin or of zinc hardened with copper and aluminum. Other investigations by technical societies of die-casting alloys include that of the British Nonferrous Metals Research Association (9) and that of the Deutschen Gesellschaft für Metallkunde (11).

The structural change (fig. 117) which has been observed in certain zinc-base die-cast alloys upon aging has been shown by Peirce (5) to be of a double nature—a phase change accompanied by changes resulting from corrosion. The nature of this change is best discussed by considering the structural diagram of the zinc-aluminum alloy system (fig. 62) based upon the work of Rosenhain and associates (18) and Hanson and Gayler (16). The range of solubility of aluminum in zinc is very limited; alloys containing aluminum in amounts greater than about 1 per cent have a 2-phase structure consisting of a eutectic of two solid solutions, I and III, often designated as α and γ, together with an excess of one of them, except for the eutectic composition. At the temperature of 270° C. a structural constituent, II (β phase), which is stable only above this temperature, breaks up and gives rise to the two phases, I and III, which are the stable constituents at normal room temperature.

In alloys cooled rapidly from above 270° C. (518° F.) much of the β constituent is retained as such, which upon standing tends to change into the two stable constituents. This change is accompanied by a slight decrease in volume. Heat accelerates this change, and in a moist warm atmosphere corrosion accompanies or follows closely upon the phase change. The corrosive attack penetrates into the interior of the alloy by intercrystalline paths, the result being a marked swelling, warping, and cracking in the course of time. No alloys based upon the zinc-aluminum alloy system can be said to be absolutely free from this tendency toward change on aging, although in a number of compositions the effect can be so retarded as to be practically negligible.

The zinc-base alloys hardened by the use of tin and copper were among the earliest used for die castings. On account of the pronounced "hot-shortness" of these alloys and their relatively low tensile properties and impact resistance (Table 63) this class of die-casting alloys has been largely replaced by others. The nominal compositon given in Table 63 (copper, 2.75 per cent; aluminum, 0.5 per cent; tin, 6.0 per cent; zinc, remainder) may be accepted as representative of this class of alloys as now used in this country. In contradistinction to the zinc-base die-casting alloys containing aluminum and copper, the zinc-base alloys containing tin are relatively stable under weathering conditions in service. Colwell (1) has recently published data emphasizing this point. Figure 118 shows the expansion noted over a period of seven years. The greater stability of the zinc-base alloys hardened with tin and copper as compared with those hardened with copper and aluminum is also shown in Figure 123, which summarizes the changes in length observed over a period of three and one-fourth years in the work carried out by the Deutschen Gesellschaft für Metallkunde (11).

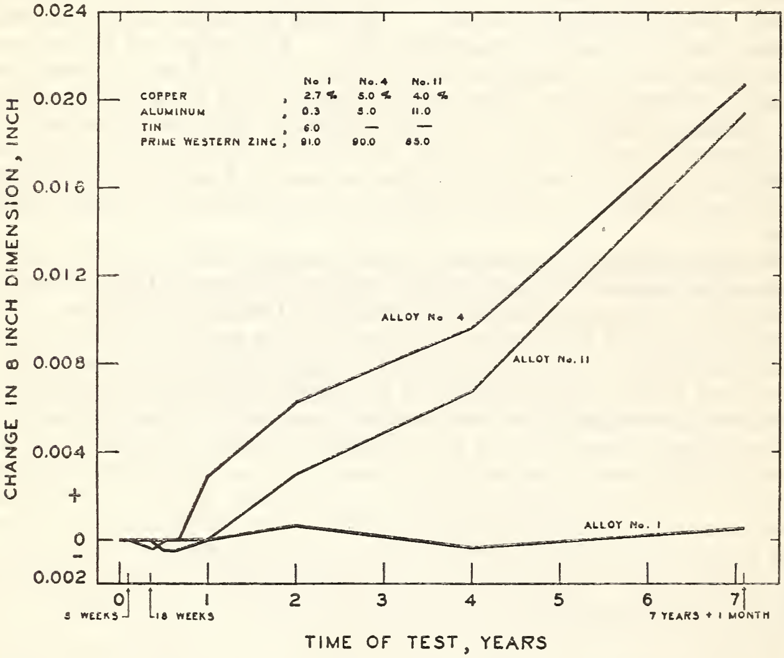


FIGURE 118.—*Dimensional changes in die-cast alloys upon aging for a period of seven years under ordinary climatic conditions*

From the program of investigation of the British Nonferrous Metals Research Association (9) it may be inferred that zinc-base die-casting alloys containing tin are still of relatively greater industrial importance in Great Britain than they are in this country.

An early development in die-casting alloys was the zinc-base class containing 1 to 5 per cent copper and 1 to 20 per cent aluminum. Many failures from warping, cracking, swelling, and general weakening of the alloy occurred. Alloys of this general composition are no longer recommended and the class of zinc-base alloys containing aluminum has been greatly improved during the past few years. Of these, the alloys containing about 4 per cent aluminum and 3 per cent copper are in very wide use.

Peirce and his associates (4, 5, 10, 15) have shown that the rate at which the unstable β constituent present in the zinc-aluminum alloys tends to revert to the more stable phases is greatly retarded by the presence of copper and, in addition, that the presence of a small amount of magnesium appears to have a truly remarkable stabilizing effect. Largely as a result of this work, zinc-base alloys for die casting have been developed which have been characterized (1) as "reliable engineering materials." For these alloys, containing 4 per cent aluminum, 3 per cent copper, with or without 0.1 per cent magnesium, exceptionally valuable properties have been claimed.

In Table 63 are summarized the mechanical properties of a number of die-cast alloys, including those just described, as determined by Peirce and Anderson (10). The effect of using different grades of zinc in preparing such alloys is also illustrated.

TABLE 63.—*Mechanical properties of typical zinc-base die-cast alloys* (*10*)

Nominal composition of alloy (in per cent)	Tensile strength [1]	Resistance to impact	Transverse deflection [2]	Modulus of rupture [3]	Brinell hardness No. [4]
	Lbs./in.^{2}	*Ft.-lbs./in.*^{2}	*Inch*	*Lbs./in.*^{2}	
Zinc [5]	14, 200	1	0. 15	19, 300	41
5 Al; 95 Zn [5]	30, 000	33	. 19	57, 100	46
6 Sn, 2.75 Cu, 0.5 Al, 90.75 Zn [5]	19, 700	14	. 18	52, 700	52
6 Sn, 2.75 Cu, 0.5 Al, 90.75 Zn [6]	20, 500	6	. 17	48, 500	50
12 Al, 3 Cu, 85 Zn [5]	38, 500	19	. 30	87, 400	89
12 Al, 3 Cu, 85 Zn [6]	45, 300	13	. 26	86, 400	87
4 Al, 3 Cu, 93 Zn [5]	41, 500	76	. 25	78, 800	58
4 Al, 3 Cu, 93 Zn [7]	37, 600	125	. 27	77, 700	61
4 Al, 3 Cu, 93 Zn [6]	39, 700	21	. 18	76, 400	78
4 Al, 3 Cu, 0.1 Mg, 92.9 Zn [5]	41, 200	90	. 19	81, 400	70
4 Al, 3 Cu, 0.1 Mg, 92.9 Zn [7]	40, 000	---	. 10	70, 800	74
4 Al, 3 Cu, 0.1 Mg, 92. 9 Zn [6]	42, 200	57	. 16	86, 400	---
4 Al, 3 Cu, 0.2 Mg, 92.8 Zn [5]	38, 100	63	. 18	82, 800	76
4 Al, 3 Cu, 0.3 Mg, 92.7 Zn [5]	35, 100	34	. 13	78, 700	75

[1] Specimens cast to size; cross section of test section ½ by ⅛ inch; the dies of the casting machine were water-cooled, 90° to 130° C; speed of pulling 0.266 inch per minute.

[2] Tension test specimens were supported on 3-inch centers.

[3] $R=\frac{3}{2}\times\frac{\text{load}\times\text{span}}{\text{width}\times(\text{depth})^2}$

[4] 10 mm ball, 500 kg load.

[5] High grade zinc, Pb 0.045 per cent, Cd less than 0.002 per cent; Fe 0.010 per cent.

[6] Prime western, A. S. T. M. specification, Pb 0.075 per cent, Cd 0.02 per cent, Fe 0.007 per cent.

[7] Intermediate, A. S. T. M. specification, Pb 0.80 per cent, Cd 0.30 per cent, Fe 0.020 per cent.

The results obtained on alloys of this type by Lancaster and Berry (2), summarized in Table 64, tend to confirm some of the advantages claimed for the use of a small amount of magnesium in such alloys although the tensile properties are not so high as have been reported for cast-to-size bars. The specimens used by Lancaster and Berry were machined from cylinders, 1.25 inch diameter, cast by gravity, in iron molds.

TABLE 64.—*Effect of magnesium on some of the mechanical properties of zinc-base die-casting alloys*

Nominal conposition	Tensile strength	Angle of torsion
	Lbs./in.^{2}	°
4 Al, 3 Cu, balance Zn	30, 250	193
4 Al, 3 Cu, balance Zn+0. 1 Mg	35, 150	270
4 Al, 3 Cu, balacce Zn+0. 2 Mg	26, 600	90
4 Al, 3 Cu, balance Zn+0.5 Mg	24, 100	95

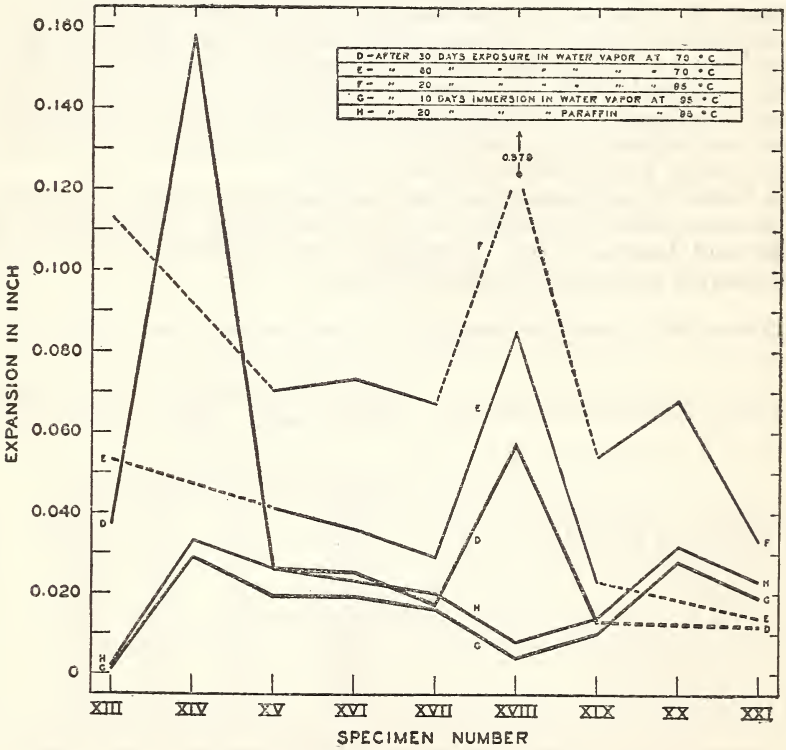


FIGURE 119.—*Dimensional changes in die-cast alloys resulting from accelerated aging; tests conducted by the American Society for Testing Materials*

The compositions of the different alloys are given in Table 64. The expansion given is that measured on a flat bar 9 inches in length. The order in which the specimens are listed (abscissae) is of no material significance. The plotted points for each test have been connected with straight lines merely for convenience in reference.

These results are in agreement with those obtained by Peirce (5) that a magnesium content much above 0.1 per cent is not advantageous and usually detrimental. One of the decided advantages claimed for the zinc-aluminum-copper alloy to which magnesium is added is the freedom from intercrystalline attack when these alloys are exposed to corrosive conditions as in a warm, moist atmosphere. Some results illustrating this behavior are given in a succeeding figure. (Fig. 121.)

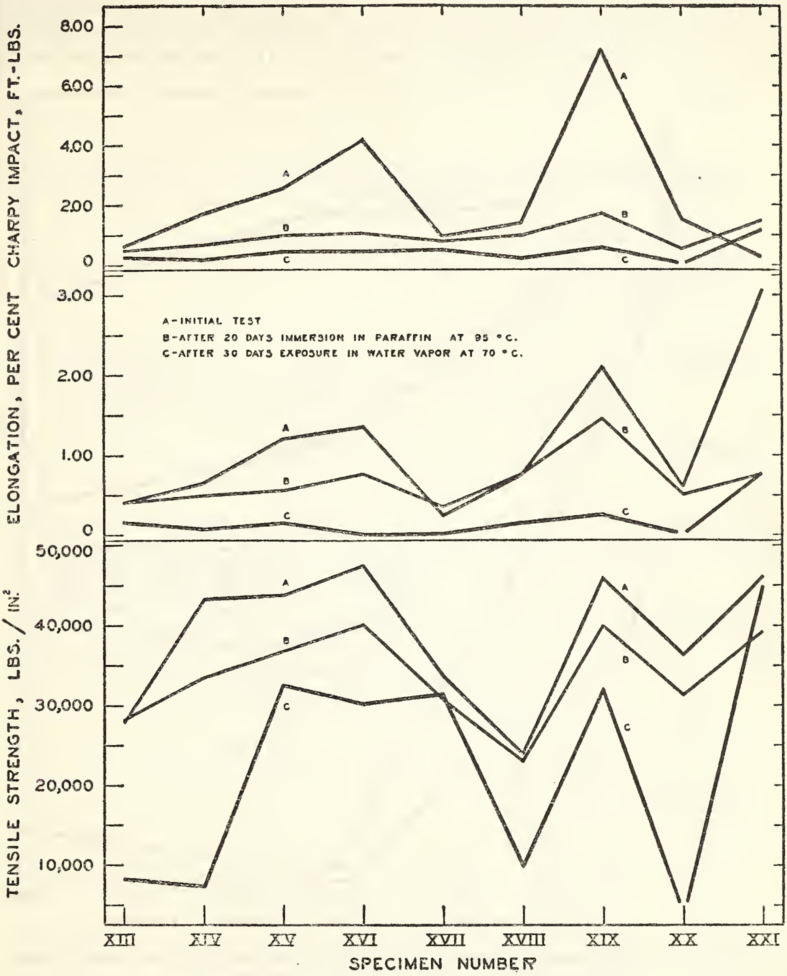
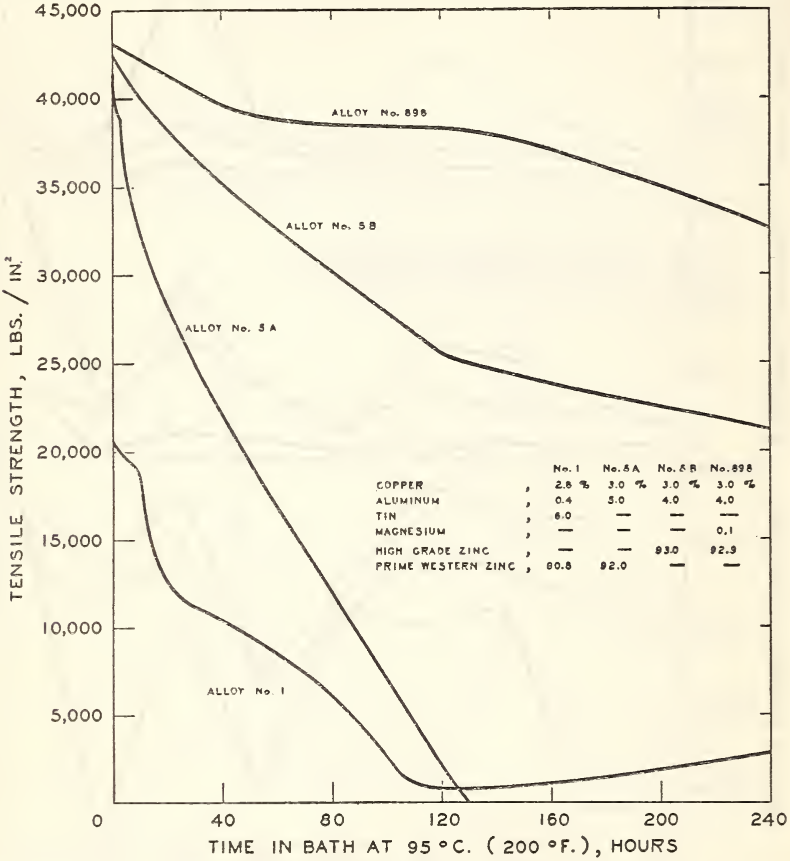


FIGURE 120.—*Changes in tensile properties and impact resistance of die-cast alloys resulting from accelerated aging; tests conducted by the American Society for Testing Materials*

See Table 65 for composition of alloys. Compare Figure 119. The specimens were not machined.

Although the investigation of the American Society for Testing Materials (6) is still far from completion, the results of the labratory tests are very enlightening as to the relative behavior of the different alloys (Table 65) under the accelerated test conditions, which may be indicative of differences in service behavior. Some of these results are given in Figure 119 and 120. Considerable emphasis has been placed upon the test in which the specimens are subjected to the action of water vapor at an elevated temperature, although it has been pointed out (1) that this test may be an excessively severe one. So far, sufficient data are not available to permit any attempt at correlation of the laboratory tests and service behavior. Specimens of all of the alloys have been exposed to the weather in various parts of the country representing rather widely differing climatic conditions, as well as in a number of indoor locations. It is expected that on the basis of the results of the tests to be made within the next few years of specimens, after exposure, reliable and definite information will be obtained concerning behavior under service conditions.



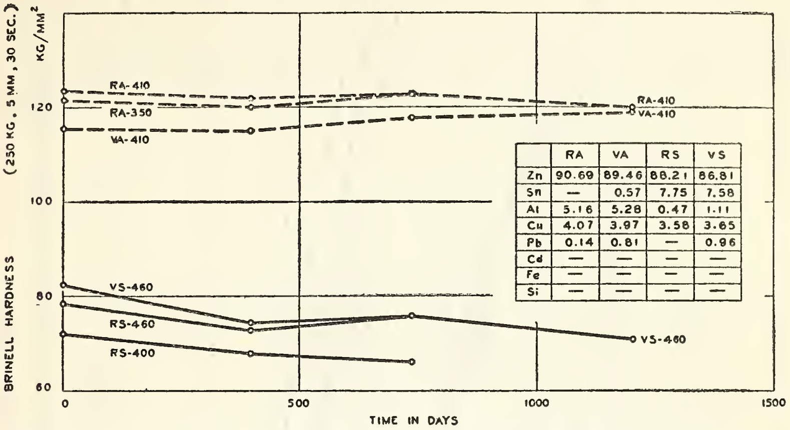
	No. 1	No. 5A	No. 5B	No. 898
COPPER	2.8 %	3.0 %	3.0 %	3.0 %
ALUMINUM	0.4	5.0	4.0	4.0
TIN	6.0	—	—	—
MAGNESIUM	—	—	—	0.1
HIGH GRADE ZINC	—	—	93.0	92.9
PRIME WESTERN ZINC	90.8	92.0	—	—

FIGURE 121.—*Changes in tensile strength in zinc-base die-cast alloys upon accelerated aging in water vapor, 95° C.*

Note the difference in results obtained with alloys made from different grades of zinc, also the effect of the presence of magnesium in the alloy

One of the important facts which the results of this investigation seem to have established definitely already is the marked advantage of the use of zinc of high purity in the preparation of the zinc-base die-casting alloys. The results in Figures 118 and 120 illustrate this. Figure,121, from Colwell (1) also emphasizes this as well as the advantage to be gained by using magnesium in such alloys.

The investigation of zinc-base die-casting alloys carried out by the Deutschen Gesellschaft für Metallkunde (11), though rather limited in its scope, is of particular interest as all the tests were carried out under atmospheric condition, a period of considerably over three years being covered. Two types of alloys were used, those hardened with copper and aluminum and those containing tin and copper. The compositions are listed in Figure 122.



	RA	VA	RS	VS
Zn	90.69	89.46	88.21	86.81
Sn	—	0.57	7.75	7.58
Al	5.16	5.28	0.47	1.11
Cu	4.07	3.97	3.58	3.65
Pb	0.14	0.81	—	0.96
Cd	—	—	—	—
Fe	—	—	—	—
Si	—	—	—	—

FIGURE 122.—*Change in hardness of die-cast alloys on being allowed to age normally indoors for a period of over three years*

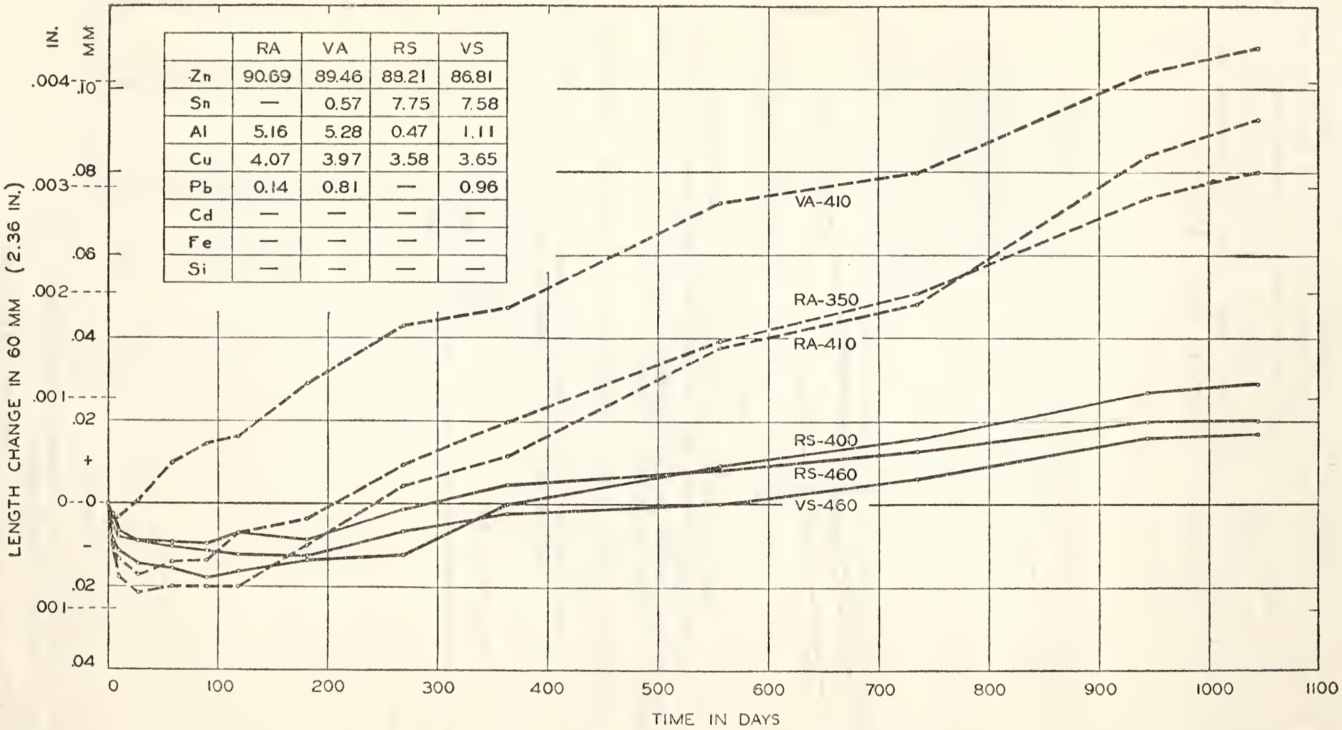
The numbers (410 —) indicate the temperature from which the alloys were cast. See Table 66 for designation of the alloys and conditions of testing.

The initial properties of the cast alloys are given in Table 66.

TABLE 66.—*Mechanical properties of die-cast alloys used in tests conducted by Deutschen Gesellschaft für Metallkunde*

Designation of alloy [1]	Casting temperature	Transverse strength[2]	Resistance to impact	Hardness [3]
	° *C.*	*kg/mm* [2]	*kg cm/cm* [2]	
RS	400	[4] 21.9 [5] 41.8 [6] [7] 32.1	19.1 72.6 51.2	66.2 78.7 [8] 72.0
RS	460	37.2 41.4 39.0	19.7 73.4 55.3	65.5 82.2 78.5
VS	460	32.5 41.2 38.0	35.9 70.6 53.9	74.7 88.8 82.4
RA	350	50.5 62.4 54.7	29.8 73.5 56.7	115 131 121.5
RA	410	56.6 62.6 54.7	37.1 73.8 55.4	115 133 123.6
VA	410	44.9 48.8 47.0	31.5 72.5 53.6	98.5 123 115.6

[1] See fig. 121 for compositions.
[2] Specimen, 60 by 8 by 4 mm.; distance between supports, 50 mm.
[3] 5 mm. ball, 250 kg. load, 30 seconds' duration.
[4] Minimum.
[5] Maximum. These apply to each block in each column of this table.
[6] Average.
[7] Average of 10 specimens throughout.
[8] Average of 20 specimens throughout.



	RA	VA	RS	VS
Zn	90.69	89.46	88.21	86.81
Sn	—	0.57	7.75	7.58
Al	5.16	5.28	0.47	1.11
Cu	4.07	3.97	3.58	3.65
Pb	0.14	0.81	—	0.96
Cd	—	—	—	—
Fe	—	—	—	—
Si	—	—	—	—

FIGURE 123.—*Dimensional changes in die-cast alloys on being allowed to age normally indoors for a period of over three years* (*11*)

See Table 66; compositions are given in Figure 122.

Data showing the change in the properties of these alloys upon exposure within doors during a period of three and one-fourth years are summarized in Figures 122, 123, 124, and 125.

According to Russell and his associates (9), the range of zinc-base alloys included in the investigation conducted by the British Nonferrous Metals Research Association has embraced alloys in which the various alloying elements were varied approximately as follows: Copper from 1 to 7 per cent; aluminum 0.25 to 4.50 per cent; and tin 0.25 to 22 per cent. One-half of the alloys used were of the copper-tin-zinc class in which tin content varied from 5 to 22 per cent. In a few alloys, special additions such a cadmium, lead, nickel and magnesium were used.

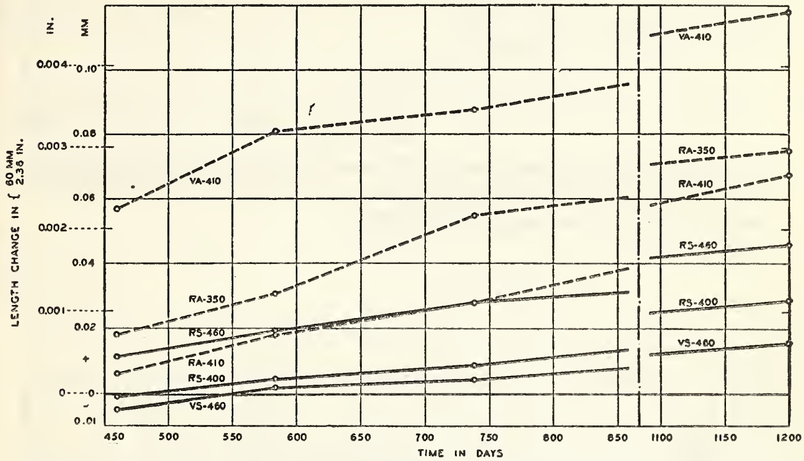


FIGURE 124.—*Dimensional changes in die-cast alloys allowed to age normally for nearly three years*

The changes during the initial aging period are shown to better advantage than in Figure 122.

Of the conclusions which have been published the most outstanding is that the form, that is, the size and shape of a die-casting, plays a very important part in the rate of "growth" of die-castings on aging. The further conclusion that "the effect of composition alone is, within fairly wide limits, comparatively small" is not in agreement with the results reported by the American Society for Testing Materials. Most of the other conclusions expressed are in good agreement in the two investigations.

The possibility of heat-treating zinc-base die-castings which contain aluminum and copper so as to accelerate and control the structural changes which normally occur on aging has been discussed by Peirce (5). As yet, however, nothing that is commercially practicable has been developed.

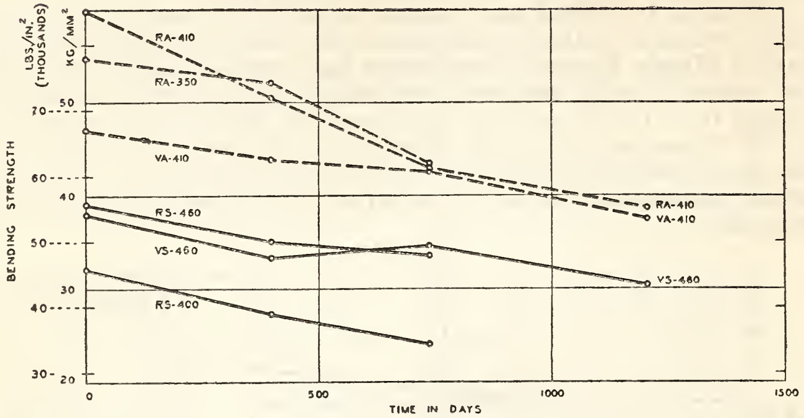


FIGURE 125.—*Changes in the transverse bending strength in die-cast alloys on being allowed to age normally indoors for a period of over three years (11)*

See Table 66; compositions are given in Figure 122.

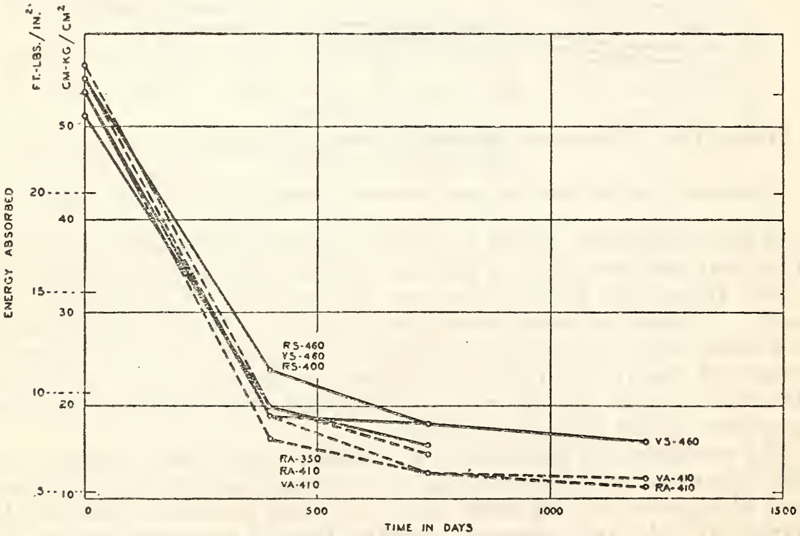


FIGURE 126.—*Changes in the impact resistance of die-cast alloys on being allowed to age normally indoors for a period of over three years (11)*

See Table 66; compositions are given in Figure 122.

TABLE 65.—*Nominal composition of representative American zinc-base die-casting alloys*

(These alloys are being used in the current investigation of the American Society for Testing Materials)

Alloy[1]	Nominal composition					Grade of zinc based on A. S. T. M. specification B6–18
	Copper	Aluminum	Magnesium	Tin	Zinc	
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	
No. XIII	5.0	0.25			Remainder (94.75)	High grade.
No. XIV	3.0	4.0			Remainder (93.0)	Do.
No. XV	3.0	4.0	0.1		Remainder (92.9)	Do.
No. XVI	3.0	4.0	.1		Remainder (92.9)	Special high grade[2]
No. XVII	3.0	3.0	.3		Remainder (93.7)	High grade.
No. XVIII	3.0	.5		6.0	Remainder (90.5)	Prime western.
No. XIX	2.0	4.0	.1		Remainder [3](93.8)	Special high grade.[2]
No. XX	3.0	4.0			Remainder (93.0)	Special grade.[4]
No. XXI	3.0	4.0	.1		Remainder (92.9)	Special high grade.[5]

[1] This identification number and the manufacturer's mark were cast on each specimen.

[2] Special grade, lead and cadmium together, permissible maximum, 0.06 per cent; tin, none; zinc, minimum 99.94 per cent.

[3] Containing nickel 0.02 per cent in addition.

[4] Slab zinc, at least 99.75 per cent zinc.

[5] Special grade, lead and cadmium together, permissible maximum, 0.02 per cent; tin, none; zinc minimum 99.98 per cent.

Die-casting alloys

Text reference	Year	Name and title
1	1930	Colwell, D. L., Development of zinc-base die-casting alloys, Am. Soc. Testing Materials, **30,** (II), pp. 473–489.
2	1930	Lancaster, R., Berry, J. G., A note on zinc-base die-casting alloys, J. Inst. Metals, **43,** pp. 241–242.
3	1930	Pack, C., Advances in die-casting metals for automotive use. Symposium on developments in automotive materials, Detroit Regional Meeting, Am. Soc. Testing Materials, **30,** (1), p. 936.
4	1930	Peirce, W. M., Metallography of zinc-base die-casting alloys. Appendix to Report of Subcommittee XV of Committee B–2, Am. Soc. Testing Materials, **30,** (1), pp. 334–335.
5	1930	——, Modern zinc base die casting, Metals & Alloys, **1,** pp. 544–546.
6	1930	Report of Committee B–2, Subcommittee XV, American Society for Testing Materials on die-cast metals and alloys, Proc, Am. Soc. Testing Materials, **30,** I, pp. 318–333.
7	1929	Pannell, B. V., Am. Soc. Testing Materials Appendix II, Rept. XV of Committee B–2, Proc. Am. Soc. Testing Materials. **29,** I, pp. 211–214.
8	1928	Curts, R. N., Zinc base die-casting alloys, Sibley J. of Engng., **42,** p. 318.
9	1928	Russell, T. F., Goodrich, W. E., Cross, W., Die-casting alloys of low melting point, J. Inst. Metals, **40,** p. 239.
10	1927	Peirce, W. M., Anderson, E. A., Zamak, the zinc-base die-casting alloy, Research Bulletin, New Jersey Zinc Co.
11	1926	Investigations on zinc-base die-casting alloys, Committee for die-casting alloys, Deut. Gesellschaft fur Metallkunde; Z. Metallkunde, **18,** pp. 359–362.
12	1925	Johnson, W. G., Growth in zinc-base die castings, Met. Ind., **23,** pp. 322–323, 362–363; J. Inst. Metals, **36,** 1926, p. 452.
13	1924	Hoffman, R., Stahl, W., The contraction and density of molten pure zinc, Metall Erz, **21,** pp. 44–45; Chem. Abst., **18,** p. 1769.
14	1923	Pack, C., A new zinc-base die-casting alloy, Met. Ind., **21,** pp. 53–54.
15	1923	Brauer, H. E., Peirce, W. M., The effect of impurities on the oxidation and swelling of zinc-aluminum alloys, Trans. Am. Inst. Mining & Met. Eng., **68,** pp. 796–826.
16	1922	Hanson, D., Gayler, M. L. V., Further study of the alloys of aluminum and zinc, J. Inst. Metals, **27,** pp. 267–294.
17	1922	Kaufmann, A., Die-cast alloys, Z. Metallkunde, **14,** pp. 8–22.
18	1920	Rosenhain, W., Houghton, J. L., Bingham, K. E., Zinc alloys with aluminum and copper, J. Inst. Metals, **23,** pp. 261–317.
19	1917	Williams, H. M., Swelling of zinc base die castings, Met. Ind., **15,** pp. 470–471; J. Am. Inst. Metals, **11,** pp. 221–224; Chem. Abst. **12,** p. 270.
20	1921	Lake, E. F., Alloys used for die casting, Iron Age, **88,** pp. 532-535

III. APPENDIX

. DIGEST OF SPECIFICATIONS

Available information on current specifications for zinc and zinc-coated steel products is summarized below.

(a) SPECIFICATIONS FOR SPELTER SOLDER (FOR BRAZING)

Specification	Designation	Grade	Copper	Lead (Maximum)	Iron (Maximum)	Zinc	Tin	Aluminum (Maximum)	Antimony (Maximum)	Arsenic	Bismuth	Remarks
			Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	
A. S. T. M.[1]	B64-28	50-50	50.00-53.00	0.50	0.10	Remainder						
		52-48	52.00-55.00	.50	.10	Remainder						
F. S. B.[2]	306 (current designation QQ-S-566)	A	49.00-52.00	.50	.10	Remainder	None [3]	0.10				Grades A and B shall be furnished in granulated form.
		B	49.00-52.00	.50	.10	Remainder	3.0-4.0					
		C	68.00-72.00	.30	.10	Remainder	None [3]					Grades C and D shall be furnished in the form of ingots, bars, or wire as may be specified.
		D	78.00-82.00	.20	.10	Remainder	None [3]					
B. E. S. A.[4]	263—1926	A	53.00-55.00	.30	.15	Remainder	(Max.) 0.05		0.05	0.05	0.05	Total of all impurities, maximum 0.50 per cent.
		B	49.00-51.00	.30	.15	Remainder	(Max.) 0.05		.05	.05	.05	
S. A. E.[5]	45		48.00-52.00	.50	.10	Remainder						Melting range, 1,560° to 1,600° F.

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[1] A. S. T. M., American Society for Testing Materials, 1315 Spruce Street, Philadelphia, Pa.
[2] F. S. B., Federal Specifications Board, Washington, D. C.
[3] As determined on a 1 g. sample.
[4] B. E. S. A., British Engineering Standards Association, 28 Victoria Street, London, S. W. 1, England.
[5] S. A. E., Society of Automotive Engineers, Handbook, 1930, p. 536; 29 West Thirty-ninth Street, New York, N. Y.

(b) SOME SPECIFICATIONS FOR ROLLED ZINC

REQUIREMENTS FOR TEMPER AND VARIATIONS IN THICKNESS

Specifications	American zinc gage	Thickness	Requirements for temper, rolled zinc [1]										Permissible variation in thickness, rolled zinc [2]				
			Type A								Type B		Type A				Type B
			Dead soft		Soft		Half hard		Hard		Dynamic ductility (minimum)	Temper (maximum)	Width				Variation by weight
			Dynamic ductility (minimum)	Temper (maximum)	Dynamic ductility (minimum)	Temper (maximum)	Dynamic ductility (minimum)	Temper (maximum)	Dynamic ductility (minimum)	Temper (maximum)			0-6 inches, inclusive	Over 6-9 inches, inclusive	Over 9-14 inches, inclusive	Over 14-20 inches, inclusive	
		Inch	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Inch* ±	*Inch* ±	*Inch* ±	*Inch* ±	*Per cent*
Rolled zinc [3]	3	0.006	0.275	70	0.255	76	0.215	80	0.165	86	0.165	83	0.0009	0.0010	0.0011	0.0012	±16
	4	.008	.280	65	.260	72	.220	75	.170	83	.170	77½	.0010	.0011	.0012	.0013	±13
	5	.010	.285	60	.265	66	.225	70	.175	80	.175	73	.0011	.0012	.0013	.0014	±10
	6	.012	.290	55½	.270	62	.230	65	.180	77	.180	69	.0011	.0012	.0013	.0014	± 9
	7	.014	.295	52	.275	58	.235	61	.185	74	.185	65	.0013	.0014	.0015	.0016	± 8
	8	.016	.300	48½	.280	54	.240	58	.190	72	.190	62	.0014	.0015	.0016	.0017	± 6
	9	.018	.305	46	.285	51	.245	54	.195	69	.195	58½	.0015	.0016	.0017	.0018	± 6
	10	.020	.310	43½	.290	48	.250	51	.200	68	.200	57	.0016	.0017	.0018	.0019	± 6
		.022	.315	41½	.295	45	.255	48	.205	65	.205	55½					
	11	.024	.320	40	.300	43	.260	45	.210	63	.210	54	.0018	.0019	.0020	.0021	± 6
		.026	.325	39	.305	40	.265	43½	.215	61	.215	52½					
	12	.028	.330	37½	.310	37	.270	42½	.220	59	.220	51	.0019	.0020	.0021	.0022	± 6
		.030	.335	37	.315	37	.275	42	.225	58	.225	49					
	13	.032	.340	36½	.320	36½	.280	41	.230	57	.230	48	.0020	.0021	.0023	.0024	± 6
		.034	.345	36	.324	36	.285	40½	.235	56	.235	47					
	14	.036	.347		.326		.290		.240		.240		.0021	.0023	.0025	.0026	± 6
		.038	.349		.328		.295		.245		.245						

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[1] 3 Types: A, Ribbon zinc and sheets or strips cut from ribbon zinc; B, sheet zinc or strips cut from sheet zinc; C, boiler plate, name plates, tags, etc. No classification for temper for type C.

[2] The requirements for type C are the same as those for either type A or type B rolled zinc, and depending upon whether the material is cut from a ribbon or sheet.

[3] American Society for Testing Materials, 1315 Spruce Street, Philadelphia, Pa. A. S. T. M. Standards, 1930, p. 588; designation B69-29.

(b) SOME SPECIFICATIONS FOR ROLLED ZINC—Continued

REQUIREMENTS FOR TEMPER AND VARIATIONS IN THICKNESS—Continued

Specifications	American zinc gage	Thickness	Requirements for temper, rolled zinc										Permissible variation in thickness, rolled zinc				
			Type A								Type B		Type A				Type B
			Dead soft		Soft		Half hard		Hard				Width				
			Dynamic ductility (minimum)	Temper (maximum)	Dynamic ductility (minimum)	Temper (maximum)	Dynamic ductility (minimum)	Temper (maximum)	Dynamic ductility (minimum)	Temper (maximum)	Dynamic ductility (minimum)	Temper (maximum)	0–6 inches, inclusive	Over 6–9 inches, inclusive	Over 9–14 inches, inclusive	Over 14–20 inches, inclusive	Variation by weight
		Inch	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Inch* ±	*Inch* ±	*Inch* ±	*Inch* ±	*Per cent*
Rolled zinc	15	0.040	0.350		0.329		0.300		0.250		0.250		0.0022	0.0024	0.0026	0.0028	± 6
		.042	.352		.330		.300		.250		.250						
		.044	.353		.331		.305		.255		.255						
	16	.045											.0023	.0025	.0027	.0029	± 6
		.046	.354		.332		.305		.255		.255						
		.048	.355		.333		.310		.260		.260						
	17	.050	.356		.334		.310		.260		.260		.0024	.0026	.0028	.0030	± 6
	18	.055											.0025	.0027	.0029	.0031	± 6
	19	.060											.0026	.0028	.0030	.0032	± 6
	20	.070											.0027	.0029	.0031	.0033	± 6
	21	.080											.0028	.0030	.0032	.0034	± 6
	22	.090											.0029	.0031	.0033	.0035	± 6
	23	.100											.0030	.0032	.0034	.0036	± 6
	24	.125											.0032	.0033	.0035	.0037	

TOLERANCES IN DIMENSIONS

Width (in inches)	Permissible variations in width of all types of rolled zinc up to 0.100 inch thick				Permissible variations in length of plates, sheets and strips up to 20 inches wide				
	Permissible variation		Nominal of stock lengths	Required percentage by weight of stock lengths	Maximum permissible percentage by weight of short ends				
	Plus	Minus			8 to 10 feet	6 to 8 feet	4 to 6 feet	2 to 4 feet	Under 2 feet
	Inch	*Inch*							
2 and under	0.010	0	10	60	40	30	20	10	0
Over 2 to 5, inclusive	.025	0	8	70		30	20	10	0
Over 5 to 14, inclusive	.050	0	6	80			20	10	0
Over 14	.125	0							

Specification	Chemical composition						Bending test requirements			
	Lead (maximum)	Iron (maximum)	Cadmium (maximum)	Aluminum (maximum)	Total of lead, iron and cadmium (maximum)	Zinc	Thickness		Bending test	
							From—	To—	Degrees	Radius of pin equal to—
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*		*Inch*	*Inch*		
Zinc plates, sheets and strips [2], [4]	0.80	0.04	0.75	None(5)	1.25	Remainder	0.002	0.036	180	2T.(6)
							.040	.090	120	3T.
							0.100 and over		45	0.5 inch

NOTE.—The following requirements Federal Specifications Board are the same as those of B69–29, American Society for Testing Materials: Permissible variation in thickness rolled zinc types A and B; permissible variation in width of all types of rolled zinc up to 0.100 inch thick; permissible variation in length of plates, sheets and strips up to 20 inches in width.

[2] The requirements for type C are the same as those for either type A or type B rolled zinc, and depending upon whether the material is cut from a ribbon or sheet.

[4] Federal Specifications Board, Washington, D. C. No. 531, Current designation QQ–Z–301.

[5] As determined on a 25 g. sample.

[6] T=thickness of material.

(*b*) *A. R. A. specification.*[8]—When copper-bearing sheets are specified, the base metal shall contain not less than 0.18 per cent copper.

The weight of the zinc coating shall conform to the requirements given below, the average being taken of the chemical determinations from three specimens 2¼ inches square cut from the ends and middle of the 2½ inches wide test specimen. The test specimen from which they are cut shall have been cut diagonally across the sheet, the ends terminating within 2 inches of the sides and 4 inches of the ends of the sheet. The coating on any one of the three specimens shall be at least 75 per cent of the minimum weight of coating specified below.

The weight of the zinc coating shall be determined by the basic lead acetate, hydrochloric acid-antimony-chloride, or sulphuric-permanganate method.

The minimum weight of coating specified in the table below is the total coating on both sides of a sheet 1 foot square, the numerical value of which in ounces is the same as that determined in grams from a sample 2¼ inches square.

United States standard gage No.[1]	Nominal thickness of base sheet	Weight of galvanized sheets			Minimum weight of coatings
		Minimum [2]	Nominal	Maximum [2]	
	Inch	*Oz./ft.*^{2}	*Oz./ft.*^{2}	*Oz./ft.*^{2}	*Oz./ft.*^{2}
8	0.172	106.9	112.5	118.1	1.75
9	.156	97.4	102.5	107.6	1.75
10	.141	87.9	92.5	97.1	1.75
11	.125	78.4	82.5	86.6	1.75
12	.109	68.9	72.5	76.1	1.75
13	.094	59.4	62.5	65.6	1.75
14	.078	49.9	52.5	55.1	1.75
16	.063	40.4	42.5	44.6	1.75
18	.056	33.6	34.5	35.4	1.50
20	.038	25.8	26.5	27.2	1.50
22	.031	21.9	22.5	23.1	1.50
23	.028	20.0	20.5	21.0	1.30
24	.025	18.0	18.5	19.0	1.30
25	.022	16.1	16.5	16.9	1.30
26	.019	14.1	14.5	14.9	1.10
27	.017	13.2	13.5	13.8	1.10
28	.016	12.2	12.5	12.8	1.10
30	.013	10.2	10.5	10.8	1.10

[1] The thickness may vary from the specified gage, the average being controlled by the minimum and maximum weights specified.

[2] The average weight per square foot of the galvanized sheets as determined by the weighing of lots not exceeding 6,000 pounds shall conform to these requirements, which are based on a maximum variation from the nominal weight of 5 per cent for gages 8 to 16, inclusive, and 2½ per cent for gages lighter than 16.

Any portion of the test specimen, specified above, of sheets lighter than No. 16 gage shall stand bending in any direction without flaking of the coating on either side when bent flat on itself over from thicknesses of the material, and for sheets ordered to gages 26 to 30, inclusive, when made in the form of a double lock seam.

One of each test specified shall be made from one sheet in each lot of 1,000 sheets or fraction thereof of each gage on each order. When any specimen fails to meet the requirements a retest will be allowed on two other sheets in the same lot, both of which shall meet the requirements.

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[8] American Railway Association, mechanical section.

The width shall be not less than specified, but may be up to one-fourth inch greater for sheets 48 inches wide and under and up to three-eighths inch greater for sheets over 48 inches wide.

The length shall not be less than specified, but for sheets 96 inches long and under may be up to three-fourths inch greater, to which latter figure add one-fourth inch for each 24 inches or fraction thereof above 96-inch length.

Where sheets are required accurate to size they shall be specified "to be resquared."

(c) SPECIFICATIONS FOR COMMERCIAL ZINC-COATED PRODUCTS

(1) ZINC-COATED SHEETS.—(*a*) *A. S. T. M. specification.*[1] —

Chemical requirements of base sheet	Galvanized sheet gage	Desired or ordered weight of coating					Weight of galvanized sheets, all classes[2]		Permissible tolerances in weight of sheets, plus or minus, in percentages of theoretical weights[3]		
		Class					Ounces per square foot	Pounds per square foot	All of one gage and size in shipment[9]	Single packages	Single sheets
		A[4]	B[5]	C[6]	D[7]	E[8]					
		Oz./ft.^{2}	*Oz./ft.*^{2}	*Oz./ft.*^{2}	*Oz./ft.*^{2}	*Oz./ft.*^{2}					
The only chemical requirement is that base metal containing copper shall contain 0.20 per cent minimum (ladle analysis) or 0.18 per cent (check analysis).	8	2.75	2.50	2.00	No specified coatings	No specified coatings	112.5	7.031	5.0	7.0	10.0
	9	2.75	2.50	2.00			102.5	6.406	5.0	7.0	10.0
	10	2.75	2.50	2.00			92.5	5.781	5.0	7.0	10.0
	11	2.75	2.50	2.00			82.5	5.156	5.0	7.0	10.0
	12	2.75	2.50	2.00			72.5	4.531	5.0	7.0	10.0
	13	2.75	2.50	2.00			62.5	3.906	5.0	7.0	10.0
	14	2.75	2.50	2.00			52.5	3.281	5.0	7.0	10.0
	16	2.75	2.50	2.00			42.5	2.656	5.0	7.0	10.0
	18	2.75	2.50	1.75			34.5	2.156	3.5	5.5	10.0
	20	2.75	2.50	1.75			26.5	1.656	3.5	5.5	10.0
	22	2.75	2.50	1.75			22.5	1.406	3.5	5.5	10.0
	24	-------	2.50	1.50			18.5	1.156	2.5	4.0	10.0
	26	-------	2.25	1.25			14.5	.906	2.5	4.0	10.0
	27	-------	2.00	1.25			13.5	.844	2.5	4.0	10.0
	28	-------	1.75	1.25			12.5	.781	2.5	4.0	10.0
	29	-------	1.50	1.25			11.5	.719	2.5	4.0	10.0
	30	-------	1.25	1.25			10.5	.656	2.5	4.0	10.0

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[1] American Society for Testing Materials, 1315 Spruce Street, Philadelphia, Pa., A. S. T. M. Standards, 1930, p. 288; designation, A93-27.

[2] The gage of galvanized sheets shall be determined by weight only.

[3] References are to gross weights of bundled material and to net weights of crated and boxed material. If minimum or maximum only be ordered, double tolerance is to be taken on permissible side.

[4] Class A, extra heavily coated sheets that are not intended to be formed other than by corrugation.

[5] Class B, heavily coated sheets that are not intended to be formed other than by corrugating and curving to large radii.

[6] Class C, moderately heavily coated sheets for moderate bending.

[7] Class D, ordinary coated sheets for general utility, representing material generally available in warehouse stocks. Not intended for relatively long life as classes A, B, and C or severe forming as class C.

[8] Class E, sheets having lighter, more tightly adherent coating to reduce liability of flaking in severe forming.

[9] All of one gage and size in shipment shall apply to lots of not less than 6,000 pounds.

MINIMUM WEIGHT OF COATING TEST LIMITS, OUNCES PER SQUARE FOOT

Class according to desired or ordered coating	Rejection limits by different tests					
	Average of weight tests [10]	Any one weight test	Average of triple spot test [11, 12]	Any one triple spot test	Average of minimum spot test [12, 13]	Any one minimum spot test
2.75	2.60	2.45	2.40	2.30	2.20	2.00
2.50	2.30	2.20	2.15	2.00	1.95	1.80
2.25	2.10	2.00	1.95	1.80	1.75	1.60
2.00	1.90	1.80	1.75	1.60	1.55	1.40
1.75	1.65	1.55	1.50	1.35	1.30	1.20
1.50	1.40	1.30	1.25	1.15	1.10	1.00
1.25	1.15	1.10	1.05	0.95	0.90	0.85

[10] Weight test to be preferred and shall consist of 10-sheet lot of a light gage or a 5-sheet lot of No. 16 gage or heavier. Specimens shall be weighed after thorough cleaning and again after galvanizing. Scale should be good to one-half pound.

[11] The triple spot test shall be the average of not less than ten successive tests on three 2¼-inch square pieces cut from the test sheet and shall include all such tests made.

[12] The weight of coating by the triple and minimum spot tests shall be determined by the hydrochloric acid-antimony chloride or sulphuric-permanganate method described in Standard Methods of Determining Weight of Coatings on Zinc-Coated Articles. (A. S. T. M. designation, A90.)

[13] The minimum spot test shall be that one of the triple spot test specimens bearing the lightest coating or the purchaser may select a single specimen taken from any part of the sheet 2 inches from the side and 4 inches from the end. The average shall be determined from not less than 10 successive minimum spot tests and shall include all such tests.

(2) ZINC-COATED STEEL WIRE STRAND.[14]—These specifications cover zinc-coated wire of iron or steel of such quality and purity that, when drawn and galvanized to the size of wire specified the finished strand will have the properties and characteristics specified. The strands to be composed of a multiplicity of wires and suitable for use as gage wires, messenger wires, span wires, etc.

Any grade of zinc conforming to the requirements of the Standard Specifications for Slab Zinc (Spelter) (A. S. T. M. Standards, 1930, p. 582; designation, B 6–18) may be used.

The weight of zinc coating shall be tested for quantity by a stripping test only and for uniformity by the Preece test. These tests shall be in accordance with the Standard Methods of Testing Zinc Coated (Galvanized) Iron and Steel Wire and Wire Products (A. S. T. M. Standards, 1930, p. 409; designation, A110) of the American Society for Testing Materials.

The weight and uniformity of the coatings of the various sizes of wire composing the strand shall be specified by the purchaser and in accordance with weights and dips as follow:

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[14] American Society for Testing Materials, 1315 Spruce Street, Philadelphia, Pa. A. S. T. M. Standards, 1930, p. 311; designation, A122–30.

ZINC-COATED STEEL WIRE STRAND

Nominal diameter of wire in the strand (in in.)	"Galvanized" common			"Extra double galvanized," common, Siemens-Martin, high strength, and extra high strength				
	Weight 5, dip 3	Weight 3.5, dip 2	Weight 1.5, dip 1	Weight 9, dip 4	Weight 8, dip 4	Weight 7, dip 3	Weight 6, dip 3	Weight 5, dip 2.5
0.207	X	—	—	X	—	—	—	—
.188	X	—	—	X	—	—	—	—
.165	X	—	—	—	X	—	—	—
.145	X	—	—	—	X	—	—	—
.125	—	X	—	—	X	—	—	—
.104	—	X	—	—	X	—	—	—
.093	—	X	—	—	—	X	—	—
.080	—	X	—	—	—	—	X	—
.072	—	—	X	—	—	—	X	—
.062	—	—	X	—	—	—	X	—
.052	—	—	X	—	—	—	—	X
.041	—	—	X	—	—	—	—	X

NOTE.—Sizes in which any given weight of coating may be regularly obtained on the open market are indicated by an "x" opposite the nominal diameter in the above table. For intermediate sizes of wire in the strand the weight and dip designations are the same as for the next finer size shown in the above table.

PHYSICAL PROPERTIES AND PERMISSIBLE VARIATIONS IN DIAMETER OF ZINC-COATED STEEL WIRE STRAND

Nominal or approximate diameter of the strand	Number of wires in strand	Nominal diameter of the wires in strand	Approximate weight of strand per 1,000 ft.	Minimum breaking strength				Diameter of wire	
				Common	Siemens-Martin	High strength	Extra high strength	Maximum	Minimum
Inches		*Inch*	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Inch*	*Inch*
⅛	7	0.041	31.8	540	910	1,330	1,830	0.043	0.039
5/32	7	.052	51.3	870	1,470	2,140	2,940	.054	.049
3/16	7	.062	72.9	1,150	1,900	2,850	3,990	.065	.059
7/32	7	.072	98.3	1,540	2,560	3,850	5,400	.075	.069
¼	7	.080	121	1,900	3,150	4,750	6,650	.083	.077
9/32	7	.093	164	2,570	4,250	6,400	8,950	.097	.089
5/16	7	.104	205	3,200	5,350	8,000	11,200	.108	.100
⅜	7	.120	273	4,250	6,950	10,800	15,400	.125	.115
7/16	7	.145	399	5,700	9,350	14,500	20,800	.151	.139
½	7	.165	517	7,400	12,100	18,800	26,900	.171	.159
½	19	.100	504	7,620	12,700	19,100	26,700	.104	.096
9/16	7	.188	671	9,600	15,700	24,500	35,000	.194	.182
9/16	19	.113	637	9,640	16,100	24,100	33,700	.118	.108
⅝	7	.207	813	11,600	19,100	29,600	42,400	.213	.201
⅝	19	.125	796	11,000	18,100	28,100	40,200	.130	.120
¾	19	.150	1,155	16,000	26,200	40,800	58,300	.156	.144
⅞	19	.177	1,581	21,900	35,900	55,800	79,700	.183	.171
1	19	.200	2,073	28,700	47,000	73,200	104,500	.206	.194
1	37	.143	2,057	28,300	46,200	71,900	102,700	.149	.137
1⅛	37	.161	2,691	36,000	58,900	91,600	130,800	.167	.155
1¼	37	.179	3,248	44,600	73,000	113,600	162,200	.185	.173

(3) ZINC COATINGS ON STRUCTURAL STEEL SHAPES, PLATES, AND BARS AND THEIR PRODUCTS.[15]—The slab zinc shall conform to the requirements of the Standard Specifications for Slab Zinc Spelter (A. S. T. M. Standards, 1930, p. 582; designation: B6) of the American Society for Testing Materials, and shall be at least equal to the grade designated as "prime western." The lead or iron in the bath

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[15] American Society for Testing Materials, 1315 Spruce Street, Philadelphia, Pa. A. S. T. M. Standards, 1930, p. 284; designation: A123-3.

during actual galvanizing operations shall not exceed the limits allowed for "prime western" slab zinc (spelter) namely, lead 1.60 per cent, and iron 0.08 per cent. The aluminum content shall not exceed 0.01 per cent.

The weight of zinc coating per square foot of actual surface shall not average less than 2.0 ounces, and no individual specimen shall show less than 1.8 ounces. The weight of zinc coating shall be determined by weighing one or more specimens after pickling and drying and again after coating, or for material manufactured without inspection the weight of coating may be determined by stripping an entire piece in accordance with the Standard Methods of Determining Weight of Coating on Zinc-Coated Articles (A. S. T. M. Standards, 1930, p. 385; designation: A90–30.

The uniformity of the zinc coating shall be determined by visual inspection. If this is not conclusive the inspector may use the Preece test as described in the Appendix to the "Standard Methods for Determining Weight of Coating on Zinc Coated Articles (A. S. T. M. Standards, 1930, p. 390; designation: A90–30.

(4) Zinc-Coated Barb Wire.[16]—Specifications cover zinc-coated barb wire, of good commercial quality of steel or iron wire of which the copper content shall be not less than 0.2 per cent, if copper is desired, in which the wire is coated before or after fabrication. Any grade of zinc conforming to the requirements of Standard Specifications for Slab Zinc (Spelter) A. S. T. M. Standards, 1930 p. 582; designation: B6–18 of the American Society for Testing Materials may be used.

The weight and uniformity of coating shall be defined and tested in accordance with the requirements of Standard Methods of Testing Zinc Coated (Galvanized) Iron and Steel Wire Products, A. S. T. M. Standards, 1930, p. 409; designation: A110–30 of the American Society for Testing Materials; and the weight and uniformity of the coating for the various gages of wire composing the barb wire shall be specified by the purchasers and in accordance with weights and dips as follows:

Zinc-coated barb wire

Size steel wire gage	Nominal diameter of strand wire	Class designation, weight 3½, dip 2
	Inch	
12	0.105	x
12½	.098	x
14	.080	x

Note.—Sizes in which any given weight of coating may be regularly obtained on the open market are indicated by an "x" opposite the gage in the above table.

(5) Zinc-Coated Chain-Link Fence Fabric Galvanized After Weaving.[17]—These specifications cover zinc-coated chain-link fence fabric of good commercial quality of steel or iron wire in which the individual pickets are helically wound and interwoven in the form of a continuous link fabric without knots or ties.

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[16] American Society for Testing Materials, 1315 Spruce Street, Philadelphia, Pa. A. S. T. M. Standards, 1930, p. 284; designation: A123-30.

[17] American Society for Testing Materials, 1315 Spruce Street, Philadelphia, Pa. A. S. T. M. Standards, 1930, p. 305; designation: A 117-30.

Any grade of zinc conforming to the requirements of Standard Specifications for Slab Zinc (Spelter), A. S. T. M. Standards, 1930, p. 582; designation: B6–18 of the American Society for Testing Materials may be used.

The weight and uniformity of the coating shall be defined and tested in accordance with the requirements of Standard Methods of Testing Zinc Coatings (Galvanized), Iron and Steel Wire and Wire Products, A. S. T. M. Standards, 1930, p. 409; designation: A110–30 of the American Society for Testing Materials; and the weight and uniformity of coating for various gages shall be specified by the purchaser and in accordance with weights and dips as follow:

Nominal diameter of wire	Size steel wire gage	Class designation, minimum weight 12, dip 4
Inch		
0.192	6	x
.148	9	x
.120	11	x

NOTE.—Sizes in which any given weight of coating may be regularly obtained in the open market are indicated by an "x" opposite the gage in the above table.

(6) ZINC-COATED IRON OR STEEL TELEPHONE AND TELEGRAPH LINE WIRE.[18]—The zinc used for coating shall be any grade of zinc conforming to the requirements of Standard Specifications for Slab Zinc (Spelter), A. S. T. M. Standards, 1930, p. 582; designation: B6–18 of the American Society for Testing Materials.

The weight and uniformity of coating shall be defined and tested in accordance with the requirements of the Standard Methods of Testing Zinc-Coated (Galvanized) Iron and Steel Wire and Wire Products, A. S. T. M. Standards, 1930; designation: A110–30 of the American Society for Testing Materials.

The weight and uniformity of the coating of the various gages of wire shall be as specified by the purchaser and in accordance with the weights and dips designated as follow:

Zinc-coated iron or steel telephone and telegraph line wire

Nominal diameter of wire	Size steel wire gage	Class designation	
		Weight 8, dip 4	Weight 7, dip 3½
Inch			
0.238	4	x	----------
.203	6	x	----------
.165	8	x	----------
.148	9	x	----------
.134	10	x	----------
.120	11	x	----------
.109	12	x	----------
.083	14	----------	x

NOTE.—Sizes in which any given weight of coating may be regularly obtained in the open market are indicated by an "x" opposite the gage in the above table.

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[18] American Society for Testing Materials, 1315 Spruce Street, Philadelphia, Pa. A. S. T. M. Standards, 1930, p. 294; designation: A 111–30.

(7) ZINC-COATED IRON OR STEEL TIE WIRES.[19]—These specifications cover galvanized soft grade of iron or steel tie wires for use in tying galvanized iron or steel telephone or telegraph line wires to insulators.

The zinc used for coating shall be any grade of zinc conforming to the requirements of Standard Specifications for Slab Zinc (Spelter), A. S. T. M. Standards, 1930, p. 582; designation: B6–18 of the American Society for Testing Materials.

The weight and uniformity of coating shall be defined and tested in accordance with the requirements of the Standard Methods of Testing Zinc-Coated (Galvanized) Iron and Steel Wire and Wire Products, A. S. T. M. Standards, 1930, p. 207; designation A110–30 of the American Society for Testing Materials.

The weight and uniformity of the coating of the various gages of wire shall be as specified by the purchaser and in accordance with the weight and dips designated as follows:

Zinc-coated iron and steel tie wires

Nominal diameter of wire	Size steel wire gage	Class desingation	
		Weight 8, dip, 4	Weight 7, dip, 3½
Inch			
0.165	8	x	
.148	9	x	
.134	10	x	
.109	12	x	
.083	14		x

NOTE.—Sizes in which any given weight of coating may be regularly obtained in the open market are indicated by an "x" opposite the gage in the above table.

(8) ZINC-COATED FARM-FIELD AND RAILROAD RIGHT-OF-WAY WIRE FENCING.[20]—The weight classification and all test procedure shall be in accordance with the Standard Methods of Testing Zinc-Coated (Galvanized) Iron and Steel Wire and Wire Products, A. S. T. M. Standards, 1930, p. 409; designation: A110–30.

It is recommended that the styles and sizes be in accordance with the Simplified Practice Recommendation No. 9 of the United States Department of Commerce.

The zinc used for coatings shall be any grade of zinc conforming to the requirements for the A. S. T. M. Specification for Slab Zinc (Spelter), A. S. T. M. Standards, 1930, p. 582; designation: B6–18 of the American Society for Testing Materials.

The base metal shall be of a good commercial quality of steel or iron wire, and, if copper is desired, its content shall conform to the following requirements:

Copper, minimum:	Per cent
Ladle analysis	0.20
Check analysis	.18

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[19] American Society for Testing Materials, 1315 Spruce Street, Philadelphia, Pa. A. S. T. M. Standards. 1930, p. 209; designation: A112–30.

[20] American Society for Testing Materials, 1315 Spruce Street, Philadelphia. A. S. T. M. Standards, 1930, p. 302; designation: A116–30.

The weight and uniformity of coating shall be specified by the purchaser and in accordance with the weights and dips designated below:

Nominal diameter of wire	Steel wire gage	Zinc-coated farm-field fence wire		Zinc-coated railroad right-of-way fence wire
		Class designation		Class designation
		Weight 5, dip 3	Weight 3½, dip 2	Weight 6, dip 4
Inch				
0.192	6	x	----------	x
.177	7	x	----------	x
.162	8	x	----------	x
.148	9	x	----------	x
.135	10	----------	x	----------
.120	11	----------	x	----------
.105	12	----------	x	----------
.098	12½	----------	x	----------

NOTE.—Sizes in which any given weight of coating may be regularly obtained in the open market are indicated by an "x" opposite the gage in above table. In special cases wire may be obtained carrying weights 6 and 5 on small gages. The size of the finished wire shall be expressed in decimal fractions of an inch and the permissible variations from the nominal diameter shall be;

	Inch
For wire, 0.109 inch or over in diameter	±0.004
For wire, under 0.109 inch in diameter	± .003

(9) WIRE ROPE.[21]—Under the heat of "galvanizing" it is specified that galvanized wires shall be uniformly and continuously coated, by "hot process galvanizing" with zinc which adheres firmly to the wire. Using the Preece test, the wire shall not show the appearance of bright, adherent copper, indicating exposed iron for the number of immersions shown below:

Diameter of wire	Number of immersions	Diameter of wire	Number of immersions
Inch		*Inch*	
0.028–0.047	1	0.064– 0.079	3
.048– .054	2	.080– .092	3½
.055– .063	2½	.093 and larger.	4

This test for the thickness of the zinc coating may be required at the option of the purchaser, and, if required, it shall be so stated in the order. For one immersion the specimen is dipped in the solution for 1 minute and then removed; for one-half immersion it is dipped for one-half minute and then removed.

(10) FENCING; WIRE (BARBED, NETTING, AND WOVEN) BLACK AND GALVANIZED.[22]—Type A: Wire, Barbed Zinc-coated.—The minimum zinc coating shall be: Weight, 3½; dip, 2. Type B: Wire, Woven, Farm or Field Fences, Zinc-coated.—The zinc coatings for the various gages of wire composing the fence shall be specified by the purchaser

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[21] Federal Specifications Board, Washington, D. C., F. S. B., No. 297; current designation: RR-R-571.
[22] Federal Specifications Board, Washington, D. C., F. S. B., No. 297; current designation: RR-F-221.

and in accordance with the weights and dips of commercially available zinc-coated fence wire designated below:

Diameter (in inches)	Weight 5, dip 3	Weight 3½, dip 2	Weight 2, dip 1	Diameter (in inches)	Weight 5, dip 3	Weight 3½, dip 2	Weight 2, dip 1
0.192	x			0.098		x	
.177	x			.091			
.162	x			.080			
.148	x			.076			
.135		x		.072			
.120		x		.062			
.105		x		.054			

Type C: Wire, Netting, Zinc-coated.—The weight and uniformity of the zinc-coating shall not be less than weight 2, dip 1. The classes of weights of coating per unit area on zinc-coated products shall be designated in accordance with the following illustration scheme:

Class designation	Weight of coating
Weight 15	Minimum of 1.5 oz./ft.^{2}
Weight 10	Minimum of 1.0 oz./ft.^{2}
Weight 6	Minimum of 0.6 oz./ft.^{2}
Weight 1	Minimum of 0.1 oz./ft.^{2}
Etc.	Etc.

(d) STANDARD METHODS OF DETERMINING WEIGHT OF COATING IN ZINC-COATED ARTICLES (CONDENSED FORM)

American Society for Testing Materials, Standards, 1930, page 385; designation: A90–30.

(1) Shop Weighing Tests.—Select a pickled and washed sheet. Stand the sheet on edge and allow to drain for two minutes. The water remaining on the sheet will then amount to approximately 0.01 lb./ft.^{2}

Weigh this sheet with an accuracy of 0.05 pound, and subtract the weight of the water to obtain the real weight of the uncoated sheet. After galvanizing, reweigh the sheet. The increase in weight represents the coating.

(2) Sampling.—(a) *Sheets.*—The laboratory samples for determining the average weight of coating upon a galvanized sheet shall be taken as follows:

A 2½-inch strip shall be cut transversely or diagonally across the middle of the sheet with its ends approximately 1 inch from each edge. Three samples, 2¼ by 2¼ inches, shall be accurately cut from the middle and the two ends of this strip. These samples shall be cleaned with gasoline or benzol, then with alcohol and dried thoroughly before proceeding with the test.

The weight of coating in grams on a 2¼ by 2¼ inch piece (5.08 square inches) is numerically equal to the coating in ounces per square foot.

(b) *Wire.*—For determining the weight of coating on zinc-coated wire, the use of a sample of a specific length is not necessary, since the density of the steel (0.283 lb./in.^{3}) is known, it is only required to determine the diameter of the stripped wire and the ratio of the weight of zinc to the weight of the stripped wire. The sample of galvanized wire may be of any length over 12 inches, but preferably about 24 inches.

(3) STRIPPING METHODS.—*Hydrochloric acid-antimony chloride method* (standard method).—

Solutions required.—Antimony chloride solution.—Dissolve 20 g of antimony trioxide or 32 g of $SbCl_3$ in 1,000 cc of HCl (specific gravity 1.19).

Hydrochloric acid.—Concentrated HCl (specific gravity 1.19).—Method.

(a) *Sheets.*—Cut three 2¼ by 2¼ inch laboratory samples, as described under "sampling," and weigh together after cleaning and drying. They should be immersed singly in 100 cc of hydrochloric acid (specific gravity 1.19) to which has been added 5 cc of antimony chloride solution, and allowed to remain therein until the evolution of hydrogen has ceased or until only a few bubbles are being evolved. This requires only about 15 to 30 seconds, except in the case of sherardized coatings which require a somewhat longer time. The same 100 cc of hydrochloric acid can be used for at least five samples, but 5 cc of the antimony chloride solution should be added before the immersion of each sample. After stripping, the samples should be washed and scrubbed under running water, dried with a towel and laid in a warm place for a short time. The samples should again be weighed together and the number of grams lost divided by the number of samples taken. Each gram then corresponds numerically to one ounce of coating per square foot.

(b) *Wire.*—The sample shall be cleaned with gasoline or benzine and dried thoroughly and then carefully weighed to 0.01 g.

The sample shall then be stripped of the zinc coating by immersing in a solution made by adding 1 cc of the antimony chloride solution to 100 cc. of the concentrated HCl.

As soon as the violent chemical action on the wire ceases, the wire shall be removed from the acid, washed thoroughly and wiped dry.

The diameter of the wire shall then be determined to 0.001 inch by taking the mean of two measurements at right angles to each other. The stripped sample shall then be weighed to 0.01 g.

Calculation.—The original weight minus the weight of the stripped sample, divided by the weight of the stripped sample, gives the ratio of zinc to iron for the sample under test. The weight of coating, in ounces per square foot of stripped wire surface, is determined by multiplying the constant 163 by the diameter in inches of the stripped wire by the above ratio. This calculation may be expressed by the following formula:

Ounces of zinc per square foot of stripped wire surface $= 163\ dr$, where $d =$ the diameter in inches of stripped wire; and

$$r = \frac{\text{original weight} - \text{stripped weight}}{\text{stripped weight}}.$$

For details concerning the alternate methods, basic lead acetate method, and sulphuric acid permanganate method the reference should be consulted.

(4) FIELD TESTS FOR DETERMINATION OF ZINC-COATED ARTICLES.—

(a) *Preece or copper-sulphate dip test.*—The samples for the Preece test may be of any size, but should be free from as much cut surface as possible, and should be carefully cleaned before starting the test. The samples are then dipped into not less than 100 cc of copper-sulphate solution maintained at a temperature of 18° C. The samples are allowed to remain exactly one minute in the solution. They are then washed in running water, and the copper deposit lightly rubbed off. Successive immersions of one minute each are continued, with the washing and cleaning of the sample between each one, until the appearance of bright adherent copper indicates that the iron beneath the coating has been exposed. Should a small amount of copper be coated adherently to the zinc coating, it must not be mistaken for the end point in which the copper plates out onto the iron. The appearance of copper within 1 inch of a cut surface is likewise not considered to be the end point of the test.

The copper-sulphate solution is prepared by dissolving 36 parts of commercial copper-sulphate crystals in 100 parts of water, then adding enough cupric oxide to neutralize any free acid. The solution is filtered or allowed to settle and decanted, then diluted with water until its specific gravity is 1.186 at 18° C. It should always be used at this temperature.

When material is tested by the Preece or copper-sulphate method, the number of 1-minute immersions which the sample shall withstand is specified.

The amount of coating removed by a 1-minute immersion in the copper-sulphate solution is roughly between 0.20 and 0.25 oz./ft.^{2} of actual surface, or double this per square foot of sheets.

This test is not as accurate in determining the average weight of coating upon a sample as is the hydrochloric acid-antimony chloride method, but is useful, however, in determining which are the thinnest portions of the coating.

Other field-test methods listed are (*a*) thermal method, (*b*) evolution of hydrogen method.

Other specifications including similar methods of determining weight of coating in zinc-coated articles are:

1. Federal Specifications Board: Hardware; Builders' (Nontemplate) F. S. B. No. 336; Current Designation FF–H–101.
2. American Railway Association, signal section: "BB, Line Wire, Double Braided Weatherproof." R. S. A. Specification 3212 (1912).
3. American Railway Association, signal section: "Galvanizing for Iron and Steel" R. S. A. Specification 2912.
4. American Railway Association, telephone and telegraph section: "General Specifications for Galvanizing for Iron and Steel." 1–D–5.
5. American Electric Railway Engineering Association: "Specification for Galvanizing and Sherardizing on Iron and Steel" (revised 1914).

2. DEFINITIONS OF PHYSICAL TERMS

Absorption index.—When monochromatic light traverses a distance equal to its own wave length, λ, in a material the ratio of the amplitude of the emergent J'_λ to that of the entering light, $J_\lambda°$, is

$$\frac{J'_\lambda}{J_\lambda^\circ}=e^{-2\pi\kappa}$$

when κ is the absorption index.

(A variety of usage prevails regarding the definition of this term. This definition is used in the Smithsonian physical tables.)

Density.—The density of a substance is the mass per unit volume. It is usually expressed in terms of grams per cubic centimeter.

Electrical conductivity and resistivity (χ, ρ).—There are two methods of expressing electrical resistivity in common use, each being defined quantitatively in terms of the resistance of a unit specimen. The volume resistivity is ρ in the equation

$$R=\frac{\rho l}{s}$$

in which R=resistance, l=length, and s=cross section. The volume resistivity thus defined may be expressed in various units, such as microhm-cm (microhm per centimeter cube), ohms per foot of a uniform wire 1 mil in diameter, etc. The commonly used units in abbreviated terminology, are:

microhm-cm.
microhm-inch.
ohm (meter, mm).
Ohm (meter, mm^2).
ohm (mil, foot).

The other kind of resistivity is mass resistivity, and is defined as δ in the equation

$$R=\frac{\delta l^2}{m}$$

in which m=mass of the wire. The usual units of mass resistivity are:

ohm (meter, gram).
ohm (mile, pound).

Per cent conductivity.—The term "conductivity" means the reciprocal of resistivity, but it is used very little in wire calculations. In connection with copper, however, extensive use is made of the per cent conductivity, which is calculated in practice by dividing the resistivity of the International Annealed Copper Standard at 20° C. (×100) by the resistivity of the sample at 20° C.

Temperature coefficient of resistance.—The temperature coefficient of electrical resistance is the fractional change of resistance per degree change of temperature. Its value varies with the temperature, and hence the temperature from which the resistance change is measured must always be stated or understood. For a temperature t_1, the temperature coefficient t_1 is defined, for a metal like copper, by

$$R_t=R_{t_1}[\mathrm{I}+\alpha_{t_1}(t-t_1)],$$

in which R_{t_1}=resistance at the temperature t_1 and R_t=resistance at any other temperature t. The temperature coefficient that is usually used at 20°, for example, is

$$\alpha_{20}=\frac{R_t-R_{20}}{R_{20}(t-20)}$$

Boiling point.—The boiling point of a liquid is the temperature at which it boils under atmospheric pressure, or better the temperature at which its vapor pressure is equal to the external pressure.

Brinell test.—An indentation is made, by pressure, on a polished plane surface of the material, by using a hardened steel ball. There are several ways of expressing the hardness:

The most common definition of the Brinell hardness is the pressure in kilograms per unit area (square millimeters) of the spherical indentation. Hardness numeral = H. N.)

$$\text{H. N.} = \frac{\text{Pressure}}{\text{area of spherical indentation}} = \frac{P}{t\pi D}$$

where

$$t = \tfrac{1}{2}\left(D - \sqrt{D^2 - d^2}\right)$$

P = pressure used,
t = depth of indentation,
D = diameter of sphere,
d = diameter of indentation.

Electrolytic solution potential (E).—At the junction of a metal and any conducting liquid there is developed an electrical potential, which is a measure of the free energy change of the chemical reaction which is possible at the surface of the metal liquid. In particular if the chemical reaction consists in the solution of the metal, forming ions, the e. m. f. is given by the formula:

$$E = \frac{RT}{nF} \log_e \frac{P}{p}$$

R = the gas constant,
T = absolute temperature,
n = valence of metal,
F = 96,500 coulombs, the Faraday constant,
P = solution pressure of metal,
p = osmotic pressure of metal ion formed in solution.

In any electrolytic cell the sum or difference of two such potentials is measured, one of which may be a standard electrode; for example, the hydrogen or the calomel electrode. The e. m. f. of an electrolytic cell of the following type: Metal-solution-normal hydrogen electrode is often called the single potential (e_h) for the metal in the solution; that is, the e. m. f. of the normal hydrogen electrode is taken as the zero of reference. These potentials are expressed in terms of the potential of the metal with respect to the solution. Thus, the normal potential of zinc/zinc ions is −0.76 volt and of copper/cupric ions is +0.34 volt.

Emissivity (E *or* E_λ).—The coefficient of emissivity E for any material represents the ratio $\frac{J'_\lambda}{J_\lambda}$ of the intensity, J'_λ, of radiation of some particular wave length or color, λ, emitted by the material at an absolute temperature T to that, J_λ, emitted by a black body radiator at the same temperature.

The coefficient of total emissivity E for any material represents that ratio $\frac{J_1}{J}$ of the intensity of radiation of all wave lengths, J_1, emitted by the material at an absolute temperature, T, to that, J, emitted by a black body radiator at the same temperature.

This coefficient is always less than 1, and for metals is equal to 1 minus the reflection coefficient for normal incidence (Kirchhoff's law).

For any optical pyrometer using monochromatic light a value of the observed or "black body" temperature of any substance (not inclosed) is reduced to the true temperature by the following formula:

$$\frac{1}{T}-\frac{1}{T_0}=\frac{\lambda \log 10 E_\lambda}{6232}$$

T = true absolute temperature,
T_0 = observed absolute temperature,
λ = wave length in microhm (0.001 mm),
E_λ = relative emissivity of substance for wave length.

Erichsen test.—This test is carried out to determine the ductility of sheets. An indentation is made in the sheet with a die with hemispherical end. The greatest depth of indentation which can be made without incipient cracking of the sheet, measured in inches or millimeters, is known as the Erichsen value for the sheet.

Heat of fusion.—The heat of fusion of a substance is the quantity of heat absorbed in the transformation of unit mass (1 g) of the solid substance to the liquid state at the same temperature.

Magnetic properties.—The usual magnetic characteristics of a substance are given either by the permeability, μ, or the susceptibility, κ. Permeability is the ratio of the magnetic induction (B: in gausses or maxwells per square centimeter) to the magnetizing force (H: in oersteds or gilberts per centimeter). This is indicated by the relation

$$\mu=\frac{B}{H}$$

Susceptibility is given, in corresponding units, by

$$\kappa=\frac{\mu-1}{4\pi}$$

For all materials except iron and a few other ferromagnetic metals μ is very nearly unity and κ is only a small decimal. When κ is negative in sign the substance is diamagnetic. The susceptibility as thus defined is sometimes called volume susceptibility and indicated by κ_v. A quantity called mass susceptibility is also used, and is equal to the volume susceptibility divided by the density of the material; it is represented by κ_m.

Meltingpoint.—The melting or fusing point of a substance is the temperature at which it fuses (under atmospheric pressure), or, more accurately, the temperature at which the solid and the liquid substance are in equilibrium with each other.

Peltier effect (π).—When at the junction of two metals current flows from one to the other, heat is, in general, absorbed or liberated (see "thermoelectromotive force" below); the coefficient, the amount of heat liberated when a unit quantity of electricity flows across the junction, is known as π (measured either in calories per coulomb, or in volts), the Peltier effect.

Refractive index.—The ratio of the velocity of light in vacuum to that in any material is called the refractive index (η) of that material. (This physical quantity ceases to have a meaning at or near an absorption band in the material.)

Scleroscope test (*Shore*).—A hardened hammer falls from a constant height onto a polished surface of the material, and the distance of rebound is measured on a scale 10 inches long, divided into 140 equal parts. The scleroscope hardness is expressed as the distance of rebound on this arbitrary scale, the value 100 representing the hardness on this scale of hardened (martensitic) steel.

Specific heat (σ).—The true specific heat of a substance is $\frac{du}{dt}$ when u is the total internal heat or energy of unit mass of the substance. The mean specific heat is defined as $\frac{q}{t_1 - t_2}$ per unit mass when q is the quantity of heat absorbed during a temperature change from t_1 to t_2. It is generally considered as the quantity of heat (calories) required to raise the temperature of unit mass (grams) by unity (degrees centigrade), either at constant volume or at constant pressure. Unless otherwise noted the specific heat of solids refers to that at constant (atmospheric) pressure. The true specific heat (constant pressure) of metals may usually be expressed sufficiently by an equation of the type

$$\sigma = A + Bt + (Ct^2 \; . \; . \; . \; . \; .)$$

Tension test.—The quantities in the tension test are the following:

The *ultimate tensile strength* is the maximum load per unit area of original cross section borne by the material.

The "*yield point*" (American Society for Testing Materials) is the load per unit of original cross section at which a marked increase in the deformation of the specimen occurs without increase of load. Without further definition, "yield point" is a vague value upon alloys of the class described in this circular. There is no true yield point comparable to that found in mild steel. In commercial testing of zinc alloys yield point is usually taken as the stress at which a given extension occurs under load, the extension being chosen so as to lie somewhere on the knee of the stress-strain curve. The extension chosen varies with the experimenter and the equipment he has available. Yield-point values cited from various sources in this circular are only roughly intercomparable because of failure of most investigators to report in sufficient detail the exact criterion chosen for yield point.

The *elastic limit* (American Society for Testing Materials) is the greatest load per unit of original cross section which does not produce a permanent set.

It is seldom determined on zinc alloys. Values given for it in the literature usually refer to some yield point well above the true elastic limit.

The *proportional limit* (American Society for Testing Materials) is the load per unit of original cross section at which the deformations cease to be directly proportional to the loads.

The *percentage elongation* is the ratio of the increase of length at rupture between arbitrary points on the specimens to the original length between these points.

The *percentage reduction of area* is the ratio of the decrease of cross section at the "neck" or most reduced section when ruptured, to the original section.

Thermal conductivity (λ).—The coefficient of thermal conductivity (λ) expresses the quantity of heat (small calories) which flows in unit time (seconds) across a unit cube (centimeter) of the material whose opposite faces differ in temperature by unity (1° C.). The mean *temperature coefficient* of thermal conductivity is expressed as

$$a_{to}=\frac{\lambda_t-\lambda_{to}}{\lambda_{to}(t-to)}$$

Thermal expansion.—If l_t is any linear dimension of a solid at any temperature, $\frac{I}{l}\frac{dl}{dt}$ is the linear thermal expansivity of that solid in the direction of I. It is not in general proportional to the temperature except approximately over small temperature intervals, but may be expressed in the following manner:

$$\frac{I}{l}\frac{dl}{dt}=a+bt+ct^2\ \ldots$$

For small temperature intervals a mean coefficient (a) is often determined; that is

$$a_{to}=\frac{l_t-l_{to}}{l_{to}(t-to)}$$

Thermoelectromotive force (E).—In an electric circuit composed of two dissimilar conductors, the two junctions being at different temperatures, there exists in general an electromotive force, called the thermoelectromotive force, between the two metals, the value of which is a function both of the temperature and the difference of temperature between the two junctions. It is shown thermodynamically that this emf is related to the Thomson and Peltier effects in the following manner:

$$\left.\begin{aligned}\pi &= \frac{T}{J}\frac{dE}{dt}\\ \sigma_1-\sigma_2 &= -\frac{T}{J}\frac{d^2E}{dt^2}\end{aligned}\right\}\text{and expressed in calories per coulomb}\quad J=\frac{418\text{ dynes}\times 10^6}{\text{calories}}$$

when E is the thermal emf, T the absolute temperature, $\frac{dE}{dt}$ the thermoelectric power (see below), and $\sigma_1-\sigma_2$ the difference in the Thomson effect of two materials. The form of the function $E=E(T)$

is not known. In general, the equation $\frac{dE}{dt} = A + BT$ satisfactorily fits the experimental data over a limited range of temperautre of a few hundred degrees.

It has been shown that the Thomson effect for lead is practically zero. This metal has served as a comparison metal in studying the thermoelectric forces of others.

Thermoelectric power.—If E is the thermoelectromotive force of any two dissimilar metals, $\frac{dE}{dt}$ = the thermoelectric power; it is at any temperature therefore approximately the thermal emf of a couple of which the temperatures of the two junctions differ by 1° C.

The Thomson effect.—When a current flows in a conductor from a point at one temperature to one at another, heat is in general liberated, or absorbed, and an emf or counter emf is produced. The coefficient of the Thomson effect is the amount of heat liberated or absorbed when unit quantity of electricity flows from a point at temperature, t, to one at a temperature, $t+dt$, and is equal to σdt calories per coulomb where σ is the so-called Thomson specific heat of electricity. It is called positive for any material when heat is generated in that material as a current flows from a region of higher to one of lower temperature.