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ADVANTAGES OF ALUMINUM AS A BUILDING MATERIAL

Aluminum made tremendous advances as a structural construction material in the last thirty years. To understand the reasons why, it is necessary to develop an appreciation for the basic fundamentals that make it so well suited for many construction applications.

The following is an item by item review of the reasons:

Non-Rusting: "Rust" is by definition iron oxide formed by oxidation of iron, or steel containing the element, iron (Fe). Since there is no iron in aluminum building products, by definition, they will never "rust". Aluminum will oxidize forming an Aluminum Oxide film on the surface.

Competition, however, tries to draw a parallel between the oxidation of steel (rusting) and the oxidation of aluminum. As a matter of fact, the oxidation action is similar, but the results are totally different. Iron oxide (rust) is very porous, allowing moisture to penetrate the film of rust and thus permitting additional rusting until over time, structural failure results. Aluminum oxide, on the other hand, is a dense, tight film covering that effectively forms a barrier to moisture, resulting in the protection of the metal underneath against further oxidation. Thus, the oxidation rate of aluminum decreases rapidly as the film builds.

An actual bare-aluminum roof installation exposed to salt air with no applied barrier coating or maintenance, had an oxide penetration of only 0.002-inch in 40 years. At this rate, it would require 200 years to penetrate 0.010-inch . . . halfway through a 0.020-inch sheet of aluminum.

Penetration Tests: Results of exposure tests for aluminum by the American Society for Testing Materials, in nine locations (including industrial, sea coast, and rural) indicated an average penetration of only 0.00002-inch per year . . . or 500 years to penetrate midway through an 0.020-inch thick sheet of aluminum.

By contrast, it is not uncommon for rust to completely penetrate 29-gage (0.014-inch) galvanized steel sheet within 8 years after the galvanizing has ceased to provide protection . . . and some new galvanized roofs exhibit the characteristic red-brown tint of rust within a week or two of application.

Surface Marking: Shearing, bundling, shipping, fabrication, and erection of any building products are bound to produce a certain amount of surface marking. It is difficult to erect galvanized roofing without scratching, chipping, breaking, or peeling off some of the galvanizing, exposing the underlying metal to moisture, which causes rust. Fastener holes in particular offer effective starting points for rust, regardless of how careful the application. Deterioration here is particularly harmful to the roofing, siding, and flashing.

Aluminum, however, being a homogeneous material, has no protective coating to come off. Any scratches that may be produced are quickly protected by the natural protective coating of aluminum oxide. Fastener holes similarly provide their own protection. Thus, holes in aluminum are not weak points for deterioration.

Corrosion of Aluminum: Competition attempts to point out that while aluminum does not "rust", it does corrode. That is true, but we need to understand the principles of the corrosion. The corrosion of aluminum is easily controlled and need never be serious. Here are some common occurrences that you may incur in this connection (See also attachment 1):

Watermarking: Pure water allowed to pond on aluminum does not produce a water spotting. However, it is an unfortunate fact that most water (even moisture condensing from the atmosphere) contains some chemicals, enough to react with aluminum, and its alloying elements, to form gray or white salts, if the water is allowed to pond on the aluminum for an appreciable length of time. These salts will mark the surface of the aluminum.

It should be emphasized that this attack is superficial, hardly being enough to mark the top layer. However, these spots or streaks may be unsightly. Such marks are easily removed by mechanically abrading the surface with a power driven wire brush or using some cleanser such as Simonize cleaner, etc. A warm caustic solution or commercial etching compounds also may be used, but acids should not be used.

Watermarking can be prevented by simply not allowing water to pond on the aluminum. Store fabricated aluminum in a place where it is protected from rain. Prevent rapid changes in atmospheric temperature that may cause condensation. If the sheets get wet, stand them on end and separate them so they may dry out. Protection in outside areas include covering sheets with breathable tarps, but not plastics or solid polyethylene.

Salt Air Attack: Aluminum will withstand exposure to the salt air encountered near seacoasts, provided an aluminum alloy is used that contains no copper. The high strength alloys such as 2024 used in aircraft contain copper, so stock of this type gave aluminum a bad name when used on coastal installations.

Today, most aluminum building products are made from alloys containing no copper, so they are not subject to this corrosion. They can be relied upon to give long life on seacoast installations, as well as elsewhere.

Industrial atmospheres contain comparatively large amounts of chemicals which will increase the tendency to watermark. Aluminum roofs and siding may develop streaks from uneven flow of water over them in such areas. These marks may be removed by suitable cleaners and further marking retarded by correct selection of treating solution. Remember that other roofing materials such as galvanized iron and steel also develop similar markings under these conditions.

Alloy content greatly influences susceptibility of aluminum to attack. Today, most aluminum building products are made from the purer alloys (3004, 3003, etc.) which are most resistant to chemical attack. When an incident of corrosion of aluminum is brought to your attention, inquire as to the alloy involved and point out the deleterious effect of high alloy contents such as those of 2024, etc., especially a high copper content. See also Attachment 2

Electrolytic Reactions: Competition says, “Care must be taken to protect aluminum against electrolytic action. The use of non-aluminum fasteners or lapping sheets of aluminum and other metals is particularly dangerous.” There are several distortions of fact in this statement.

First, let’s see what we mean by “electrolytic reactions”. Any two dissimilar metals in an electrolyte (conductive solution) sets up an electrolytic cell (electric battery). If the two metals touch each other or immersed in this solution, an electric current will flow, causing one of the metals to go into solution (be dissolved), resulting in pitting and corrosive attack.

For such electrolytic action, the two metals must possess widely differing solution potentials, they must actually contact each other, the contact points must be wet or moist, and these conditions must exist for a sufficient period of time to produce pitting.

Solution Potentials: Therefore, electrolytic action can almost never be serious where aluminum contacts galvanized iron or galvanized steel because the zinc coating has practically the same solution potential as aluminum. Likewise cadmium-plated bolts, screws, and fittings may be used in contact with aluminum, for the same reason.

Industrial and Seacoast vs. Rural Atmospheres: The higher salt content of moisture condensing from industrial and seacoast atmospheres makes such moisture a better electrical conductor, thus promoting electrolytic action.

Mechanical Contact: Since mechanical contact is necessary for electrolytic action, separating the adjoining metals afford an easy method of protection. Thus, where it is necessary for aluminum to contact black sheet iron, cover the iron with aluminum paint, zinc dust paint, or some non-metallic material such as asphalt or bituminous paint, building paper, or asbestos paper.

Immune to Most Chemicals: Aluminum is unaffected by many chemicals and acids that seriously attack galvanized steel and iron. Sulfur fumes that necessitate replacement of ordinary galvanized roofing every few months have no effect whatever on aluminum roofing which has withstood years of use in the same plant.

Alkali Attack: Aluminum is subject to attack by the free alkali in cement, plaster, and mortar where the aluminum contacts are likely to be moist for extended periods, as on wall, roof, and chimney flashing. In such applications, protect the aluminum by coating the contacting areas with asphalt or bituminous paint. No attack will occur if so protected.

From the above, it is evident that the non-rusting characteristic of aluminum is an important feature of real value. The deleterious effect of dissimilar metal contacts, oxidation, and corrosion are all relatively unimportant as they are either easily avoided or do insignificant damage.

No Painting: Competition says, “Aluminum engineers recommend that the same protection be given aluminum as that used for other materials”.

That is not true. Aluminum manufacturers advertise, sell, and recommend the use of bare untreated aluminum for all sorts of building products including roofing and siding of many different types. Painting is not necessary to protect aluminum.

Easy to Handle … Lighter Roof Loads: Competition says, “The difference in weight is not considered important in roofing”. While it may not be important to the man selling steel roofing, it is important to the warehouser, applicator, and user of roofing sheet. To say that a reduction of nearly 200 lbs. for every 100 lbs. of aluminum used is unimportant is just plain distortion of fact.

Labor involved in application is a definite and large factor in cost of a roof. The favorable difference in weight of aluminum can be important in reducing the installed cost.

Comparison of Weights: A 10’ sheet of 29-gage galvanized weighs 16-3/4 lbs. A 10’ sheet of aluminum 0.019” thick (35% thicker than the galvanized) weighs only 6-1/4 lbs. A barn roof requiring 30 squares of sheet would weigh 1.25 tons in galvanized, but only 937 lbs. in aluminum. This great weight of galvanized accounts for the sagging roofs readily found in many installations. A sagging roof distorts and leaks. To say that a lighter roof load is unimportant completely disregards the importance of leaks.

Lapping Sheets of aluminum over galvanized sheets can be done without undesired reactions because the zinc coating has approximately the same solution potential as aluminum. However, perfect guarantee against any reaction can be had simply by applying common asphalt roofing paint to one of the contacting surfaces.

COMPARISON OF DENSITIES:

Material	Density (Lb/inch^3)	
AL 3003 H16 and H14	0.0986	Used in dome panels
AL 6061 T6	0.0975	Used in dome struts
Steel A 36 & A 283	0.284	

In average Steel density is 2.9 greater than aluminum density.

Heat Reflectivity … Means Cooler Buildings: Aluminum is much superior to other metals in its ability to reflect the infra-red or heat rays of the sun. And this high reflectivity (up to 95%) is reduced only very slightly as the aluminum weathers and loses its brilliance. Remember that light reflectivity (up to 85% for aluminum) has little relation to heat reflectivity.

On the other hand, galvanized steel rapidly loses its heat reflectivity as it weathers. Here are the figures: Aluminum, 90-95% when bright; 85-94% when weathered. Galvanized steel, 92% when bright; 55-65% when weathered. Carbon steel heat reflectivity 50% new to 20% oxidize

Don’t let anyone tell you that aluminum and galvanized steel have the same reflectivity. Aluminum is far superior, especially in heat reflectivity, the factor that makes for cooler buildings. Tests have shown an aluminum roof will often reduce inside temperatures by as much as 15º F.

Emissivity: On the other hand, aluminum has lower emissivity than other metals including galvanized steel … but this is good, and here’s why:

Emissivity means heat radiating power, the ability to dissipate heat by radiation. If two solid blocks of metal, the same size, one of aluminum, the other of galvanized steel, are both heated to the same temperature and allowed to stand, the aluminum will stay hot longer because it radiates less heat.

But radiation of heat through the roof and sidewalls of a building is not the way to cool any building. It is much better to reflect the heat off the roof and prevent the building from getting hot in the first place. That's what an aluminum roof does, it prevents it from getting hot.

Fire Protection: Competition says, "Steel has an advantage over aluminum; aluminum melts at about 1220º F., steel at about 2700º F. Also, aluminum is more combustible than steel." Both statements are misleading.

Any fire that melts aluminum (1200º F. approx.) will also damage the galvanizing (or painted steel) that the galvanized steel will be worthless because the zinc coating melts at 787º F. The fact that the steel doesn't melt till 2500º F. therefore is of no importance. Once the galvanizing is gone, the steel is of no value as a building material and very little as scrap. On the other hand, damaged aluminum has a high scrap value.

During a fire in a contiguous tank is more likely that the steel roof reaches the melting point first than aluminum. The reasons for that are:

a) Reflectivity: Most of the radiation heat will be reflected by the aluminum (95% to 85%)
b) The heat conductivity for aluminum is in average 3 times larger than steel, therefore when exposed to fire it takes much longer to heat aluminum to its limit temperature than it does steel (the heat is concentrate rapidly in one spot). This property is especially important with respect to the fire safety of the roof structural frame.

Material	Heat conductivity (BTU-inch/(hr-Ft^2-^{o}F)
AL 3003 H16 and H14	1100
AL 6061 T6	1160
Steel A 36 & A 283	360

c) The specific heat of aluminum is almost twice as great as that of steel. The specific heat is the amount of heat required to raise 1 pound of metal 1 oF. Thus a pound of aluminum will absorb almost twice as much heat as a pound of steel for a given rise of temperature

Material	Specific Heat (BTU/(pound-^{o}F)
AL 3003 H16 and H14	0.213
AL 6061 T6	0.214
Steel A 36 & A 283	0.116

Combustibility of aluminum vs. steel is unimportant because neither will burn unless in finely divided powder form. Even the thinnest aluminum foil (0.00017" thick) can not be made to burn, it simply melts. See attachment 3

Strength at high temperature: Aluminum maintains at high degree of strength at high temperature. If the metal is held at 400 ^{o}F for one hour its tensile strength will drop approximately 5%. If it is held at 400 ^{o}F for 16 hours its tensile strength will drop approximately 10%. Niether of these reductions in strength will be critical to the Aluminum dome since the dead weight of the structure (approximately 3 pounds per square foot) is about 17.5 of its live load design capacity (20 pounds per square foot). It is also a fact that aluminum return to almost 100% of its original strength, this fact is not true for steel. This property is also especially important with respect to the fire safety of the roof structural frame. See attachment 4

Less Rigidity: Aluminum is more flexible than steel, having a modulus of elasticity (a measure of its rigidity) about one-third that of steel. However, aluminum sheet can be made as rigid as steel by increasing its thickness approximately 40%. But if the aluminum is embossed it is possible to obtain the same rigidity with the same thickness … offering important additional economies. The embossed pattern greatly strengthens the sheet structurally.

The owner of a building is not so much interested in elasticity figures as he is in maintenance and replacement costs. Remember too, that in cases where the span of the roof sheet or purlin spacing is a factor, as in industrial buildings, ample rigidity can easily be obtained by using more deeply corrugated sheet designs which are available. Greatly increased load-carrying ability can be had with only a small amount of added material.

Initial Cost: Many distorted pictures of the cost of aluminum vs. galvanized steel have been presented.

In the first place, equal rigidity may not be required at all. Minimum steel thicknesses are determined by rolling and galvanizing costs. In other words, a thinner steel sheet would not cost less because cost of rolling and galvanizing would more than offset the saving in reduced amount of steel. Since aluminum roofing and siding is homogeneous material, these factors do not enter and it is only necessary to use a sheet of sufficient thickness to give the actual strength required.

Many such cost comparisons disregard the economies possible from use of aluminum, its light weight and ease of application, substantially reducing erection costs; its immunity to rust assuring longer life and less maintenance; the complete elimination of any need for painting or repainting, etc. So watch the initial cost comparisons.

Quiet . . . No Excessive Noise From Wind, Rain, Etc.: Aluminum is acoustically dead material; that is, it tends to deaden sound waves and not transmit them as freely as other metals. The net result is that a building covered with aluminum roofing and siding is noticeably quieter than one covered with other metallic materials.

Finally, aluminum has been in the building construction market place for many years now. New paint coatings and surfaces have added aesthetics to a substrate that only needed these coatings and surfaces for good looks, not protection from the elements.

ADVANTAGES OF ALUMINUM AS A BUILDING MATERIAL

ATTACHMENT 1

CORROSION IN ALUMINUM

SOLVING REFINERY CORROSION PROBLEMS WITH ALUMINUM

BY

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Aluminum heat exchanger tubes are being used in the production of gasoline from natural gas. Natural gas compressor intercoolers and aftercoolers have been tubed with aluminum and have been in continuous operation for more than 9 years. Depropanizer and debutanizer overhead condensers with aluminum alloy tubes also are proving very successful. Lean oil-rich oil heat exchangers having aluminum tube bundles are being substituted for steel, both because of their lower initial cost and because of excellent resistance to hydrogen sulfide contamination. The temperature of operation of lean oil-rich oil coolers is about 475° F. A number of these units have been operating satisfactorily at this temperature with aluminum tubes rolled directly into steel tube sheets. Generally, however, the use of aluminum tube sheets, rather than steel, would be recommended where temperatures above 250° F are encountered. This eliminates possible loosening of the tubes from differential thermal expansion when the temperature fluctuates widely.

The percentage of sulfur-laden (sour) crudes and products to be handled is increasing. Because of their special resistance to these corrosives, aluminum tubes have been used successfully in the desulfurization of gaseous and liquid hydrocarbons. Various aqueous amine and glycol amine solutions are common absorbents used in desulfurization as well as carbon dioxide removal. Gas coolers, solution coolers, lean-rich exchangers, towers, and tower packing used in conjunction with amine strippers employ aluminum because of its excellent resistance to corrosion by hydrogen sulfide and carbon dioxide.

Extended surface aluminum tubes used for cooling hydrocarbon fractions and jacket water in a petroleum refinery.

The success of aluminum tubes in many oil refineries, gasoline plants, and chemical installations has been primarily the result of the outstanding performance of alclad aluminum tubes with fresh, salt, and brackish cooling waters. No failures attributable to the cooling water (either fresh or salt water) have yet been observed where alclad tubes have been employed, either in service installations or in experimental units. In the case of fresh water, one installation has been in service 17 years, while in salt water nearly 10 years have elapsed since installation. There is considerable interest in utilization of aluminum heat exchangers, pipe and evaporation equipment for saline water conversion plants. Installations on the Texas Gulf and Atlantic coasts, where heavy industrial contamination exists, bear testimony to the excellent resistance of alclad aluminum heat exchanger tubes to these waters. Although alclad tubes are generally recommended in preference to nonclad tubes, especially when there is no service experience or where complete analysis of the water being used is lacking, nonclad alloy tubes are being used with cooling waters where it has been determined that the waters being handled are not corrosive to the alloy. When nonclad tubes are used, it must be established that the cooling water is free of traces of compounds of metals such as copper, lead, tin, etc.

Aluminum alloy tube sheets generally are recommended for use with aluminum tubes. With cooling waters having a chloride content less than approximately 50 ppm, aluminum tubes have been used successfully with mild steel tube sheets. If subsequent inspection reveals galvanic corrosion, aluminum anodes or zinc bolted or sprayed on the the water-side face of the tube sheet can effectively reduce galvanic attack. In many instances, organic coatings may be used to protect steel tube sheets.

TANKAGE, PIPING AND EQUIPMENT

TANKAGE AND PIPING

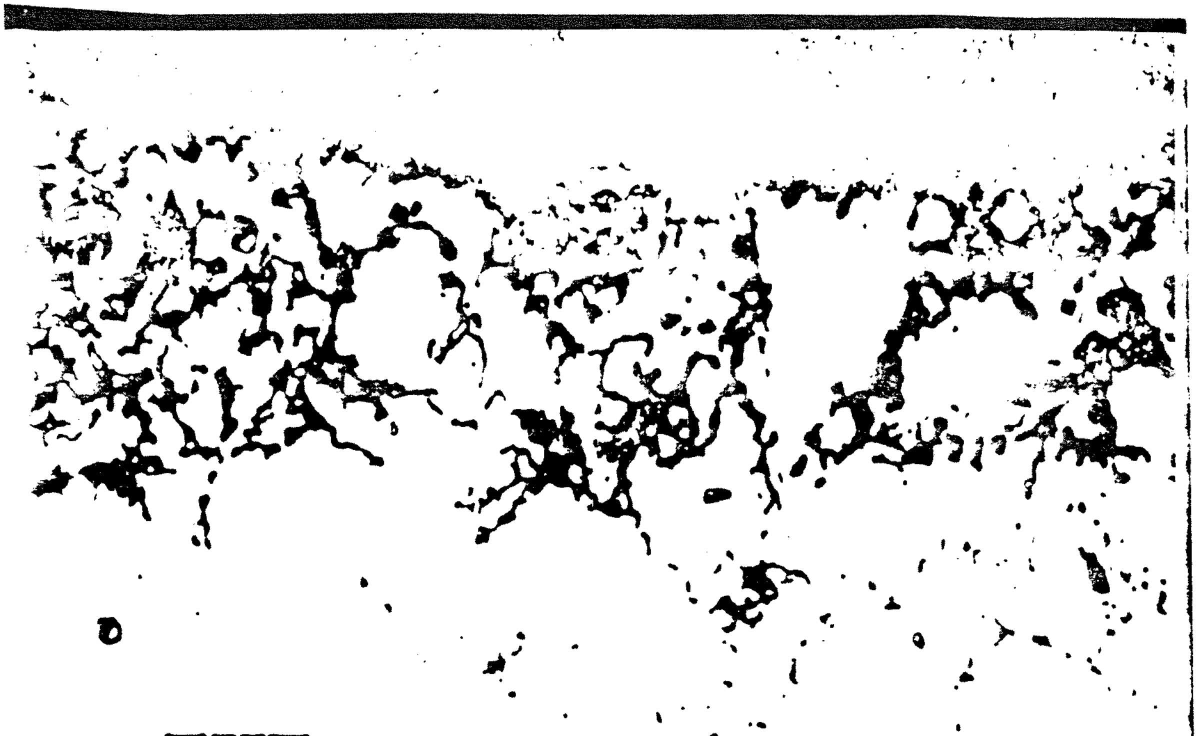
Aluminum storage tank roofs for sour crude oils have been in service for more than 20 years in locations where steel roofs failed in less than 5 years. At present, there are several hundred aluminum tank roofs in service. Particular interest in all-aluminum tankage exists among chemical producers and in the petrochemical departments of oil companies. Typical commodities handled are given in Table I. In most environments, external painting is not required to protect aluminum tanks. American Petroleum Institute Tentative Standard 12G entitled, "Welded Aluminum Alloy Storage Tanks" contains information on the design and fabrication of aluminum tanks.

TABLE I

RELATED ALUMINUM APPLICATIONS IN THE CHEMICAL AND PETROCHEMICAL INDUSTRIES

Aluminum alloys have been used successfully in the processing and handling of the following commodities:

- Acetaldehyde
- Acetanilide
- Acetic Acid
- Acetic Anhydride
- Acetone
- Acrylic Acid, Glacial
- Acrylonitrile
- Aerosol Propellants
- Alcohols – methyl, ethyl, propyl and higher
- Amines
- Ammonia Gas and Solutions
- Ammonium Nitrate and Ammoniated Ammonium Nitrate
- Amyl Mercaptan
- Asphalt
- Benzaldehyde and Benzyl Alcohol
- Benzene
- Butyric Acid and Anhydride
- Carbon Dioxide Gas and Solutions
- Creosote
- Crude Oils
- Diethanolamine
- Dimethyl Formamide
- Essential Oils, Edible Oils, Vegetable Oils
- Ethyl Benzene
- Ethylene
- Explosives
- Fats, all types
- Fatty Acids – oleic, palmitic, stearic, etc.
- Formaldehyde
- Gases as Butane, Propane, etc.
- Glycerine
- Glycols – ethylene, propylene
- Hexane
- Hydrocyanic Acid
- Hydrogen
- Hydrogen Peroxide
- Hydrogen Sulfide
- Ketones
- Latex and Ammoniated Latex Solutions
- Lube Oils
- Methane
- Methyl Ethyl Ketone
- Mineral Spirits
- Mixed Acids
- Monoethanolamine
- Naphthalene
- Naphtha, Solvent
- Naphthenic Acids
- Naval Stores – rosins, turpentine
- Nitric Acid, Concentrated
- Nitroparaffins, crude and refined
- Orthodichlorobenzene
- Oxygen, Nitrogen, and Liquid Air
- Paraffin
- Phenol
- Phthalic Anhydride
- Polyethylene
- Polypropylene
- Resins, Synthetic
- Styrene, Monomer & Polymer
- Sulfur
- Tar and Tar Products
- Thinners, Paint
- Toluene
- Trichlorobenzene
- Urea
- Waxes – petroleum, tar
- Water – distilled, fresh, brackish, sea



THE CORROSION OF LIGHT METALS

Hugh P. Godard W. B. Jepson
M. R. Bothwell Robert L. Kane

1

THE SURFACE OXIDE FILM ON ALUMINUM

1.1 INTRODUCTION

It is appropriate to introduce a treatise on the corrosion behavior of aluminum with a discussion of the surface film of aluminum oxide, for it is the properties of this film that provide aluminum with its resistance to corrosion.

When a fresh aluminum surface is created and exposed to air, it oxidizes rapidly, and acquires a compact, adherent, protective film of aluminum oxide (commonly termed *alumina*) which tends to resist further oxidation. On a freshly rolled aluminum sheet the film is extremely thin —about 25 Å (0.0000001 in.). Aluminum oxide is relatively inert chemically, and it is on this inactivity that the good corrosion resistance of aluminum depends. When the oxide film dissolves, as it does in the presence of certain chemicals, dissolution of the metal also occurs (i.e., the metal corrodes uniformly). Alternatively, when the film is damaged under conditions that prevent normal self-healing, localized corrosion ensues. This corrosion may take the form of pitting or intergranular attack, depending on the circumstances.

It is commonly stated that the oxide film is stable over a pH range of about 4.5 to 8.5. However, the pH value alone does not determine the solubility of the film, because the presence of certain anions and cations, as well as OH^- and H^+ ions, exerts an influence [1]. For example, aluminum is rapidly attacked in sodium hydroxide solutions not far from the neutral point (pH 7), whereas it is resistant to ammonium hydroxide even at pH 13. Other exceptions include the resistance of aluminum to concentrated nitric acid at pH 1 and to glacial acetic acid at pH 5. The film, however, is dissolved in most strong acids and alkalis, and accordingly aluminum is termed an *amphoteric* metal.

been found to range in the order of 0.03 to 0.11 mpy. In a few especially severe industrial locations, somewhat higher rates have been encountered (to 0.5 mpy). In rural atmospheres, the corrosion rate is less than 0.01 mpy. The slope of the initial portion of the curve, and its height, depend on the atmosphere and the alloy, but rates for the linear portion are remarkably similar for many aluminum alloys in any one atmosphere.

Influence of Atmospheric Type

Rural. In rural atmospheres, the corrosion of aluminum is hardly detectable: less than 0.01 mpy. Even light-gage sheet (for example, 0.019 in.) will have an almost infinite life, provided mechanical damage does not occur. Experience with all alloys is generally good, including the less-resistant Al-Cu and Al-Zn-Mg-Cu alloys. The surface remains shiny for years, and gradually dulls to a soft bluish-gray color that is ultimately not recognizable as aluminum. Anodized surfaces retain their original appearance indefinitely and wind-borne dirt is easily removed with a cloth.

Marine. In marine atmospheres commercially pure metal (for example, AA-1150), Al-Mn (AA-3003, AA-3004), Al-Mg (AA-5052, AA-5083, etc.), Al-Si (AA-4043), and Al-Mg-Si (AA-6061, AA-6063, etc.) exhibit good corrosion behavior, and some are widely used for superstructures on boats and ships. The first merchant ship to be launched with an aluminum superstructure was *MS Fernplant*, built in Denmark in 1939, and still in service with no corrosion problems. In 1951, in America, *SS United States*, a 52,000-ton passenger vessel, was built with over 2200 tons of aluminum in her superstructure. In 1954 Saguenay Shipping Co. Ltd., of Montreal, placed the *Sunrip* in service. This ship was a 12,700-ton freighter (bauxite-ore carrier) with a completely unpainted aluminum superstructure (AA-5083 type plate, AA-5056 extrusions). When the *Sunrip* was examined carefully after 10 years on the high seas, no corrosion damage requiring repair had occurred [244]. Since then this vessel has been followed by three sister ships, all with unpainted aluminum superstructures. Alloys that contain more than about 0.5% copper—for example, AA-2014, AA-2017, and AA-2024—have rather poorer resistance to corrosion in marine atmospheres and require surface protection in the form of cladding or maintained paint coatings to avoid corrosion. Today hundreds of oceangoing ships have painted-aluminum superstructures. Experience indicates that it is necessary to repaint them to restore appearance about half as often as it is necessary to repaint steelwork for the same reason. In a marine atmosphere the surface of aluminum dulls to a gray color in a few years.

Resistance of Aluminum Alloys to Weathering

By C. J. WALTON, D. O. SPROWLS and J. A. NOCK, JR.

and

Resistance of Aluminum Alloys to Chemically Contaminated Atmospheres

By W. W. BINGER, R. H. WAGNER and R. H. BROWN

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Resistance of Aluminum Alloys To Weathering*

By C. J. WALTON, D. O. SPROWLS
and J. A. NOCK, JR.

Figure 1—View during construction of Alcoa Office Building, Pittsburgh, Pa., showing the pyramidal facets made by aluminum alloy panels and windows which sheath this new thirty story building. This innovation is a reflection of considerable background of experience, such as that obtained from the ornamental church steeple (foreground) composed of aluminum alloy castings (alloy 43), in service since about 1926.

Abstract

Extensive data selected from tests of many thousands of specimens of aluminum alloys, exposed in various natural atmospheres for periods as long as 20 years, are presented graphically. These data provide comprehensive coverage of the resistance to weathering of outstanding types of wrought and cast aluminum alloys, with particular emphasis on alloys used in architectural and structural applications. Effects of weathering were evaluated by measurement of change in strength and depth of attack of specimens exposed for periods up to 20 years in natural atmospheres and for as long as 52 years in actual service.

Aluminum alloys have been evaluated in a sufficient number of different types of atmospheres at widely separated geographic locations to predict with reasonable assurance the performance expected under most conditions normally encountered. The corrosion of aluminum alloys, both wrought and cast, exhibits a "self stopping" characteristic; that is, the rate of attack after an initial exposure period of about one to two years decreases to a very low value, generally to less than 0.2 mil per year. The aluminum alloys displayed high resistance to corrosion and although some differences were noted, these differences often were subordinate to other characteristics of interest, such as strength, formability, appearance and cost.

THE IMPORTANCE of information on the atmospheric weathering characteristics of aluminum alloy products is commensurate with the large tonnage of these products being used in the building and construction industries. This usage is attributable to the good resistance to corrosion of aluminum alloys complemented by other desirable characteristics, such as light weight, adequate strength and good formability. Also, the pleasing appearance of aluminum alloy products and their adaptability for various decorative coatings provide interesting architectural effects (Figure 1).

A large number of aluminum alloys is available in the form of various wrought and cast products. Alloy compositions and metallurgical treatments are selected in order to secure the best combination of properties for specific applications. Although physical properties, such as density, hardness, strength and ductility can be established with sufficient accuracy to enable the engineer to use the data in mathematical expressions concerning design, it is impracticable, if not impossible, to use such expressions with regard to the resistance to atmospheric weathering of metals and alloys. This characteristic must be stated in relative terms, because the corrosivity of atmospheric conditions varies markedly from one locality to another and even within a given area.

Laboratory tests, such as the salt spray test, may provide useful information of a comparative nature but are not adequate for predicting the actual performance in outdoor exposures. In fact, such accelerated corrosion tests have been found to exaggerate differences among alloys that are negligible as judged by actual exposure of specimens to the weather. There is no reliable laboratory test that duplicates the effects of long time atmospheric exposures.

The Aluminum Research Laboratories of Aluminum Company of America has, during the past 25 years, exposed many thousands of specimens to the atmosphere in many localities in this country and at several places outside this country. The magnitude of the coverage may be appreciated from the fact that one of the initial comprehensive investigations, started 20 years ago, involved exposure of about 25,000 individual test specimens. Tests which formed the basis of several earlier publications[1,2,3] and subsequent investigations on newer alloys are now sufficiently inclusive to demonstrate convincingly the atmospheric weathering characteristics of aluminum alloys when subjected to a wide variety of conditions, including industrial, seacoast and tropical environments. Corrosive conditions within or immediately adjacent to chemical or petro-chemical plants, etc., are unique and have been found worthy of separate consideration.[4]

★ A paper presented at the Ninth Annual Conference, National Association of Corrosion Engineers, Chicago, Ill., March 16-20, 1953.

NOTE: See page 16 for the new designations of aluminum alloy numbers used in these two articles.

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D. O. SPROWLS—Chemical Metallurgy Division, Aluminum Research Laboratories, Aluminum Company of America. He has been with the Aluminum Research Laboratories since 1936 except for five years attending Drexel Institute of Technology, where he obtained a BS in chemical engineering. His work has been associated with the evaluation of the resistance to corrosion and stress corrosion cracking of aluminum alloys, particularly in natural environments. He is a member of NACE and The American Society for Metals.

J. A. NOCK, JR.—Graduated from Pennsylvania State College in 1923 with a BS degree in Electrochemical Engineering. Since then he has been employed by Aluminum Company of America in research work, particularly in development of wrought alloys presently in use. His work has also included the development of fabricating practices and thermal treatments for aluminum alloys and he has presented a number of technical papers covering these subjects. A number of patents have been granted to him. His present position is Assistant Chief of Physical Metallurgy Division of Aluminum Research Laboratories.

Materials

This paper presents corrosion data on a variety of Alcoa wrought and cast aluminum alloys (Tables I and II), with emphasis given to those alloys commonly employed in building and architectural applications. Most of the products exposed were from routine plant production, but some laboratory fabricated lots were used also. None of the items was given any special surface treatments. The test specimens were simply solvent cleaned and exposed without benefit of any protective coatings.

Exposure Stations

The majority of the test specimens have been exposed at two basic weathering stations maintained by Alcoa: a seacost station (Figure 2) 300 feet from the Atlantic Ocean at Point Judith, Rhode Island, and an industrial atmosphere station located on the roof of the Aluminum Research Laboratories at New Kensington, Pennsylvania. Correlation of the relative corrosivity of conditions at these basic stations with those elsewhere was obtained by the exposure of duplicate sets of specimens at several auxiliary Alcoa exposure stations. In addition, specimens were exposed at Kure Beach, N. C., through the courtesy of the International Nickel Co. and at Miami Beach, Florida by arrangement with the South Florida Test Service. Cooperative tests sponsored by the American Society of Testing Materials[3] have provided valuable data on the performance of several aluminum alloys when exposed for 10 years to the atmosphere at nine weathering stations of ASTM. The location and characteristics of these exposure stations are described in Tables III and IV.

Methods of Evaluation

Weight loss measurements or average penetration of attack data based on loss in weight, although useful for metals, such as steel, zinc and copper, which undergo relatively uniform overall reduction in thickness, have been found[2] less informative for aluminum alloys. The thin protective oxide film, characteristic of aluminum alloys, limits corrosion to a relatively few points so that some, if not most of the original surface of the metal generally remains intact even after many years of weathering. Experience has shown that the most informative and practicable methods for evaluating the effect of weathering are by

a) changes in tensile strength and
b) determination of actual depth of attack.

The former method is a more sensitive criterion because it selects the cross section that has weathered to the greatest degree. The latter method provides a more realistic measure of the rate of penetration. Both methods have engineering significance.

All tensile tests reported herein were conducted using standard ASTM tension specimens.[5] Wrought alloys were commonly exposed to the weather as machined tension specimens, usually 0.064-inch thick.

TABLE I

Composition and Typical Tensile Properties of Wrought Aluminum Alloys Under Discussion

ALLOY	NOMINAL COMPOSITION—Percent						TYPICAL TENSILE PROPERTIES[4]				
										Elongation—% in 2"	
	Cu	Si	Mn	Mg	Zn	Cr	Temper	Tensile Strength PSI	Yield Strength (Offset = 0.2%) PSI	Sheet Specimen 0.064" Thick	Round Specimen 0.50" Dia.
2S		99.0% Minimum Aluminum					H14	17500	16000	9	20
3S	....	....	1.2	....	....	....	H14	21500	19000	8	16
Alclad 3S[1]	....	....	1.2	....	....	....	H14	21500	19000	8	16
4S	....	....	1.2	1.0	....	....	H34	34000	27000	9	12
Alclad 4S[1]	....	....	1.2	1.0	....	....	H34	34000	27000	9	12
50S	....	....	....	1.4	....	....	H34	27500	24000	8	....
52S	....	....	....	2.5	....	0.25	H34	37000	31000	10	14
A54S	....	....	....	3.5	....	0.25	H34	40000	33000	13	....
53S	....	0.7	....	1.3	....	0.25	T6	37000	32000	....	13
61S	0.25	0.6	....	1.0	....	0.25	T6	45000	40000	12	17
62S	0.25	0.6	....	1.0	....	....	T6	45000	40000	....	17
63S	....	0.4	....	0.7	....	....	T5	27000	21000	12	....
Alclad 14S[3]	4.4	0.8	0.8	0.4	....	....	T6	68000	60000	11	....
Alclad 17S[2]	4.0	....	0.5	0.5	....	....	T3	56000	33000	18	....
Alclad 24S[2]	4.5	....	0.6	1.5	....	....	T3	64000	44000	18	....
Alclad 75S[1]	1.6	....	....	2.5	5.6	0.3	T6	76000	67000	11	....

[1] Alclad coating is alloy 72S (1% zinc).
[2] Alclad coating is high purity aluminum.
[3] Alclad coating is alloy 53S.
[4] "Alcoa Aluminum and Its Alloys," Aluminum Company of America, 1950.

In some cases, panels were exposed and tension specimens were machined from them after different periods of weathering. Casting alloys were evaluated in the form of round tension bars: 0.500-inch in diameter for sand castings and 0.250-inch in diameter for die castings. The effect of weathering on the strength of all materials was established by comparing the tensile strengths—based on the original cross sectional areas—of the exposed specimens with those of storage specimens tested concurrently.

Depth of attack was determined metallographically. Several cross sections including the most conspicuous areas of attack were polished and the depth of attack measured (X100) using a microscope fitted with a Filar micrometer eye piece. For each lot of material after each exposure period, the maximum depth of attack observed was measured. In addition, a number of sites of attack were measured in order to establish the average depth of penetration. In substantially all cases, the original surface was sufficiently intact (Figure 5) to provide a reference for accurate measurement of depth of attack. It should be appreciated that this latter value is the mean of the individual sites of attack and does not integrate the large area over which no attack or insignificant attack had occurred. The penetration, as estimated from these measurements, will always be considerably greater than that calculated from weight losses.[2]

Calibration at Atmospheric Exposure Stations

The geographical location, as pointed out by Dix and Mears,[2] is often of less importance in determining the corrosivity of the environment than are other factors, such as direction of prevailing winds, type

TABLE II

Composition and Typical Tensile Properties of Aluminum Casting Alloys Under Discussion

ALLOY	NOMINAL COMPOSITION—Percent					TYPICAL TENSILE PROPERTIES[3]				
	Cu	Si	Mn	Mg	Zn	Temper	Tensile Strength PSI	Yield Strength (Offset = 0.2 %) PSI	Elongation—% In 2" Round Specimens ½" Dia.	Elongation—% In 2" Round Specimens ¼" Dia.
Sand Casting Alloys:										
43	....	5.0	....	....	....	As-cast	19000	8000	8.0	....
12	8.0	....	....	....	....	As-cast	22000	14000	2.0	....
112	7.0	....	....	....	1.7	As-cast	24000	15000	1.5	....
195	4.5	0.8	....	....	....	T4	32000	16000	8.5	....
195	4.5	0.8	....	....	....	T6	36000	24000	5.0	....
214	....	....	....	3.8	....	As-cast	25000	12000	9.0	....
B214	....	1.8	....	3.8	....	As-cast	20000	13000	2.0	....
220	....	....	....	10.0	....	T4	46000	25000	14.0	....
356	....	7.0	....	0.3	....	T6	33000	24000	3.5	....
406	....	....	2.0	....	....	As-cast	19000	9000	12.0	....
Die Casting Alloys:										
43	....	5.0	....	....	....	As-cast[2]	30000	16000	....	9.0
13	....	12.0	....	....	....	As-cast[2]	39000	21000	....	2.0
A13[1]	....	12.0	....	....	....	As-cast[2]	35000	16000	....	3.5
85	4.0	5.0	....	....	....	As-cast[2]	40000	24000	....	5.0
380	3.5	9.0	....	....	....	As-cast[2]	45000	26000	....	2.0
A380[1]	3.5	9.0	....	....	....	As-cast[2]	46000	25000	....	3.0
384	3.8	12.0	....	....	....	As-cast[2]	46000	27000	....	1.0
360	....	9.5	....	0.5	....	As-cast[2]	44000	27000	....	3.0
A360[1]	....	9.5	....	0.5	....	As-cast[2]	41000	23000	....	5.0
218	....	....	....	8.0	....	As-cast[2]	45000	27000	....	8.0

[1] Prefix "A" indicates that alloy has impurities, notably iron, controlled to closer limits.
[2] Test bars produced on a cold chamber (high-pressure) die-casting machine.
[3] "Alcoa Aluminum and Its Alloys," Aluminum Company of America, 1950.

TABLE III—Description of Various Seacoast Exposure Stations

LOCATION	Climatic Zone	Distance From Ocean or Bay	Type of Shore	Direction of Prevailing Winds	Remarks	Station Operated By
Kure Beach, N. C.	Temperate	80 ft.	Sandy	From Ocean	Sea rough, considerable salt mist.	International Nickel Co.
Pitcairn Island, British Oceania	Sub-Tropical	150 ft.	Rocky	From Ocean	Sea rough, considerable salt mist.	Alcoa
La Jolla, Cal.	Temperate	"Several hundred feet"	Rocky	From Ocean	Sea rough, frequent fogs, little rain to wash specimens.	ASTM
Point Judith, R. I.	Temperate	300 ft.	Stony	From Ocean	Sea rough, considerable salt mist and fogs.	Alcoa
Key West, Florida	Sub-Tropical	"Close to ocean"	Sandy	Across Island	Station on leeward side of island.	ASTM
Miami Beach, Fla.	Sub-Tropical	300 ft.	Sandy	From Ocean	Warm, humid without fogs.	South Florida Test Service
Sandy Hook, N. J.	Temperate	300 ft.	Sandy	From Bay	Station at tip of Hook jutting into bay.	ASTM
Oakland, Cal.	Temperate	1 mile	....	From Bay	On roof of warehouse, seasonal fogs.	Alcoa
Georgetown, British Guiana	Tropical	1.5 miles	....	From Ocean	On low building by Demerara River. Hot, humid.	Alcoa

TABLE IV—Description of Various Industrial and Inland Atmospheric Exposure Stations

LOCATION	Type of Environment	Predominant Fuel Used	Remarks	Station Operated By
New Kensington, Pa.	Industrial	Bituminous Coal	Located on roof of Aluminum Research Laboratories, exhaust from Analytical Laboratory hoods add to the severity of the atmosphere.	Alcoa
Pittsburgh, Pa.	Industrial	Bituminous Coal	Racks were on Brunot's Island, 3 miles below Golden Triangle. Exposures made before smoke control, when specimens were subjected to atmosphere highly contaminated by heavy industries.	ASTM
Altoona, Pa.	Industrial	Bituminous Coal	Racks on roof of building in the Pennsylvania Railroad yards. The atmosphere contained unusually large amounts of smoke and gases from the busy yards and shops.	ASTM
St Louis, Mo.	Industrial	Bituminous Coal	Racks on two-story building in heart of city. Exposures made before smoke control when atmosphere contained appreciable amounts of sulphur dioxide.	Alcoa
New York, N. Y.	Industrial	Oil and Anthracite Coal	Racks on roof of Bell Telephone Laboratories on West Street. Atmosphere contains much smoke and gases from fuels used in this metropolitan area.	ASTM
Edgewater, N. J.	Industrial	Oil and Anthracite Coal	Racks on roof of Alcoa plant on Hudson River, across from New York City. Specimens subjected to fumes from plant and other waste gases associated with this highly industrial area.	Alcoa
Rochester, N. Y.	Industrial	Bituminous Coal	Racks in gorge of Genesee River, below a water fall; high humidity, with waste gases from nearby factories.	ASTM
State College, Pa.	Rural	....	Clean, rural district—no industrial contamination.	ASTM
Phoenix, Arizona	Rural	....	Hot and dry; semi-arid.	ASTM

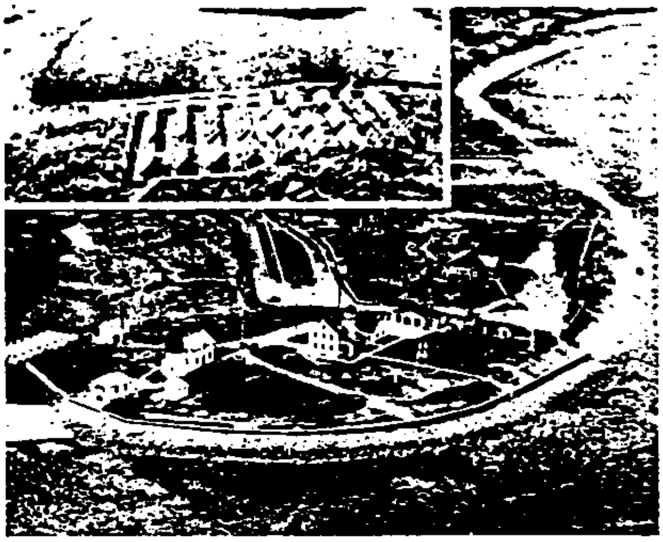

Figure 2—Aerial view and close-up (inset) of Alcoa's seacoast exposure station at Point Judith, R. I. The station is located on a stony beach about 300 feet from the water's edge and it faces the prevailing winds from the ocean. Corrosion conditions here are severe indeed. At this and all of the other Alcoa exposure stations the test specimens were inclined at an angle of 45 degrees, facing south.—(Aerial photo—courtesy of Providence [R. I.] Sunday Journal.)

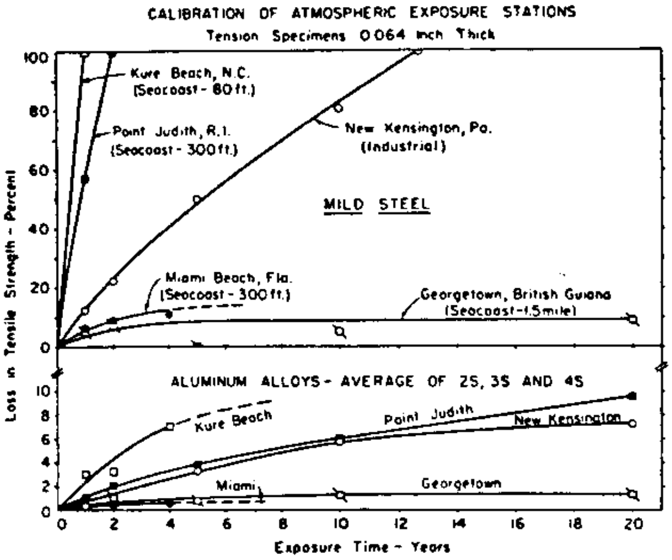

Figure 3—Graph illustrating the relative severity of several exposure stations employed by the Aluminum Research Laboratories using losses in tensile strength of 0.064-inch thick mild steel (0.09% carbon, 0.07% copper) as the criterion. The aluminum alloys (also 0.064-inch thick) rate the stations in essentially the same order as does mild steel. The corrosivity of a seacoast atmosphere varies not only with distance from the ocean, but also with other inherent location factors.

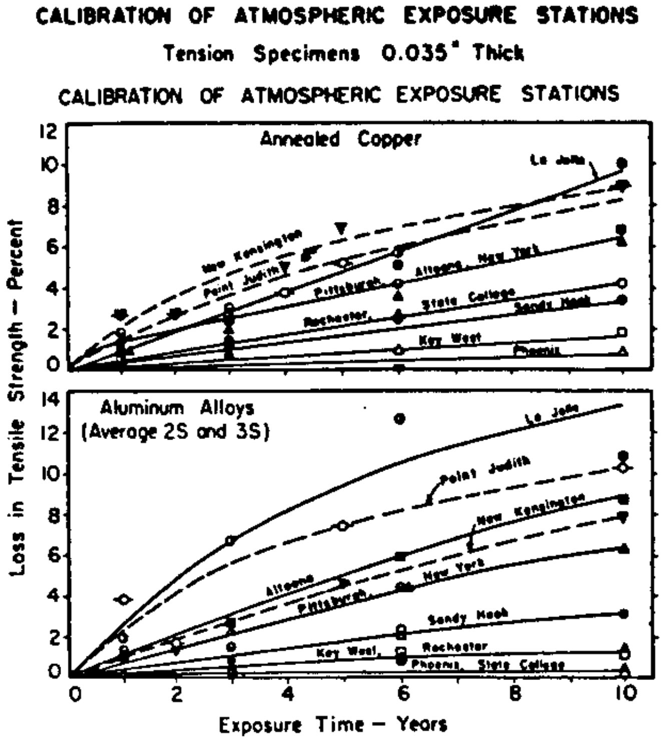

Figure 4—Data obtained on aluminum alloys and copper were used to indicate the relative severity of the atmospheric conditions at the two Alcoa exposure stations at New Kensington (industrial) and Point Judith (seacoast) and the nine different ASTM stations. This comparison was made possible, even though different thicknesses of material were employed at the Alcoa stations (0.064-inch) and the ASTM stations (0.035-inch), by the conversion of the percent losses in tensile strength for 0.064-inch thickness to the equivalent percent loss for 0.035-inch thickness. The curves representing Point Judith and New Kensington were drawn as broken lines indicating that these data were calculated.

ONE YEAR 20 YEARS

SEACOAST ATMOSPHERE—Point Judith, R. I.

ONE YEAR 20 YEARS

INDUSTRIAL ATMOSPHERE—New Kensington, Pa.

Figure 5—Micrographs of full cross sections of 0.064-inch thick sheet of alloy 3S after exposures indicated. Note that the corrosion develops at isolated spots, slowly spreads to new sites but is not appreciably deeper after 20 years than after one year. This pattern is typical for other corrosion resistant aluminum alloys, such as 4S, 52S, 61S.

of topography, frequency of precipitation and proximity to bodies of water or industrial plants. The corrosivity of the atmosphere may vary as much or more within a given geographic region than between widely separated locations. It is imperative, therefore, to calibrate the severity of the conditions at each atmospheric weathering station. Conditions at Alcoa's basic seacoast station at Point Judith, Rhode Island and the industrial atmosphere station at New Kensington, Pa. were calibrated by determining their effects on veteran metals, such as steel and copper and by comparing the corrosivity of atmospheric conditions at these stations with those at many widely scattered localities.

The relative severity of corrosive attack at the seacoast station at Point Judith and at the industrial one at New Kensington is indicated in Figures 3, 4 and 24. It is obvious that corrosive conditions at the Point Judith station, 300 feet from the ocean, are very severe indeed, being more corrosive than at most seacoast locations evaluated and almost as severe as those at Kure Beach (80-foot site) and at

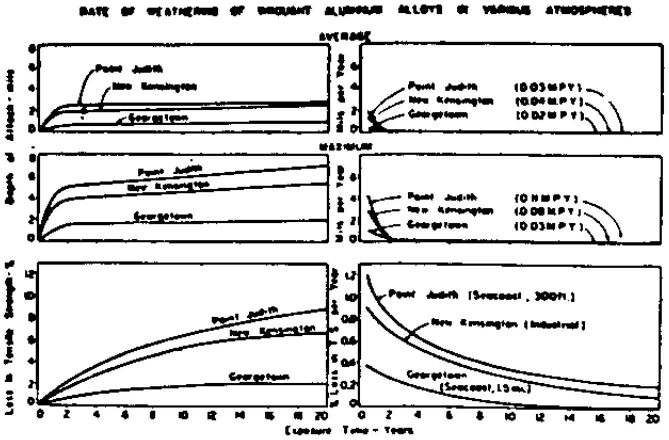

Figure 6—The rate of weathering (curves at right) based on the average performance of alloys 2S, 3S and 4S exposed at Georgetown and on the eight wrought alloys included in Figures 7 to 10 illustrate the "self-stopping" nature of the corrosion of aluminum alloys. A comparison of the abrupt reduction in rate of penetration (top) with the more gradual reduction of loss in tensile strength (bottom) indicates that although the penetration of corrosion at local sites has been stifled, corrosion is still proceeding elsewhere but at a reduced rate.

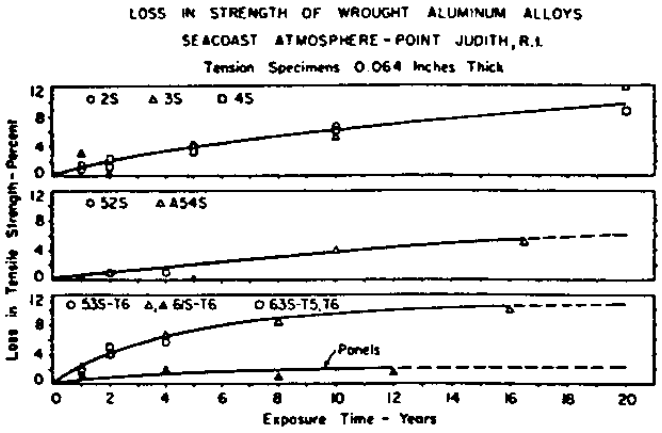

Figure 7—The curve for each family of aluminum alloys is the mean of individual curves that had been drawn for each alloy. (Curves for Figures 8, 9, 10 were drawn on same basis.) The conformity of the data to these average curves indicates that the resistance to corrosion is similar for the alloys in each group. The high resistance to this severe seacoast atmosphere is indicated by the small losses in strength in exposure periods of 16 to 20 years.

La Jolla, California. The gratifying significance of this is that data obtained at the Point Judith station can be used with confidence to indicate the expected performance of metals, especially aluminum alloys, at most seacoast environments, including island exposures. For example, an incidental opportunity resulted in exposure of various metals for four years on Pitcairn Island. Aluminum alloys were not affected any more at this location, about 150 feet from ocean, than at Point Judith.

The corrosivity of the atmosphere at New Kensington is about as severe as that at Altoona, New York and Pittsburgh (before smoke control) and generally more severe than the atmosphere at other inland areas evaluated. This suggests that data obtained from exposures at New Kensington can be used to indicate conservatively the resistance of aluminum alloys to the atmosphere in most industrialized areas and by comparison to atmospheres at substantially all non-industrial (rural, etc.) areas.

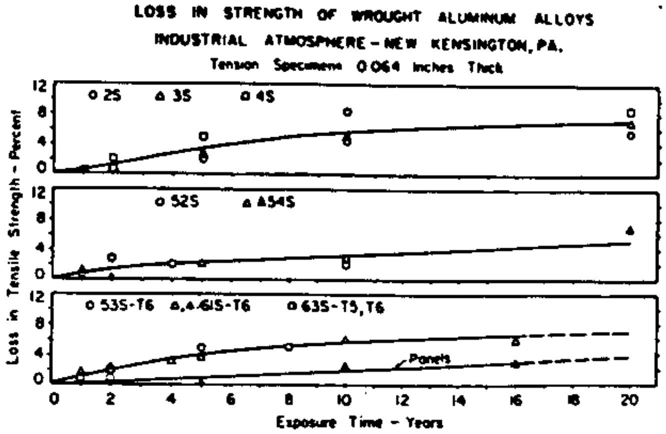

Figure 8—These average curves (determined as per Figure 7) demonstrate that exposures for as long as 20 years in a relatively severe industrial atmosphere had little effect on the structural integrity of the various aluminum alloys.

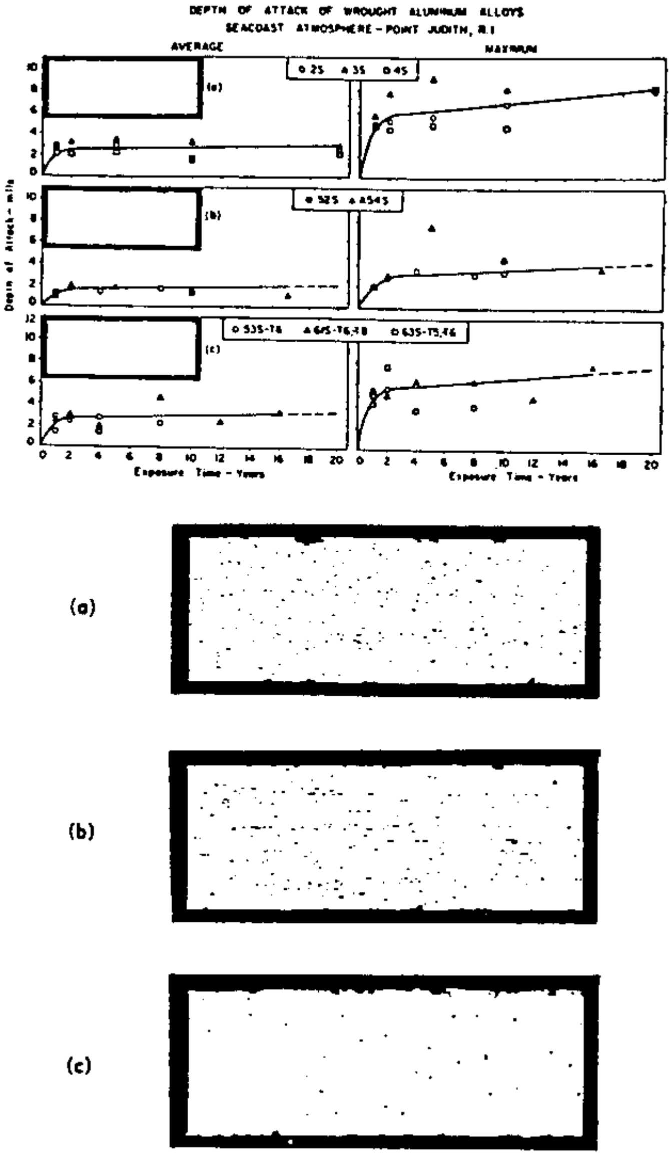

Figure 9—These average curves (determined as per Figure 7) show that corrosion of all alloys decreases with time and that the attack after as long as 20 years is shallow. Although the differences are small, the aluminum-magnesium alloys (52S, A54S) display their characteristic superiority when exposed to marine environments. Micrographs of typical cross sections of 0.064-inch thick sheet include (a) 3S at 20 years, (b) A54S at 16.5 years, (c) 61S-T6 at 16 years.

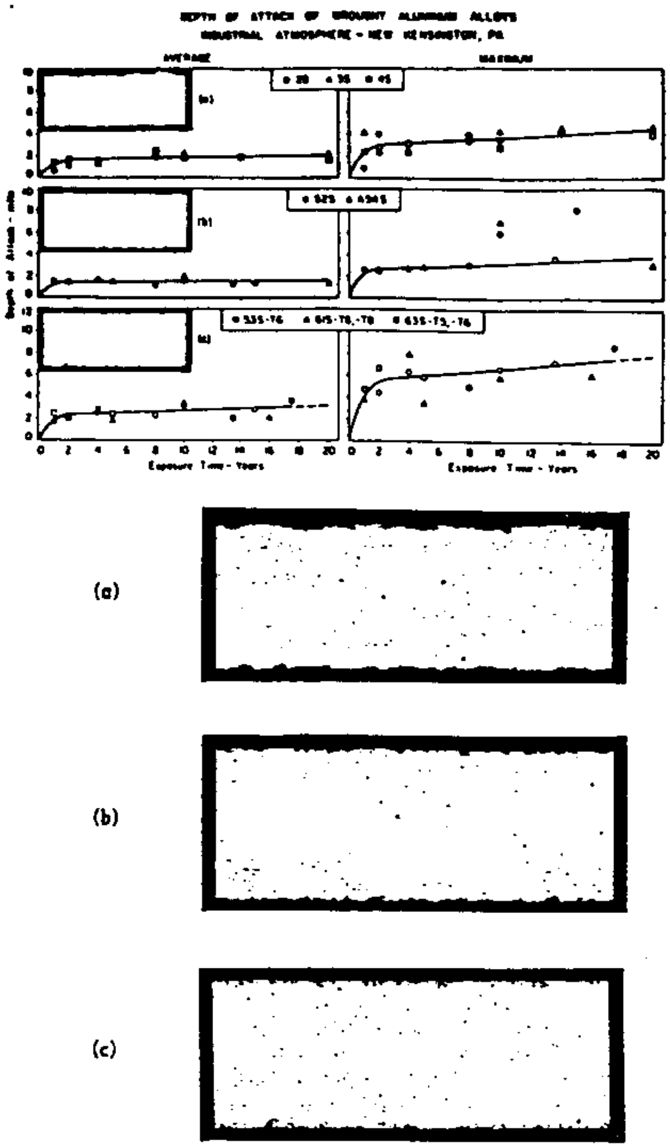

Figure 10—These average curves (determined as per Figure 7) resemble those obtained in exposures at the seacoast (Figure 9). Although the attack was more shallow in this industrial atmosphere than at the seacoast, the surface attack was more widespread as indicated by the micrographs of typical cross sections of 0.064-inch thick sheet of (a) 3S at 20 years, (b) A54S at 20 years and (c) 61S-T6 at 16 years.

Rate of Weathering

The outstanding characteristic apparent from the graphical presentation of the corrosion data (Figures 7 to 23) is that the rate of weathering for wrought aluminum alloys and for cast aluminum alloys decreases with time. This decrease in rate of attack (Figure 6) is demonstrated both by depth of attack data and by tensile test data. The decrease in rate of penetration of corrosion is the most striking. The attack penetrates, at isolated spots, at an initial rate of about 4 mils per year (Figure 6); but this rate rapidly decreases so that after one or two years the maximum rate does not exceed about 0.11 mil per year for severe seacoast conditions (Point Judith) and may be as low as 0.03 mil per year for less severe atmospheres.

The rate of weathering, as judged by changes in tensile strength (Figure 6), also decreases with time but not as sharply as it does when judged by the depth of attack. Since tensile strength is a function of the cross sectional area of the test coupon, any significant change in tensile strength reflects a decrease in cross sectional area resulting from corrosion. The differences in slopes of the curves in Figure 6 indicate that although corrosion at local sites seems to stop after one or two years' weathering, new sites of attack develop. Thus, the tendency under conditions of atmospheric weathering is for attack to proceed laterally (Figure 5) along the surface rather than to become progressively deeper. The decreased rate of attack as shown by tensile tests also indicates that corrosion over the entire surface diminishes with time. The products of corrosion form a protective film to stifle further attack.

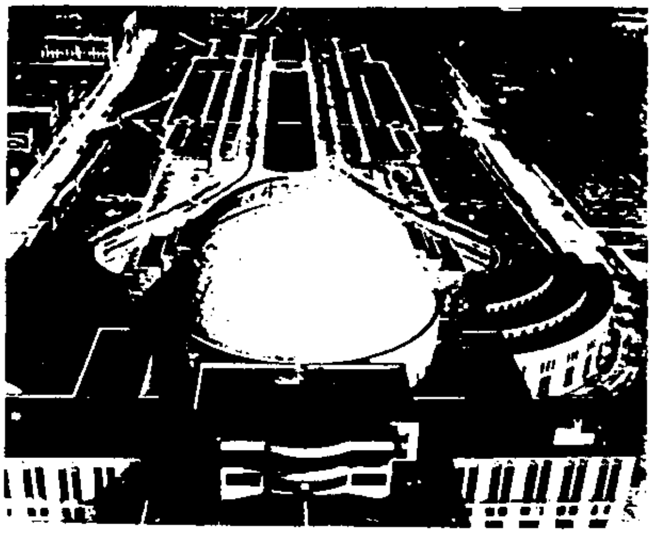

Figure 11—Aerial view of Cincinnati Union Terminal, Cincinnati, Ohio (erected in 1932), showing the large dome-shaped roof sheathed in 1946 with bare aluminum alloy 3S.

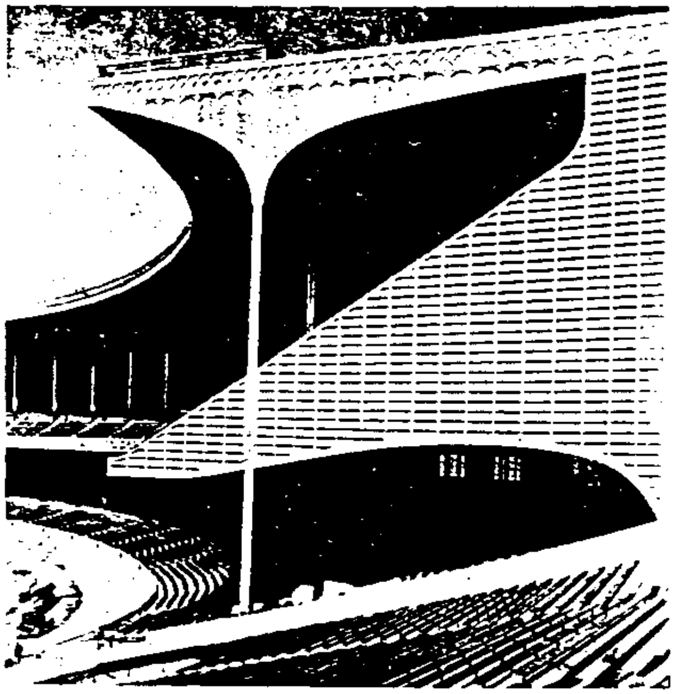

Figure 12—Municipal Stadium, Cleveland, Ohio. Erected in 1931, using 70 tons of aluminum alloys for louvers, flashing or siding, ceilings of marquee roofs and score board. In 1946, after 15 years' service, a sample of alloy 4S-H34 siding 0.032-inch thick was examined in cross section and the metal found to be in an excellent state of preservation (Figure 24).

This tendency for the corrosion of aluminum alloys to decrease to a very low rate has been observed in other environments as well as the atmosphere and has been referred to as a "self-stopping" or "self-limiting" effect. Appreciation of this desirable characteristic will dispel unnecessary concern one might otherwise have over some initial surface attack.

Wrought Aluminum Alloys

The family of wrought aluminum alloys under discussion (Table I) has a high inherent resistance to weathering. Exposures for as long as 20 years to relatively severe industrial and seacoast atmospheres have resulted in shallow attack, with corrosion proceeding at a low rate (Figure 6). These extended exposures have caused only small losses in tensile strength of 0.064-inch thick materials. Although the data were obtained primarily on sheet, other tests have shown that equally favorable results are obtained for these alloys in the form of other products, such as plate, extruded sections, rolled sections and tubes.

It is noteworthy that these aluminum alloys (Figures 7 through 10) possess a high resistance to corrosion, with only small differences existing among them. Final choice, therefore, is usually based on other requirements, such as strength, formability, weldability, appearance and economy. The various alloys are discussed in this light.

Strain Hardenable Alloys

The strength of pure aluminum and of aluminum alloys containing manganese and magnesium alone or in combination is determined by the degree of strain hardening present. In general, these alloys do not show any real difference in weathering between materials in the annealed temper and that in the strain hardened temper. In fact, the data in Figures 7 to 10 were obtained from materials in both the annealed and strain hardened tempers.

Aluminum alloys 2S, 3S and 4S have essentially the same high resistance to weathering. Alloy 3S (1.2% Mn) has been used widely in building applications because it is stronger than alloy 2S and equally formable. Alloy 4S (1.2% Mn, 1.0% Mg) is used where somewhat greater strength is required. These alloys have performed very well under service conditions (Figures 11 and 12) and are playing an important role in the modern trend toward use of corrosion resistant metals for the outer surfaces of various types of buildings (Figure 13).

Aluminum alloys with increasing amounts of magnesium, within a maximum value yet unresolved, provide a group of alloys with a resistance to corrosion at least as good as the preceding set of alloys in industrial atmospheres and with somewhat superior performance in seacoast environments. Alloy 52S (2.5% Mg, 0.25% Cr) has had wide use, therefore, in marine applications. The recently developed alloy 50S (1.4% Mg) is stronger than 3S and more easily fabricated and formed than 52S, thereby providing a compromise between these two alloys. Limited corrosion tests show that the resistance to corrosion of alloy 50S approximates that of alloys 3S and 52S. Considerable interest has been focused on

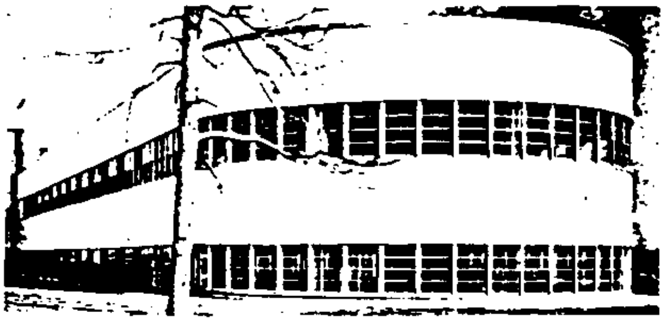

Figure 13—Laboratory of Federal Telephone and Radio Corp. Nutley, New Jersey. Easy to erect insulated panels of aluminum alloy 3S form the weathering surface of this unit erected in 1945 and for units subsequently added. Large numbers of windows of extruded aluminum alloy 63S were also employed. In this non-industrialized environment the bare aluminum alloy surfaces will slowly weather to acquire a uniform light gray patina.

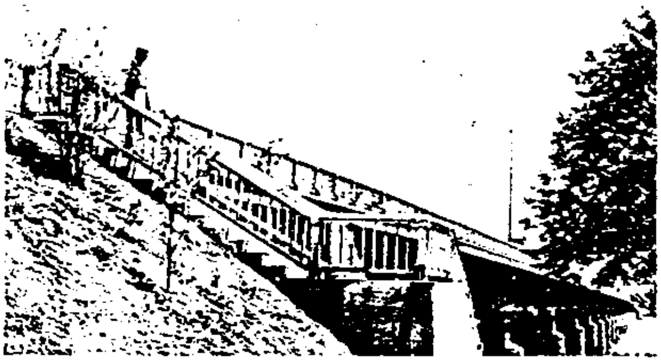

Figure 14—The M. Harvey Taylor Bridge erected over the Susquehanna River at Harrisburg, Pa. in 1952 employs more than two miles of aluminum alloy railing with integral lighting standards of aluminum alloys. The use of alloy 61S-T6 for the various components provide high strength and good resistance to weathering, thus eliminating the need for paint protection and maintenance. Sections of railing of unpainted 61S-T6 or 63S-T6 are performing very well in trials being made on the boardwalk at Atlantic City, N. J., and Virginia Beach, Va.

Figure 15—U. S. Government building at Key West, Florida, erected 1932, using windows of extruded aluminum alloy (alloy 43). The seaside conditions prevailing at Key West have had little effect on these unpainted aluminum windows. This photograph, taken in 1944, illustrates the non-staining characteristics of aluminum alloys.

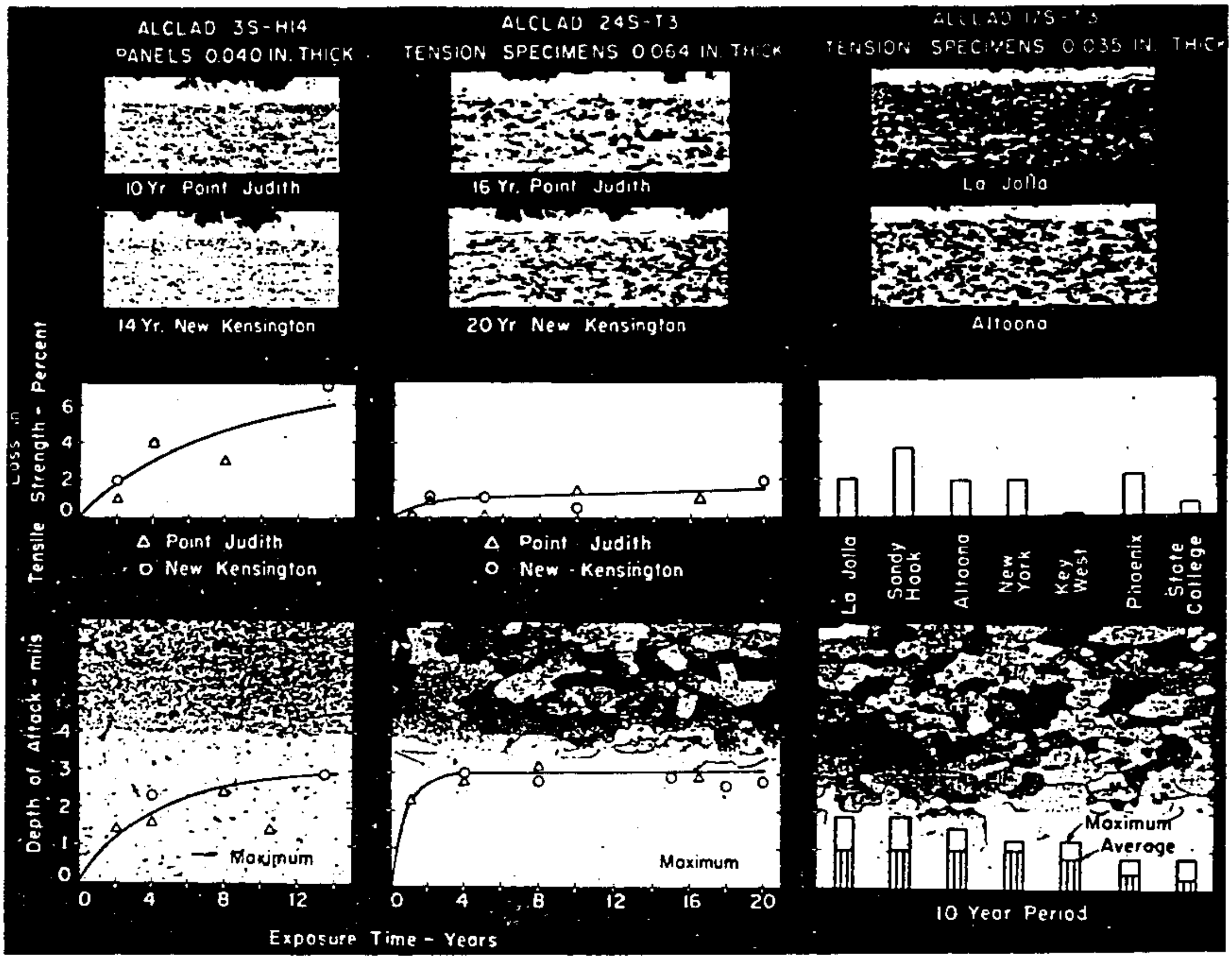

Figure 16—These illustrations show the outstanding resistance to corrosion of alclad products. Note in the bottom graphs, superimposed on unretouched photomicrographs of the alloys, that the maximum attack does not extend beyond the alclad coatings (4.0 mils on Alclad 3S; 3.5 mils on Alclad 24S-T3 and 1.9 mils on Alclad 17S-T3) even after extended exposures in various atmospheres. This is substantiated (top) by micrographs (approx. X77) showing one surface of specimens which had been subjected to the more severe environments. Considerable cladding remains for continued electrochemical protection of core alloys. This protective effect of the alclad coatings is reflected in the small or insignificant losses in tensile strength (Center). Keller's Etch.

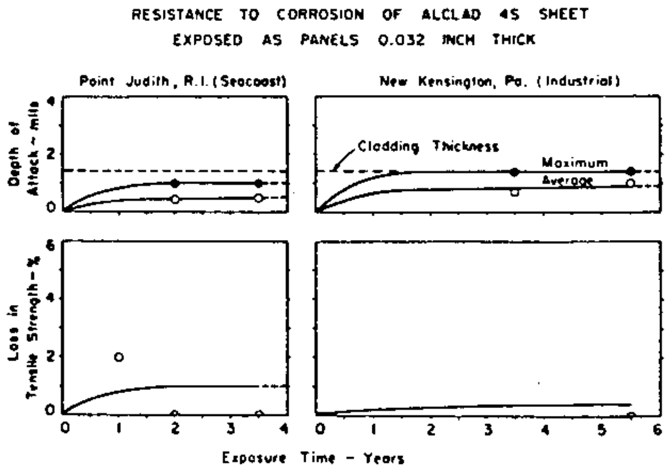

Figure 17—These data after exposures of 3.5 to 5.5 years on thin Alclad 4S are paralleling that procured for other alclad products which had been exposed for much longer periods (Figure 16). As with the preceding alclad products, the attack has been confined to the alclad coating (1.4 mils thick) and these exposures have not caused any really significant losses in strength.

aluminum alloys with magnesium contents in excess of that in 52S, because of their good welding characteristics and relatively high strength when welded. Alloy A54S (3.5% Mg, 0.25% Cr) exhibits these characteristics and has displayed a resistance to weathering almost identical to that of 52S.

Heat Treatable Alloys

Aluminum alloys 53S, 61S, 62S and 63S contain magnesium and silicon in the ratio to form the magnesium silicide compound. These alloys respond to heat treatment and artificial aging and can develop greater strengths than the preceding strain hardenable alloys. Some of the alloys contain small amounts of copper or chromium or both. The compositions of these alloys (Table I) were formulated to enhance certain characteristics, such as strength, extrudability and formability, without affecting their resistance to corrosion (Figures 7 through 10).

One of the first of these aluminum-magnesium silicide alloys was 53S. This alloy has been supplemented by alloy 61S, which was developed to obtain a substantial increase in strength over alloy 53S without effecting any real sacrifice in resistance to most corrosive conditions. This has been substantiated by 16-year exposure data (Figures 7 through 10), thus indicating the suitability of 61S alloy for structural applications, such as power substations, bridge railing and lighting standards (Figure 14), requiring moderately high strength and good resistance to weathering.

Alloy 62S, a recent development, is a modification of 61S with improved formability. Exposures of one year's duration in accelerated corrosion tests and in the atmosphere at New Kensington and Point Judith show that 62S sheet, extruded sections and tubes are performing in a manner comparable to that of 61S.

Alloy 63S contains less magnesium silicide than 61S. This alloy takes a pleasing surface finish and has adequate strength for diverse structural and architectural applications. Millions of aluminum alloy windows used in this post-war period have been made from extruded sections of alloy 63S. They have displayed a high resistance to weathering over an 8-year service period. This, together with the comparative exposure data in Figures 7 to 10, shows that installations of alloy 63S should parallel the good service record of predecessor alloys (53S and 43S) dating back to 1926.

The high strength heat treatable alloys (Table I), such as 14S, 17S, 24S, which contain large amounts of copper and minor additions of other elements, and alloy 75S, which contains large amounts of zinc, magnesium and copper, do not have as high a resistance to corrosion as the preceding groups of alloys. It is generally recommended, therefore, that adequate protection be provided these alloys when exposed to the weather. The alclad forms of these alloys possess a very high inherent resistance to corrosion and may be used without benefit of protective coatings.

Alclad Products

Alclad products are outstanding in their ability to resist corrosion and maintain the structural integrity of the product. A clear understanding of the characteristics of their performance is desirable.

Alclad products have been discussed in detail by Dix.[6] They are composite in type, consisting of an aluminum alloy core to which is bonded metallurgically protective coatings[7,8] of pure aluminum or of another aluminum alloy (Figure 16). The core alloy is chosen to develop the desired mechanical properties. The cladding alloy is of such a composition as to provide a surface that has a high inherent resistance to corrosion and is also sufficiently anodic to the core alloy to afford substantial electrochemical protection to it in most corrosive environments. Consequently, any spot of attack will penetrate only as far as the core alloy (or diffusion zone) where further progress is stopped by cathodic protection. Corrosion then proceeds laterally along the surface, being confined to the cladding. The life of the cladding is a function of its thickness and the severity of the environment. Alclad products, therefore, provide maximum resistance to perforation by limiting corrosion to a relatively thin surface layer. Furthermore, the core alloy exposed at cut edges, scratches, or abrasions is afforded adequate electrochemical protection by adjacent alclad coating.

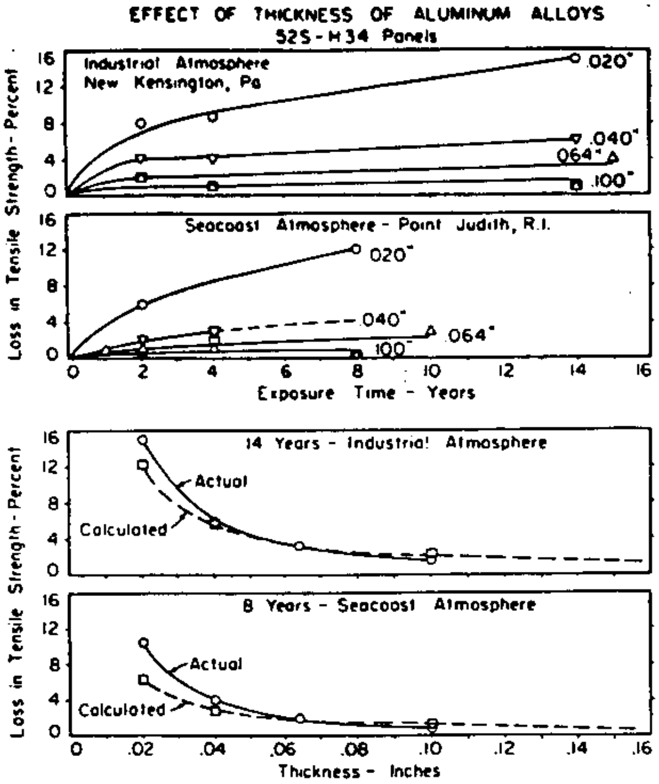

Figure 18—The data obtained at 8 years and 14 years (top curves) were plotted (bottom curves) to show the correlation between percent loss in strength and thickness of the alloy. Included for comparison are curves showing calculated percent losses in strength based on factual data obtained from 0.064-inch thick specimens.

The excellent resistance to weathering of alclad products is illustrated by the data (Figure 16) obtained on Alclad 3S, Alclad 17S-T3 and Alclad 24S-T3 specimens which have been exposed for periods of from 10 to 20 years. With regard to the tensile data included in Figure 16, the somewhat higher losses in strength for the Alclad 3S in comparison with those for the Alclad 24S-T3 and Alclad 17S-T3 do not necessarily indicate that the former had corroded to a greater extent. The pure aluminum cladding applied to the high strength alloys, 17S-T3 and 24S-T3, contributes very little to the strength of these products; thus, corrosion of the cladding causes negligible changes in strength. In the case of alloys such as Alclad 3S and Alclad 4S, the coating alloy of 72S(9) does contribute to the strength of the product, and corrosion of the cladding is reflected in proportionally higher losses in strength.

It is apparent that high resistance to corrosion can be secured from clad products of the high strength structural alloys. This has been demonstrated by Alclad 75S-T6 sheet in aircraft construction and Alclad 14S-T6 plate in bridge structures. Some idea of the value of alclad protection, especially for the high strength aluminum alloys, is apparent from the results of the ASTM tests[2] on 17S-T3 and Alclad 17S-T3. After 10 years' exposure at La Jolla, California, 0.035-inch thick tension specimens (premachined) of 17S-T3 lost 50 percent in tensile strength, whereas similar tension specimens of Alclad 17S-T3 revealed a loss of only 2 percent (Figure 16).

Although non-clad aluminum alloys, such as 3S and 4S, have exhibited a high resistance to atmospheric weathering, there are situations where it is advantageous to use these alloys in their alclad forms (Figure 17), particularly where the metal is relatively thin and where maximum resistance to perforation is required. For example, alclad sheet is especially valuable for applications involving gutters, down spouts, flashing, and valleys, etc., where the hazards of corrosion and perforation are increased by continual contact with water absorptive materials, such as wood, leaves and soil.

Effect of Thickness

Some measure of the effect of atmospheric weathering on different thicknesses of aluminum alloys is illustrated by the data in Figure 18. These tests made on panels of aluminum alloy 52S-H34 show that for all thicknesses studied (0.020-inch to 0.100-inch) the rate of corrosion decreased with time, both in industrial and seacoast atmospheres. The data have also been plotted to provide a means of interpolating the relative performance expected from the same alloy in other thicknesses.

In those many cases where the effect of atmospheric weathering on the tensile strength of a given alloy are available on one thickness only, it would be advantageous to be able to estimate the effects on different thicknesses. The percent loss in tensile strength for various thicknesses can be calculated (see Footnote) from actual data obtained for any one thickness, assuming that the magnitude and pattern of corrosion is about the same for all thicknesses of the alloy. Calculated percent losses in tensile strength for the various thicknesses of 52S-H34 are included in Figure 18.

The calculations were based on data secured from 0.064-inch thick material, since most of the tests herein were made on material of this thickness. These calculated values show reasonable agreement with actual data although they tend to overestimate the effect of the corrosion on the alloy in sections thicker than 0.064-inch and underestimate the effect of the thinner materials.

This method was used to provide a means for comparing the corrosivity of the Alcoa exposure stations at New Kensington and Point Judith with nine different ASTM exposure stations, even though the materials had been exposed in different thicknesses (Figure 4).

Cast Aluminum Alloys

Substantial atmospheric weathering data obtained over a 20-year period on several aluminum alloy sand castings and over a 19-year period on various aluminum alloy die castings are summarized in Figures 19 to 23. In general, long time atmospheric weathering caused only small losses in tensile strength of the ½-inch diameter sand-cast test specimens and the ¼-inch diameter die-cast specimens. Thus, the situation for casting alloys, especially those without substantial amounts of copper, is analogous to that for wrought alloys in that for many applications the resistance to corrosion of various casting alloys is sufficiently similar that final choice is based on other characteristics, such as castability, soundness, strength and economy. Only in the more severe environments, such as the seacoast atmosphere at Point Judith, do conspicuous differences in resistance to corrosion inherent to the various alloys become apparent. For example, aluminum casting alloys containing substantial amounts of copper are noticeably less resistant to corrosion in the more severe exposures than alloys not alloyed with copper.

Since the long time atmospheric weathering data have been obtained on alloys of varied composition, it would seem desirable to discuss them in the light of the class of alloy they represent.

Aluminum-Copper Alloys

Aluminum casting alloys containing substantial amounts of copper do not maintain as good a surface appearance as the other alloys and are not generally used in architectural applications where maximum resistance to surface attack is desired.

The data on Alloy 12 (8% Cu) are of interest because it is one of the oldest aluminum casting alloys and its performance is well known to the casting industry. This alloy provides a good basis of reference, since the alloys subsequently developed for outdoor exposures have a resistance to corrosion superior to that of alloy 12 (Figures 19, 20).

Alloy 112 is a modification of alloy 12 with improved machinability and castability and now is preferred over the older alloy. The resistance to corrosion of the two alloys has been found to be practically identical. Alloy 195, a heat treatable alloy containing less copper (4.5%) generally exhibited a better resistance to corrosion both in the naturally aged temper (—T4) and particularly in the artificially aged temper (—T6), as indicated by Figures 19, 20.

Aluminum-Silicon Alloys

The aluminum-silicon alloys are noted for their excellent casting characteristics combined with good

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1. When tension specimens are machined from panels after exposure, percent losses in tensile strength are inversely proportional to the thicknesses:

$$\frac{L_o}{L_1} = \frac{t_1}{t_o}$$

Where L_o = actual percent loss in tensile strength for specimens of original thickness, t_o

L_1 = percent loss in tensile strength to be calculated for specimens of original thickness, t_1

2. When tension specimens are machined before exposure, edge attack must be considered, and the following formulas are applicable:

$$1.\ L_o = \frac{2d\,(t_o + W - 2d)}{Wt_o}$$

$$2.\ \frac{L_o}{L_1} = \frac{t_1}{t_o} \cdot \frac{(t_o + W - 2d)}{(t_1 + W - 2d)}$$

Where: W = standard width of tension specimens (0.500 in.)

d = a geometrical corrosion factor (having the dimensions of depth of attack) responsible for the percent loss in tensile strength, L_o

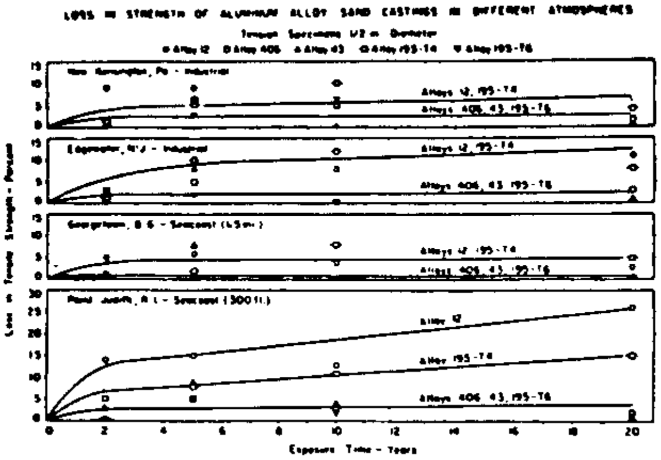

Figure 19—These curves and subsequent ones (Figures 20 through 23) show that the corrosion of aluminum alloy castings also display "self-stopping" characteristics. Note that exposures for as long as 20 years generally caused only small losses in strength of these ½-inch cast test bars.

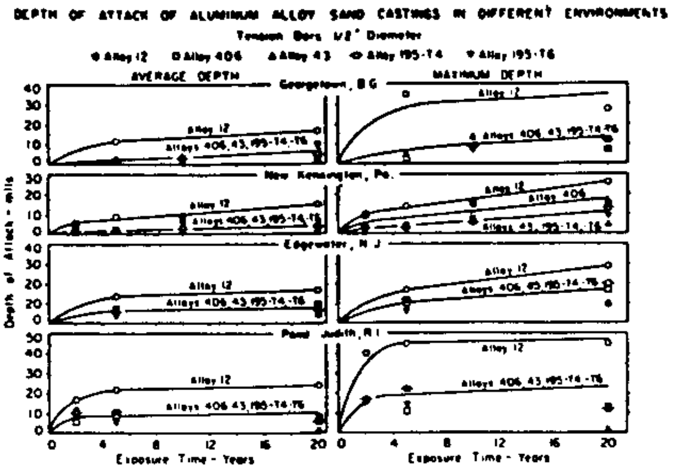

Figure 20—The depth of attack curves for the aluminum casting alloys are analogous to those for the aluminum wrought alloys, although the attack is somewhat deeper for the casting alloys. The depth of attack and losses in strength (Figure 19) were consistently greater for alloy 12 (8% copper) than for the other aluminum alloys.

resistance to atmospheric weathering. This class, represented by Alloy 43 (5% Si) and Alloy 13 (12% Si), has displayed a high resistance to weathering (Figures 19 to 23) both as sand castings and as die castings. Consequently, the aluminum-silicon alloys have been popular for many architectural applications. Because of a characteristic gray color developed by these alloys when anodically coated, they are often used advantageously to provide contrasting effects with other building materials in architectural applications.

Aluminum-Copper-Silicon Alloys

Variations in silicon and copper in this family of alloys are intended to yield good castability and high strength. Because of the copper additions, the resistance to corrosion of these alloys is not as good as that of the aluminum-silicon alloys (Figures 19 through 23) and is closer to that of the aluminum-copper alloys. Even though this class, including alloys 85, 380, 384, may show more surface attack than the aluminum-silicon alloys, it is gratifying to note (Figures 21, 22) that test specimens ¼-inch in diameter revealed shallow attack and only small to moderate losses in tensile strength after about 16 years' exposure to relatively severe atmospheres.

Aluminum-Magnesium Alloys

Aluminum-magnesium type casting alloys, such as 214, B214, 218 and 220 provide high strength and excellent resistance to corrosion. The casting characteristics of these alloys, however, are not as good as those of the preceding alloys. The aluminum-magnesium alloys show to best advantage in their ability to resist surface attack and maintain a pleasing appearance, especially to severe marine environments, as typified by the salt spray exposure (Figure 23).

Aluminum-Silicon-Magnesium Alloys

The aluminum-silicon casting alloys do not have the strength required for some applications. The addition of small amounts of magnesium makes these alloys respond to heat treatment and artificial aging, which

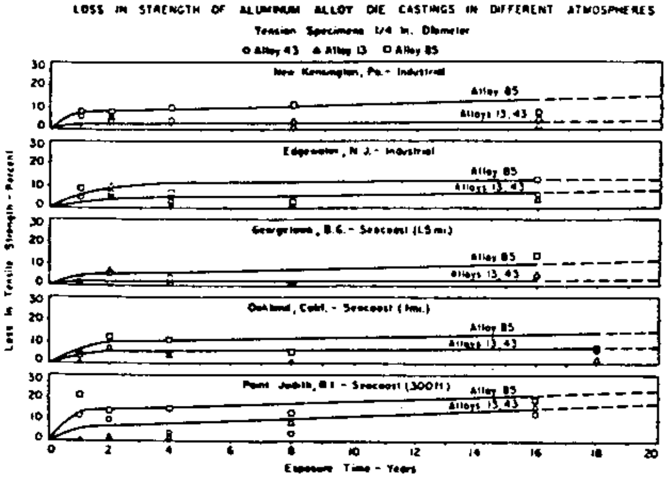

Figure 21—Specimens for this test were die cast in a gooseneck machine. These long time exposures usually caused only small losses in strength of the ¼-inch diameter bars; and alloys 13 and 43 were consistently superior to alloy 85.

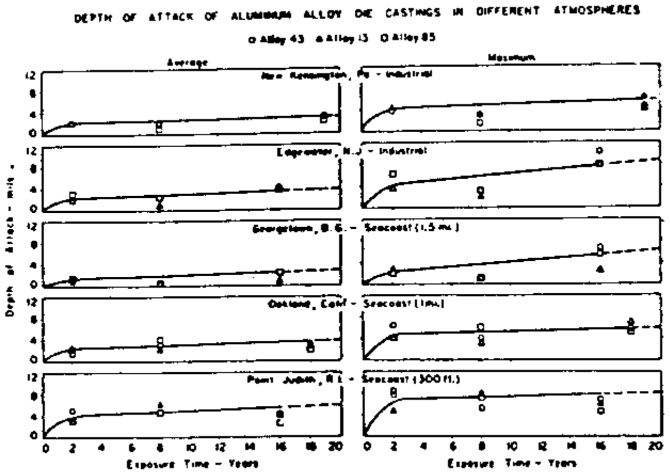

Figure 22—Depth of attack for the aluminum alloy die castings was shallower than that for sand castings (Figure 20). Differences in depth of attack of these die casting alloys were negligible. Thus, the higher losses in strength for alloy 85 (Figure 21) indicate that surface attack was more widespread on this alloy than on alloys 43 and 13.

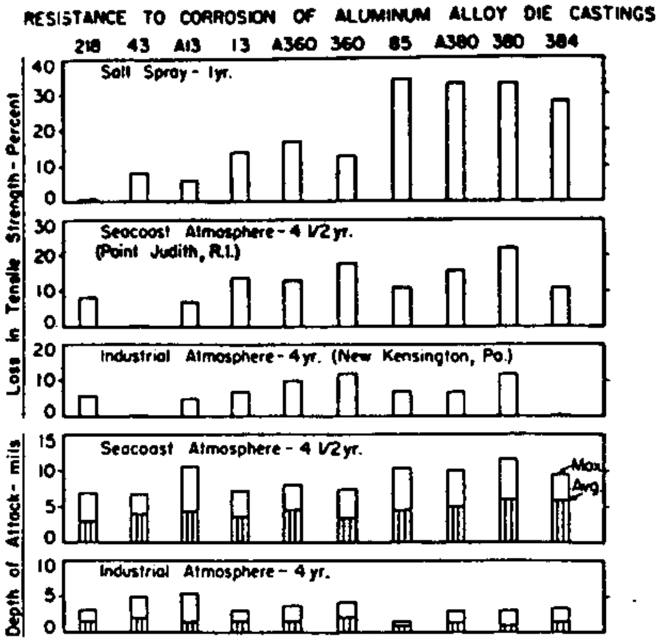

Figure 23—The ¼-inch diameter tension bars for this investigation were die-cast in cold-chamber machines, and include a wide variety of aluminum alloys (Table II). In outdoor exposures the main difference has been one of surface appearance, with the magnesium rich alloy (218) providing the best appearance, followed by the silicon bearing alloys, then the copper bearing alloys. The salt spray data were included to indicate the relative performance of these alloys under unusually severe conditions.

Figure 25—Representative coupons (1½-inch by 6½-inch) of 4S sheet illustrating the gray patina developed by aluminum alloys when exposed for many years to severe seacoast conditions (a)—8 years at Point Judith—and the darkened appearance of the metal when exposed in industrial atmosphere containing considerable carbonaceous products from bituminous fuel (c)—20 years at New Kensington. Surfaces untouched for many years in severe environments are not cleaned quickly with mild cleaners, but are more readily cleaned with certain acid type cleaners, such as proprietary phosphoric acid type solutions suitable for cleaning aluminum prior to painting. The coupons (b) and (d) at the right in each set were cleaned (after exposure) simply by swabbing the surface with one such cleaner. Such cleaners should be confined to the work and rinsed with water, with adjacent architecture protected since the cleaners may also etch or streak masonry, etc.

imparts considerable increase in strength. This is achieved without appreciable change in resistance to corrosion, as is evident from comparing the good performance of alloy 360 (9.5% Si, 0.5% Mg) with the aluminum-silicon alloys 43 and 13 (Figure 23). These data were secured on die castings, but sand casting and permanent mold casting alloy 356 (7% Si, 0.3% Mg) is performing in a similar manner, as judged by tests of shorter duration. This class of alloy (356 and 360) combines excellent castability, high strength and good resistance to corrosion.

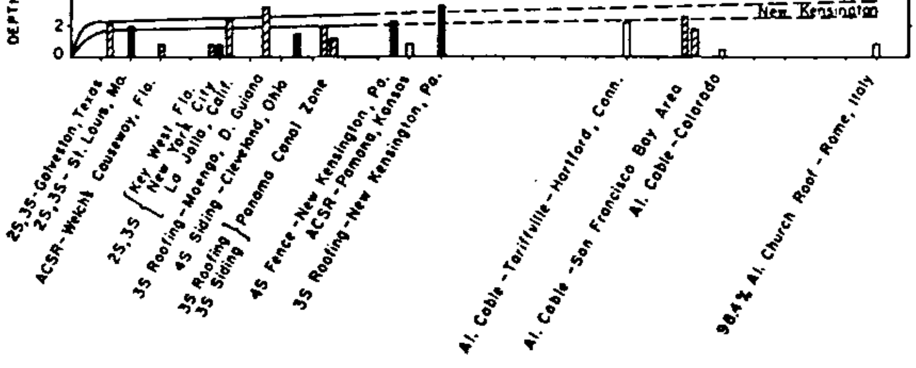

Figure 24—Curves for the atmospheres listed were based on data obtained on aluminum alloys 2S, 3S and 4S, with the curves extrapolated to 52 years. Data obtained on test specimens at other exposure stations and on related aluminum alloys from a variety of service conditions are superimposed (bars) on these curves. This supplementary information adds considerable significance to the data provided by these basic exposure stations.

Aluminum-Manganese Alloys

Aluminum-manganese casting alloys, such as alloy 406 (2% Mn) are highly resistant to corrosion (Figures 19, 20) but are being superseded by alloys, such as 43 and B214, which have better casting characteristics and comparable resistance to corrosion.

Service Experience

There have been many incidental opportunities to examine samples of aluminum alloys from actual installations in service for periods up to 52 years in widely scattered localities. These installations involved roofing and siding of alloys 2S, 3S, and 4S; fencing of alloy 4S and electrical conductors of E. C. grade aluminum either as all aluminum cable or as aluminum cable steel reinforced (Alcoa ACSR). The effect of the diverse exposures was evaluated by measurement of depth of attack. Data from a number of service installations are presented in Figure 24. It is apparent that the attack was shallow and generally less than that for related aluminum alloys when exposed at Alcoa's basic weathering stations at New Kensington and Point Judith. The data from these relatively severe exposure stations can be used, therefore, to estimate the performance expected from aluminum alloys when subjected to the weather at most localities.

Other Factors

In structures involving a variety of building materials, metallic and non-metallic, there are factors other than the weather per se which are important. A number of these have been treated categorically by Mears and Brown[10] and by Dix and Brown.[9] However, some remarks pertinent to building and construction applications are justified.

Surface Appearance

For architectural applications, in particular, the effect of weathering on the surface appearance of a metal is important. In the case of aluminum alloys, the products of weathering are light in color and usually adhere tenaciously to the metal. Thus, weathering of aluminum alloys does not result in staining of adjacent architecture. Because of the light color of their corrosion products, aluminum alloys tend to acquire a light gray patina. This transformation proceeds very slowly in clean atmospheres away from the seacoast, so that surfaces may retain some metallic sheen even after many years. Weathering proceeds appreciably faster at seacoast locations, so that over a period of several years the surface acquires a dull gray appearance, which does not change much with time (Figure 25). In industrialized or urban areas, especially those utilizing bituminous coal as fuel, the accumulation of carbonaceous materials gradually darkens aluminum alloy products (Figure 25) as well as other building materials. Vertical surfaces discolor at a much slower rate than inclined surfaces. Thus, aluminum alloy windows and doors usually remain light in color, particularly if washed occasionally, whereas roofing darkens. Sheltered surfaces of aluminum alloys (and other metals) generally develop a thicker and rougher oxide coating than do boldly exposed surfaces, which are frequently washed by rain.

Maintenance

Aluminum alloy parts respond favorably to periodic maintenance of a simplified nature. Bare surfaces usually can be kept clean simply by washing with a mild soap or detergent. The use of fine steel wool with liquid wax cleans and brightens the metal and leaves a protective film which helps to preserve a pleasing appearance. Installations that have been ignored for extended periods can also be cleaned, but they will often require stronger measures, such as the use of a mild etchant, to facilitate the removal of adherent grime and products of weathering (Figure 25).

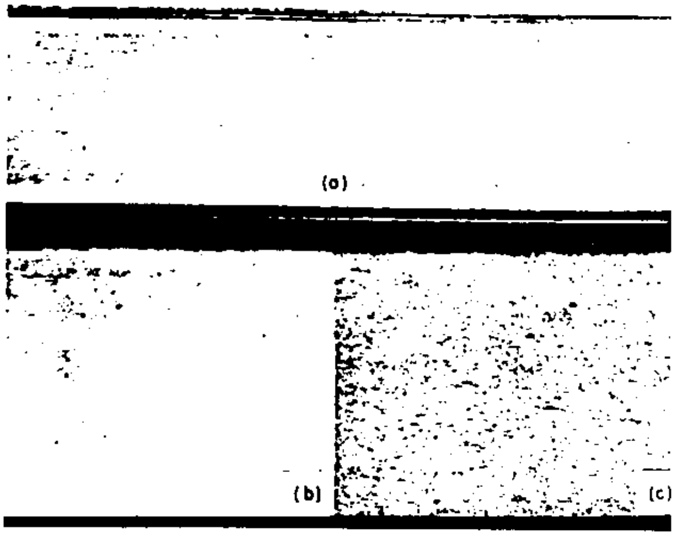

Figure 26—Anodically coated (Alumilite Finish No. 204A1) sections of alloy 53S after 15 years' exposure to the industrial atmosphere at New Kensington, Pennsylvania. Section (a) was cleaned monthly during the first year, using fine steel wool and liquid wax, and remained in excellent condition. When not maintained during the next eight years, the surface gradually darkened and the coating developed some minute breakdowns (not discernible at several feet); however, the original smooth, satin finish was restored by cleaning with fine steel wool and an abrasive wax cleaner and monthly cleaning for the last six years with steel wool and liquid wax has preserved this finish. The history of the bottom sample paralleled that of (a) except that the sample was not maintained between the 9 and 15 year periods. Thus, (c) shows dirt accumulation over six year period and (b) shows the good surface finish easily restored by cleaning with fine steel wool and abrasive wax cleaner.

Anodic Coatings

For applications where an attractive surface and a minimum of maintenance is of considerable importance, much can be gained from the use of anodically coated aluminum alloys. Anodic coatings formed in a sulfuric acid electrolyte (Alumilite coatings) can be varied in thickness to meet specific needs and the oxide coatings thus produced are much thicker, more abrasion resistant and more protective than the natural oxide film.[11] These anodic coatings enhance the surface appearance of aluminum alloys and provide excellent resistance to weathering and discoloration. If the coatings are of the desired thickness for the application and are cleaned regularly, the original surface finish can be preserved. If neglected, the surface will slowly become soiled and may show some coating breakdowns. However, in most cases the integrity of the anodic coating is not affected, so that the coated part is more easily cleaned than is bare metal (Figure 26).

Non-Metallics

Contact of aluminum alloys with non-metallic building materials does not involve any corrosion problems under the dry conditions that prevail within most buildings. Under continually wet or damp conditions, however, corrosion hazards may be associated with water absorptive materials, such as wood, insulation and masonry. Corrosion from such causes usually can be mitigated by one or a combination of the following expedients:

a) back painting the aluminum alloy with a good quality paint (free from lead pigmentation);

b) painting the non-metallic material;
c) interposing a uniform layer of a mastic compound between the aluminum alloy and the wood or masonry, etc.

During construction, exterior surfaces of aluminum alloys (and other metals) require temporary protection, especially against the diverse materials that settle over or are splashed onto them. Commonly encountered are alkaline materials, such as plaster, mortar and concrete, which can stain or even pit unprotected metals. Alkali resistant clear lacquer coatings (such as those using acrylic resins), about 0.5 to 1.0 mil thick, provide good resistance to the action of these materials and greatly facilitates subsequent cleaning of the surfaces. This protective measure is commonly used for both bare and anodically coated aluminum alloy installations.

Dissimilar Metals

Aluminum alloys are anodic to most other metals of construction, such as alloys of iron, copper, nickel, lead and tin and may suffer galvanic attack when coupled to them. It is best, therefore, to avoid the use of dissimilar metals where practicable. Atmospheric exposures, however, are far less conducive to galvanic attack than are exposures by immersion, such as in sea water. The hazards of galvanic attack can be substantially minimized through selection of the most compatible metals suitable for the job and by employing protective coatings if necessary.

Because zinc and cadmium do not stimulate galvanic attack of aluminum alloys, zinc plated (galvanized) or cadmium plated steel or other metals are suitable for use with aluminum alloys for such applications where the coatings have adequate life. Although stainless steels and chromium (also titanium) are more cathodic than mild steel, copper and nickel, they cause much less galvanic attack on aluminum alloys. Aluminum alloys and stainless steels (especially the 300 series) have successfully combined their respective advantages in many atmospheric applications. The desirable characteristics of chromium can be used to advantage as platings on alloys of iron, copper and nickel, thereby greatly reducing or even eliminating the hazards of galvanic attack, which may result when these metals are used with aluminum under adverse conditions. Best results are achieved when the chromium coating is applied over a plate of nickel.

In atmospheric exposures, galvanic attack is apt to be most severe in crevices where moisture can be trapped between dissimilar metals and remain for long periods. Such attack can be stifled by providing weather-tight joints, by painting the faying surfaces and most effectively by sealing the joints with a mastic compound.

Drainage from some dissimilar metals, notably alloys of copper and nickel, onto aluminum alloys can have deleterious effects. This results from "heavy metals," such as copper and nickel being washed from the cathodic metals and deposited on the aluminum surface where they excite electrochemical attack of the aluminum. Wash from dissimilar metal parts small in area may not supply heavy metals in sufficient quantity to be harmful, but the greater quantity draining from large surface areas (roofing, copings) can contaminate underlying surfaces of aluminum alloys sufficiently to cause severe corrosion. Wash from ferrous metals generally has not been adverse to aluminum alloys. The foregoing situation should be avoided wherever feasible; if encountered, the best remedial measure is to maintain paint protection over one or both metal components depending on circumstances.

Conclusions

1. Outdoor exposure of thousands of specimens for long periods to a variety of conditions, including severe industrial and seacoast atmospheres, shows that aluminum alloy products, both wrought and cast, have a high resistance to atmospheric weathering.
2. This is attributable to the "self-stopping" nature of the attack of aluminum alloys; that is, the formation of protective films which causes the rate of weathering to decrease markedly with time.
3. The data indicate that after an initial exposure period of about one or two years, the maximum rate of penetration of corrosion is expected to be appreciably less than 0.2 mil per year for the more adverse conditions, such as severe seacoast atmospheres and less than 0.1 mil per year for atmospheric weathering conditions normally encountered.
4. Although some differences in resistance to weathering were noted among the aluminum alloys, the differences often were of little practical significance so that final choice of alloy would be based on other important requirements, such as strength, formability, weldability, appearance and cost.
5. Alclad products are characterized by a high resistance to weathering and also by a unique resistance to perforation. The performance of alclad alloys makes them especially valuable for applications involving relatively thin sheet products for use under adverse conditions.

Acknowledgments

The work reported herein is the result of the concerted efforts of many individuals in several divisions of the Aluminum Research Laboratories. Particular credit is due E. H. Dix, Jr., who foresightedly planned many of the investigations which form the backbone of this paper; to R. H. Brown for his helpful suggestions and contributions to this paper and to F. M. Howell, E. C. Hartmann, and F. Keller under whose supervision the numerous tensile tests, engineering assistance and metallographic examinations were provided. H. C. Slaughter was of considerable help in expediting the various tests made on the many specimens evaluated at the 20-year period. The graphs were drawn by K. H. Maier.

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Aluminum Alloy Designation Conversions

OLD	NEW	OLD	NEW	OLD	NEW
Commercial Designation	**AA Number**	**Commercial Designation**	**AA Number**	**Commercial Designation**	**AA Number**
99.3(1)	1230	17S	2017	56S	5056
99.6, CD1S	1160	A17S	2117	XC56S	X5356
99.75(2)	1175	18S	2018	C57S, K157	5357
99.87, EB1S	1187	B18S	2218	61S	6061
EC(3)	EC	F18S	2618	62S	6062
AA1S	1095	24S	2024	63S	6063
BA1S	1099	25S	2025	66S	6066
CA1S	1197	B25S	2225	70S	7070
AB1S	1085	32S	4032	72S	7072
EB1S, 99.87	1187	43S, K145	4043	75S	7075
FB1S	1090	C43S, 44S, K143	4343	B77S	7277
AC1S	1070	XE43S	X4543	XA78S	X7178
BC1S	1080	44S, C43S, K143	4343	XB80S	X8280
CC1S, R998	1180	45S	4045	K112	8112
JC1S	1075	50S	5050	K143, C43S, 44S	4343
AD1S	1050	A50S, K155, R305	5005	K145, 43S	4043
BD1S	1060	XD50S	X5405	K155, A50S, R305	5005
CD1S, 99.6	1160	A51S	6151	K157, C57S	5357
ED1S	1150	XB51S	X6251	K160, J51S	6951
AE1S	1030	J51S, K160	6951	K162, R306(4)	6003
BE1S	1145	52S	5052	LK183	5083
2S	1100	F52S	5652	K186	5086
3S	3003	53S	6053	R301 Core, 14S	2014
4S	3004	B53S	6253	R305, K155, A50S	5005
XA5S	X3005	XD53S	X6453	R306, K162(4)	6003
11S	2011	E53S	6553	R308(5)	1130
14S, R301 Core	2014	A54S	5154	R399	8099
XB14S	X2214	B54S	5254	R995	1235
XC16S	X2316	X55S	X5055	R998, CC1S	1180

(1) *Cladding on Alclad 24S (Alclad 2024).*

(2) *Cladding on No. 2 Reflector Sheet.*

(3) *EC—The designation for electrical conductor metal is not being changed since it is so firmly established in the electrical industry.*

(4) *Cladding on R301 and Alclad 14S (Alclad 2014).*

(5) *No. 1 Reflector Sheet.*

Resistance of Aluminum Alloys To Chemically Contaminated Atmospheres*

By W. W. BINGER, R. H. WAGNER, AND R. H. BROWN

THE EXCELLENT resistance of aluminum alloys to atmospheric weathering is well known and has been used to advantage for many years in architectural applications and general metal work. Because of this characteristic, considerable interest has been shown in aluminum alloys for plants and industrial buildings where the atmosphere is contaminated by fumes and chemicals that promote the corrosion of many metals and alloys and attack paint systems which are required for protection.

Of the many substances causing atmospheric corrosion in the vicinity of chemical plants, refineries and other industries, those encountered most often are combinations of hydrogen sulfide, carbon dioxide, ammonia, hydrogen chloride, sulfur dioxide, moisture and dirt. Aluminum alloys are resistant to atmospheres containing these contaminants even when the conditions in many plants are further aggravated by the formation of chemical dust deposits. Laboratory and field tests continue to demonstrate that architectural aluminum alloys resist corrosion by a wide variety of organic and inorganic chemicals.

Laboratory and Field Testing

Common Industrial Contaminants

Summaries are available on the corrosive effects of gases such as hydrogen sulfide, carbon dioxide and sulfur dioxide on several commerical metals.[1, 2] A relatively simple test can be used to indicate the behavior of aluminum when exposed to environments containing such industrial contaminants. Aluminum alloys 2S-H14 and 3S-H14 were exposed for 32 hours or 96 hours, totally immersed in distilled water saturated with each gas and also the gas saturated with water vapor at room temperature. The gas flow was three liters per hour for eight hours each day and during the remainder of each day the test containers were sealed. In order to evaluate the severity of the exposure, samples of mild steel were exposed for the same periods. It is evident from Table I that aluminum alloys such as 2S-H14 and 3S-H14 possess good resistance to corrosion when consideration is given to the severe exposure.

The corrosive action of flue gases containing varying amounts of ammonia, cyanides, hydrogen sulfide and organic sulfur compounds was evaluated by Shnidman and Yeau.[3] Included in the investigation were mild steel, zinc, lead and several aluminum, copper and stainless steel alloys. They concluded that the most corrosion resistant materials tested were lead, zinc, aluminum and copper alloys.

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In a study conducted by Mellon Institute,[4] concentrations of volatile sulfur compounds found in industrial atmospheres were determined and included sulfur dioxide, hydrogen sulfide and volatile organic sulfur compounds but not sulfur trioxide. During 1936 and 1937 when atmospheres were surveyed in the cities of St. Louis, Pittsburgh, Philadelphia, Washington and Detroit, sulfur compounds were found to be highest in the St. Louis area.

Results obtained by the Aluminum Research Laboratories from tests started during 1938 in St. Louis are summarized in Table II. A graphical presentation of these data in Figure 1 demonstrates that the rate of depth of attack on aluminum alloys decreases with increasing time of exposure. Such behavior, which is frequently referred to as "self-limiting" at-

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★ A paper presented at the Ninth Annual Conference, National Association of Corrosion Engineers, Chicago, Ill., March 16-20, 1953. A condensation of this article was published in *Modern Metals*, Vol. 9, 66-68, 70-72 (1953) Apr.

Abstract

The excellent resistance of aluminum alloys to atmospheric weathering is well known and has been used to advantage for many years in architectural applications and general metal work. Because of this characteristic, considerable interest has been shown in aluminum alloys for plants and industrial buildings where the atmosphere is contaminated by fumes and chemicals that promote the corrosion of many metals and alloys.

Of the many factors connected with atmospheric corrosion problems in chemical plants, refineries and other industries those encountered most often are combinations of hydrogen sulfide, carbon dioxide, sulfur dioxide, hydrogen chloride, moisture and dirt. In general, it has been found that aluminum alloys are resistant to atmospheres containing these contaminants. In addition, the problem in most plants is further aggravated by the formation of dust and/or fumes. An active laboratory as well as field testing program is continuing to demonstrate that aluminum alloys of the type used for architectural applications are very resistant to corrosion by a wide variety of organic and inorganic chemicals.

The use of aluminum-base alloys in the coke, soda ash, sulfur, power, paper, salt, petroleum and petrochemical industries has reduced corrosion losses with resultant savings in maintenance costs. Some of the applications where aluminum alloys have proved successful are tank roofs, siding, roofing, windows, duct work, ladders, handrails, instrument tubing and tread plate.

tack, is characteristic of the performance of aluminum alloys in most atmospheric environments.[5] These data also show that short time exposure tests do not always present a true evaluation of the alloys, especially when the rate of attack is not linear with time. For example, conclusions based on exposure periods of one year or less would indicate that the rate of depth of attack of the aluminum alloys was 0.002-inch per year or greater. A more informative treatment of the data would be obtained by determining the rate of attack that occurred between the one year and the two year or four year exposure periods. Atmospheric corrosion tests must be of sufficient duration to determine the shape of the curve.

Solid Chemicals

In addition to the corrosive effects of the industrial gases discussed above, the atmospheric corrosion problem in many plant areas may be further aggravated by the presence of dusts from chemicals being processed in the area. Chemical dusts deposited on a metal surface may stimulate galvanic, chemical or concentration cell corrosion, because they can retain moisture or some may even be deliquescent.

In order to make a qualitative study of the effect of such chemical deposits in the laboratory, 2-inch diameter 3S alloy impact extruded containers either were filled to a depth of 1/16-inch with the solid chemical or had small mounds of the chemical placed in them. The containers were then exposed for one month at room temperature at 100 percent relative humidity. A large number of solid chemicals, listed in Table III, had no effect on aluminum under these conditions.

Since these test conditions were much more severe than most service conditions, many of the chemicals that caused some attack on the aluminum in this test may not be significantly corrosive under field conditions. Such data should only be used as a relative indication of the corrosive character of the dusts. For example, aluminum chloride was classified as "corrosive." However, in one field test where the atmosphere was often heavily contaminated with aluminum chloride dust, aluminum alloys were virtually unaffected after seven and one-half months of exposure.

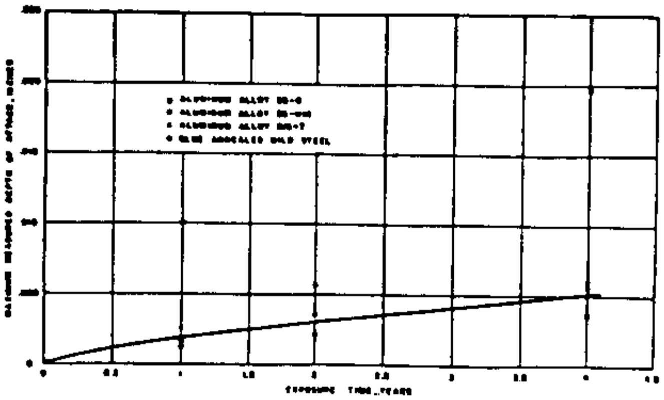

Figure 1—Behavior of aluminum alloys and mild steel exposed to the St. Louis atmosphere. For the aluminum alloys the rate of depth of attack definitely decreased with increasing time of exposure and is commonly called "self-limiting" attack.

TABLE I

Effect of Hydrogen Sulfide, Carbon Dioxide and Sulfur Dioxide on Aluminum Alloys and Mild Steel

ALLOY	Calculated Volume of Metal loss in.³/in.²/yr.[1] Aqueous Solutions	Calculated Volume of Metal loss in.³/in.²/yr.[1] Moist Vapors
HYDROGEN SULFIDE—96 HOURS		
2S-H14 Aluminum	.0003	.0005
3S-H14 Aluminum	.0003	.0007
Mild Steel	.0117	.0204
CARBON DIOXIDE—96 HOURS		
2S-H14 Aluminum	.0009	.0007
3S-H14 Aluminum	.0003	.0010
Mild Steel	.0111	.0017
SULFUR DIOXIDE—32 HOURS		
2S-H14 Aluminum	.0332	.0337
3S-H14 Aluminum	.0385	.0511
Mild Steel	45.0000[2]	.5080

NOTES: [1] Specimens .064" x .36" x 1.2" exposed to distilled water saturated with gas and also the gas saturated with moisture at room temperature. Daily cycle involved bubbling gas into water at 3 liters per hour for 8 hours and sealing the system off for 16 hours.

[2] Test terminated after one hour because of rapid attack of metal.

TABLE II

Metallographic Examinations of Various Alloys Exposed to the Atmosphere at St. Louis, Missouri

ALLOY	Maximum Measured Depth of Attack, Inches		
	1 Year[1]	2 Years	4 Years
2S-O Aluminum	.0012	.0021	.0031
3S-H14 Aluminum	.0016	.0035	.0045
Alclad 3S-H14 Aluminum	.0014	.0021	.0021
52S-H34 Aluminum	.0029	.0028	.0021
61S-T6 Aluminum	.0028	.0035	.0044
Blue Annealed Mild Steel	.010	.0056	.0197

NOTE: [1] Investigation started in 1938.

Organic Vapors

Organic vapors are another source of atmospheric contamination that may not only corrode metals but can also be particularly damaging to paint systems. Although data are meager on the effect of organic vapors as an atmospheric contaminant, it has been established by the Aluminum Research Laboratories[6] that aluminum alloys are resistant to a wide variety of organic chemicals and their vapors.

Field Test Rack Exposures

Because each plant has its own environmental conditions, laboratory data can only suggest potential applications of aluminum alloys. Therefore, the importance of cooperative field testing under actual service conditions was recognized long ago.

The Aluminum Research Laboratories' standard field test specimen is .064-inch x 4 inches x 9 inches. Several specimens of aluminum alloys are mounted (as shown in Figure 2) in a small aluminum frame, electrically insulated from each other and from the rack itself. In addition, specimens of bright finished mild steel are generally included for comparative purposes. The average composition of the mild steel specimens was 0.07 % carbon, 0.33% manganese, 0.01% phosphorus, 0.04% sulfur and 0.04% copper. Such specimens are large enough for a comprehensive evaluation including:

1. Visual examination of surface
2. Determination of change in weight
3. Measurement of depth of attack
4. Determination of changes in mechanical properties
5. Photographs

Although weight losses are measured, it has been determined that a more critical evaluation is obtained by measuring the depth of attack and changes in mechanical properties.[7]

Test racks have been exposed over a period of years in a number of process plants and have provided valuable data on the expected performance of aluminum alloys in these environments. Typical examples include:

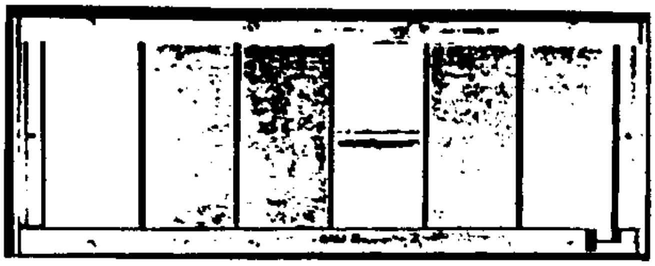

Figure 2—Aluminum Research Laboratories' standard test rack for field tests. Test panels .064-inch x 4 inches x 9 inches are insulated by micarta strips.

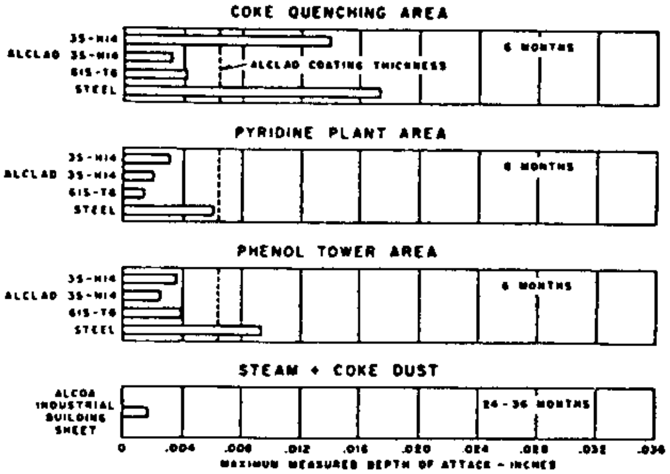

Figure 3—Results of field tests in several by-product coke plant atmospheres where maintenance problems exist.

A. **By-Product Coke.** By-product coke plants present a wide variation in atmospheric conditions. The results of field tests conducted in several areas where maintenance problems exist are graphically shown in Figure 3. Although these exposure periods were brief, service experience gained on aluminum roofing and siding installations in these areas proved that the attack was "self-limiting".

B. **Refineries.** The behavior of aluminum alloys in both inland and seacoast refinery atmospheres can readily be seen by the data presented in Figure 4. It has been demonstrated that maintenance costs can be substantially reduced in many refineries by the use of aluminum alloys.

C. **Soda Ash.** Aluminum alloys have become accepted as a standard material of construction in soda ash plants. Continued cooperative field testing programs have further corroborated the acceptability of aluminum alloys and have uncovered many more diversified applications. The results obtained in several locations are presented in Figure 5.

TABLE III

Resistance of Aluminum Alloy 3S to Solid Chemicals Under Conditions of High Humidity

Non-Corrosive		Border Line	Corrosive
Ammonium dichromate	Citric acid	Ammonium chloride	Aluminum chloride
Ammonium molybdate	Potassium thiocyanate	Ammonium fluoride	Calcium chloride
Ammonium nitrate	Sodium acetate	Copper sulfate	Ferric chloride
Ammonium sulfate	Sodium aluminum fluoride	Magnesium chloride	Potassium permanganate
Barium carbonate	Sodium bicarbonate	Oxalic acid	Sodium carbonate
Barium chloride	Sodium chlorate		Sodium fluoride
Barium nitrate	Sodium chloride		
Borax	Sodium nitrate		
Boric acid	Sodium sulfate		
Calcium oxide	Triphenyl phosphate		
Chromium trioxide			

NOTES: [1] Shallow 2" diameter impact extruded containers of aluminum alloy 3S.
[2] Chemicals placed in containers as a thin ($\frac{1}{16}$") layer and as scattered small mounds.
[3] Containers exposed to an atmosphere having a relative humidity of approximately 100% at room temperature for one month.

D. **Salt Mining & Processing.** Corrosion problems attributed to the presence of sodium chloride are legion. Figure 6 illustrates the data obtained in atmospheric exposures at both salt mining operations and salt processing plants. Although of minor importance in many applications, the inconspicuous color of aluminum corrosion products is sometimes found to be advantageous.

E. **General.** The results of a number of miscellaneous exposures in chemical plants further demonstrates the resistance of aluminum alloys to a wide variety of atmospheric contaminants. The performance of aluminum alloys in such environments is indicated in Figure 7.

Whenever possible, two or more exposure periods are recommended. While several exposure periods are desirable in determining the rate of attack, the large quantity of data and experience that has been accumulated by the Aluminum Research Laboratories over the years has been very helpful in aiding in the satisfactory evaluation of short time field test data.

Service Experience

Service experience with aluminum alloys has been obtained in a wide variety of chemically contaminated atmospheres. Rather than discuss the resistance of aluminum alloys to chemically contaminated atmospheres in specific industries, it is believed to be more desirable to discuss various proven applications of aluminum alloys. This approach will not only demonstrate the resistance to corrosion of aluminum alloys by these particular chemically contaminated atmospheres, but may also suggest potential applications that may not have been previously considered.

Roofing and Siding

One of the oldest applications of aluminum alloys is roofing and siding. The earliest known installation is the roof on the Church of San Gioacchino in Rome, which is still in excellent condition after more than 50 years. A number of other examples demonstrating the serviceability of aluminum roofing are:

A roof of 3S corrugated aluminum sheet (.051-inch thick) was installed in 1922 on the remelt building at the Aluminum Company of America's New Kensington Works, which is in a highly industrialized area. The inside surface of the roof was for many years exposed to the acidic atmosphere normally associated with remelt furnaces and etching baths. After 24 years' service, the outside surface of the sheet was still in excellent condition, having a maximum measured depth of attack of only 0.005-inch. Because conditions inside the plant were more corrosive the maximum depth of attack on the underside was 0.012-inch.

A corrugated galvanized steel building was erected in 1930 at the East St. Louis Works of Alcoa. A year later an addition to this building was completed using 18-gauge (0.040-inch) corrugated 3S aluminum sheet. Chemicals handled in this building included calcium sulfate, sulfuric acid, lime, soda ash and caustic soda. After 14 years of service, microscopic examination of the aluminum sheet revealed that the pitting of the outer and inner surfaces averaged only 0.001-inch and 0.002-inch, respectively. The deepest attack observed on any of the samples was only 0.004-inch, scarcely one-tenth of the way through the sheet. The galvanized steel required periodic painting.

Another roofing application of considerable interest is the coal conveyor cover shown in Figure 8. This corrugated 3S alloy sheet was installed more than 20 years ago over about four miles of conveyor. An examination after 15 years' service revealed that the maximum depth of attack was only 0.004-inch.

Alcoa Industrial Building Sheet (0.032-inch) was installed on the roof of a shed approximately 150 feet long and 30 feet wide and located within 40 feet of a row of coke ovens. The atmosphere was contaminated by ammonia, sulfur compounds, phenol and other by-products, plus fly ash. An inspection three years after installation showed that the top surface of the roof had suffered only superficial corrosion and the underside was free from corrosion. As the result of this good service, another aluminum roof was installed on a second building.

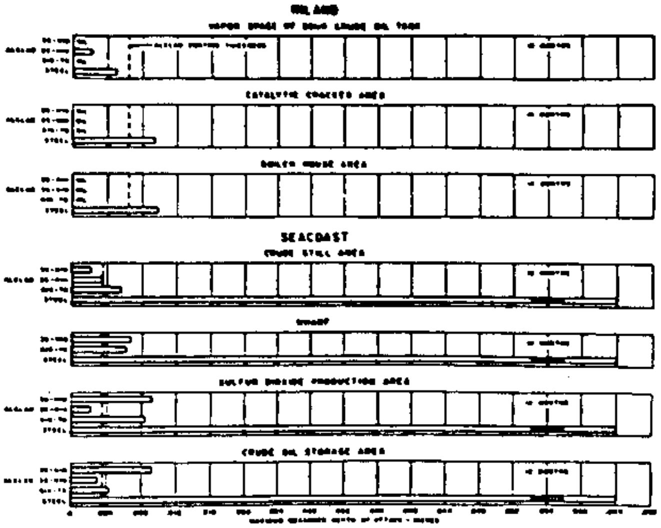

Figure 4—Data obtained from a number of refinery atmospheres. Test sites were selected at both inland and seacoast refineries.

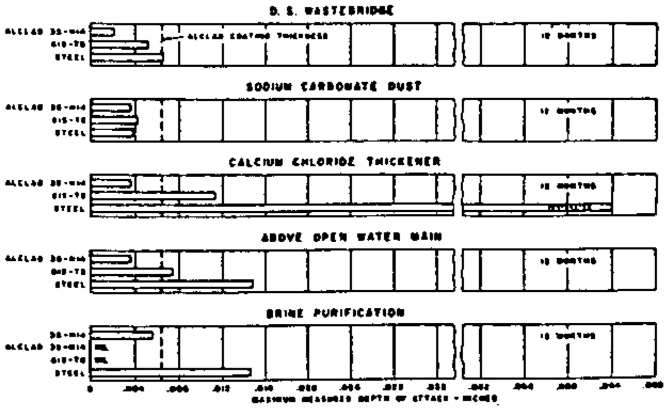

Figure 5—Field data such as these have corroborated the general acceptability of aluminum alloys in soda ash plants and have resulted in many additional applications.

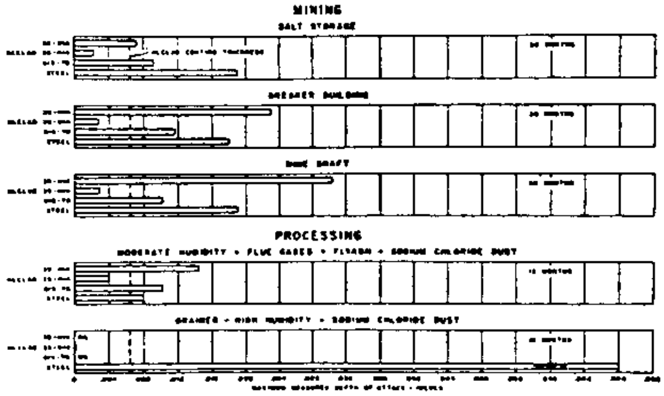

Figure 6—Data obtained on test racks exposed in both salt mining and processing plants. These test sites were considered to be representative of the more corrosive environments.

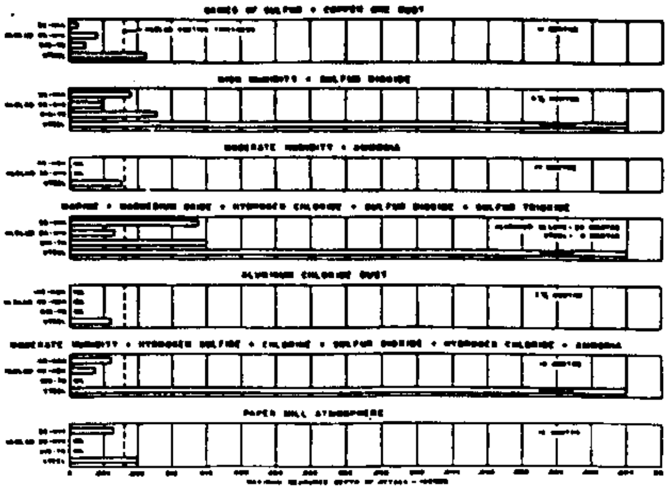

Figure 7—Data collected in chemical plants demonstrating the resistance of aluminum alloys to a variety of atmospheric contaminants.

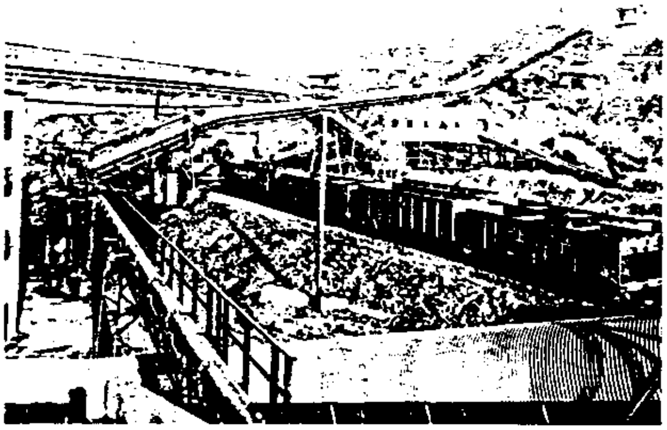

Figure 8—Coal conveyor cover fabricated of 3S corrugated aluminum sheet. The four miles of conveyor cover has been in service for over twenty years.

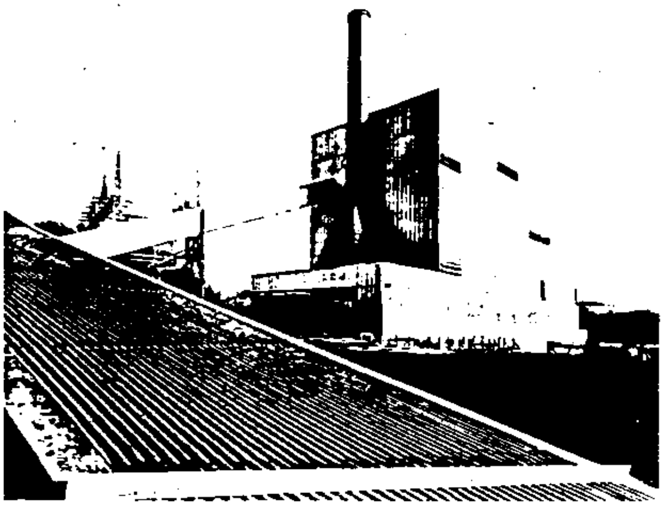

Figure 9—Modern power plant utilizing Alcoa Industrial Building Sheet, windows, etc. to not only improve the plant appearance but also reduce general maintenance. The use of the light weight aluminum curtain wall construction enables easy removal for building modifications or additions.

A panel of 0.064-inch thick, corrugated, 3S aluminum roofing sheet from the roof of the Carbon Plant Building of the Massena (New York) Works of Alcoa was examined after about 14 years of service. Although the outside surface was heavily coated with dirt and soot, especially in the valleys of the corrugations, the average depth of attack was only 0.0011-inch. On the inner surface, which had been exposed to fumes from the manufacturing of carbon electrodes, the attack averaged 0.002-inch. At no point, either inside or out, was the attack more than 0.003-inch, or about one-twentieth of the thickness of the sheet.

In addition, modern power plants similar to the one shown in Figure 9 are using substantial amounts of aluminum for siding, roofing and windows to reduce general maintenance.

Aluminum, like many other metals, is dependent upon its natural oxide film for its resistance to corrosion. Because of this fact, it has been found that when corrosive conditions are encountered, the attack is usually of the pitting type. As was previously demonstrated, the rate of attack usually decreases with time.

The life of aluminum siding and roofing is further enhanced by the use of alclad sheet. Alclad[8, 9, 10] sheet is a duplex aluminum alloy product composed of a core alloy to which is metallurgically bonded a thin aluminum alloy coating. The core alloy is chosen for its mechanical properties and the cladding alloy has a potential such that it will cathodically protect the core metal from pitting attack. The resistance of alclad sheet to perforation is many times greater than bare sheet fabricated from the core alloy. Thus, in many applications it is very desirable to employ alclad materials to increase the resistance to perforation. At the same time, it must be remembered that the general behavior of aluminum alloys indicates that the rate of attack decreases with time of exposure. Thus, it can be seen that a combination of alclad material and the "self-limiting" characteristic can be most desirable. Unless past experience has shown non-clad aluminum to be suitable, alclad products are recommended for use in chemically contaminated atmospheres.

Tanks

A demonstration of the resistance of aluminum alloys to the vapors of sour crude oils is shown by the long life of aluminum alloy tank roofs, some of which have been in service for more than 20 years. Since 1927 nearly 100 aluminum tank roofs have been installed.[11, 12] Recognizing this, the American Petroleum Institute included a section on the design and fabrication of aluminum roofs in its Standard 12C.[13]

Electrical Applications

The earliest installation of aluminum alloy bus bar conductors was 1895. Excellent service has been given both around electrolytic cells and in plating room installations. The atmospheres over the cells and plating baths were contaminated with chlorine, sulfuric acid, cyanides and cadmium oxide. Aluminum bus bars in an electro-zinc galvanizing plant are shown in Figure 10. In service since 1930, these bus bars are installed over baths containing zinc sulfate and sulfuric acid and at times are covered with a layer of salts up to one inch thick with no deleterious effect.

Aluminum alloys are being used for sub-station structures primarily because less maintenance is required, thereby reducing losses sustained by shutdowns for painting. Aluminum alloy 61S-T6 is recommended for such structures.

The first installation of all-aluminum cable took place in 1899, and ten years later ACSR (Aluminum Cable Steel Reinforced) was developed by Alcoa. Some of these early installations are still in service. Examination of cable from commercial installations, which include rural, urban, industrial and seacoast atmospheres after varying periods of service, revealed excellent resistance to weathering.

The results of an examination of ACSR (266,800 circular mils), which was installed adjacent to a sulfuric acid plant, are indicative of the performance of aluminum conductor cable. It was found after 20 years of service that the maximum depth of attack of the aluminum strands was only 0.0028-inch.

Where good appearance is important, as in food processing plants, dairies, breweries, distilleries and utility plants, aluminum conduit makes a modern, clean-looking installation. The resistance to corrosion is demonstrated by an exposure of 24 years in a steam locomotive roundhouse which resulted in a maximum depth of attack of 0.0019-inch on aluminum alloy 3S conduit.

Connections between aluminum alloys and dissimilar metals are necessary in many cases. Such connections present no problems if precautions are taken to avoid galvanic corrosion by sealing moisture out of the joints.

Heat Exchangers

There has been a marked increase in the use of air cooled aluminum fin and tube heat exchangers because of the increased demand for cooling capacity and the need for water conservation in many plant areas. Exchangers of the type shown in Figure 11 are used to cool the oil and water for the Nordberg engines at Alcoa's Point Comfort (Texas) smelting works. Units of this type are being used in a variety of atmospheric conditions.

High pressure power plant boilers use large heat exchangers to extract the remaining heat in the boiler flue gases by preheating the air used in firing the boilers. Corrosion encountered where the cold air enters the units is caused by the combination of sulfur compounds in the flue gases and water vapor condensing in the tubes. Aluminum alloy 63S-F extruded tubes are specified for this service.

Other exchanger applications employing substantial amounts of aluminum include air conditioning equipment and unit heaters.

Piping

Piping in chemical plants usually is selected on the basis of its suitability for handling a specific material. An additional factor which may be overlooked is maintenance of the outside surface.

Figure 10—Aluminum alloy bus bar conductors in service over electrozinc galvanizing baths since 1930. Although at times heavy salt deposits covered the bus, no serious corrosion occurred.

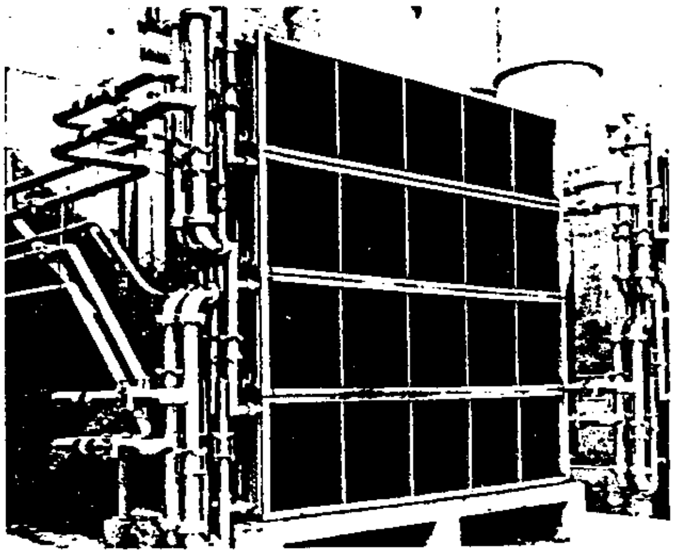

Figure 11—Aluminum alloy air cooled exchangers for cooling oil and water for the Nordberg engines at the Alcoa Point Comfort Smelting Works. Similar exchangers are employed in air conditioning equipment and unit heaters.

In 1930, a sulfur company installed several hundred feet of 3S aluminum pipe (3-inch IPS) across the sulfur storage area to serve as a cold water service line. The exterior was continuously exposed to sulfur dust and during rains to slightly acid water. After 14 years of service, the outside of the pipe was etched and roughened but there was no attack of appreciable depth. This behavior was not unexpected because aluminum alloys also have been used successfully for more than 20 years in contact with sulfur and sulfur compounds for architectural and building construction, electrical applications, materials handling equipment and chemical process equipment.

Several soda ash plants use large diameter, thin wall aluminum piping for handling moist mixtures of carbon dioxide and ammonia. Although this application does not represent an atmospheric condition, it does demonstrate the high resistance of aluminum alloys to corrosion by these gases.

Thermal Insulation Covering

Aluminum sheet is being used to weatherproof thermal insulation in many refineries. Aluminum alloys have been used for this purpose for over 20 years; however, it has only been during recent years when new plants or modernization of old plants has

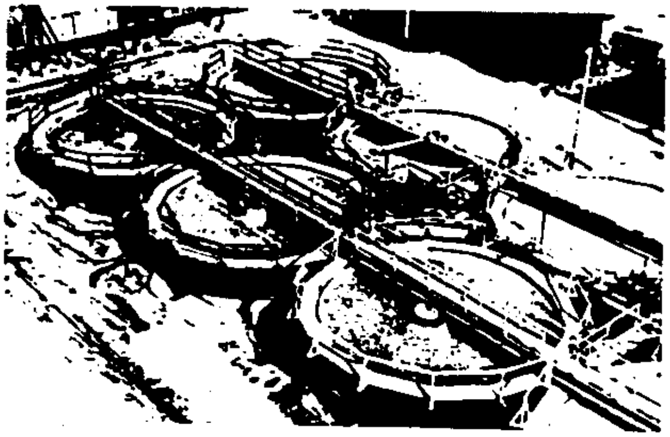

Figure 12—Aluminum alloy 61S bridge over alkaline brine settling tanks in a soda ash plant in good condition after five years' service.

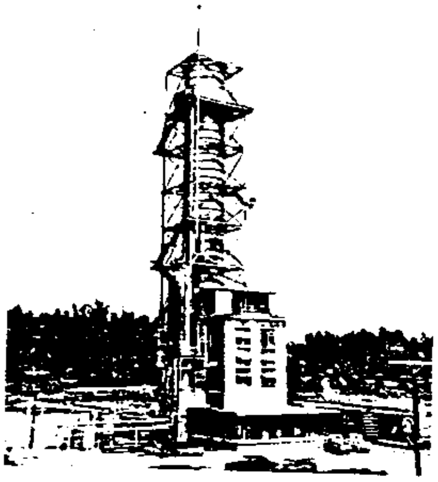

Figure 13—Aluminum alloy prilling tower in an ammonium nitrate plant. The tower is 20 feet in diameter and one hundred twenty feet high.

been undertaken that substantial quantities of aluminum have been used for this application.

Instrument Tubing[14]

The major factors stimulating interest in aluminum instrument tubing are ease of handling and economy. The superiority of aluminum instrument tubing where atmospheres containing hydrogen sulfide and sulfur dioxide are encountered was recognized early by gas and oil processing plants. Literally millions of feet of instrument tubing have been installed in instrument air service.

Ducts

The exhaust ducts, fabricated from 2S aluminum sheet (0.125-inch thick) in 1929 at the Aluminum Research Laboratories have been exposed to one of the most varied environments possible. These ducts not only handle the fumes from the Analytical Division but also the fumes and vapors from corrosion test investigations. After 18 years of such service the average depth of attack was 0.0052-inch and the maximum depth was only 0.0208-inch. In 1945, when new duct work was installed in additional areas, it was decided that these ducts could be fabricated from 0.065-inch thick sheet.

Aluminum has become a standard material of construction not only for ducts handling chemical vapors and dusts but also for air conditioning distribution systems.

General Metal Work

While soda ash, being alkaline, may be corrosive to aluminum alloys, cooperative tests and service installations prove that there are many locations in soda ash plants where aluminum is preferred. One such location shown in Figure 12 is in and around alkaline brine settling tanks. This 61S-T6 aluminum alloy bridge is in excellent condition after nearly five years' service. Where joints between dissimilar metals occur, attack can be avoided by proper installation practices. Other aluminum applications in soda ash plants include walkways, stairways, tread plates, handrails, doors, window frames, roofing and siding.

Aluminum alloys have been used for many years for process equipment by the ammonium nitrate industry, but only recently has the economy of the use of structural aluminum been recognized. It is becoming standard to specify aluminum structurals, grating, tread plate, conduit, electrical fittings, etc., in plants handling ammonium nitrate. Figure 13 shows an aluminum prilling tower 20 feet in diameter and 120 feet high.

The excellent resistance of aluminum alloys to atmospheric weathering by marine atmospheres suggested that aluminum should be a good material of construction in salt mines and process buildings. In 1934, as the result of a cooperative field test, a 53S-F aluminum alloy man cage was installed in a salt mine shaft. The fact that this piece of equipment was removed from service in 1950 only because it became obsolete is testimony of its success. Other noteworthy applications are for siding on mine skips, retractable belt conveyors and roof ventilators.

The outside of an aluminum desulfurization column in another by-product coke plant was unaffected after ten years of service. Hydrogen sulfide made this area unusually corrosive to other metals. The original steel exhaust stack failed after approximately three years and was replaced with aluminum.

The advantages of aluminum for architectural applications in sewage plants have long been recognized. Applications where aluminum alloys have been used include skylights, electrical conduit, windows, doors, ventilating ducts, sidewalk doors, floor gratings and electrical cabinets.

Aluminum alloys are used because of their resistance to the soot, fly ash, gases and vapors from the combustion of coal. For example, in 1927 aluminum stall doors were used on a roundhouse in West Virginia. In 1945, this house had become obsolete and was replaced by a new structure. The aluminum doors have resisted the effects of the smoke and moisture so well that they were merely transferred and fitted to the new roundhouse.

In 1948, a seven stall roundhouse was completed in Cleveland using aluminum columns, beams, purlins and doors. Another important factor in the selection of aluminum for this application was the saving in weight which permitted a reduction in foundation costs.

In many processing areas, loose oxides, staining or paint flaking resulting from corrosion of overhead structures have caused contamination of the products being handled. The use of aluminum alloys for roofs, structurals, electrical conduit, etc., over such areas will often minimize such difficulties.

Conclusions

Aluminum alloys used for the various applications previously discussed represent a wide range of mechanical properties[15] and each was developed to suit specific industrial requirements. Selection of alloys will depend upon such factors as mechanical properties, resistance to corrosion, workability, machineability, formability, weldability and for some applications color matching.

The use of aluminum-base alloys in the coke, soda ash, sulfur, power, paper, salt, petroleum and petrochemical industries has reduced corrosion losses with resultant savings in maintenance costs. It is believed that through cooperative field testing it will be possible to demonstrate many additional applications in these and other industries where aluminum alloys can be used to advantage. A sound, practical installation can best be obtained by taking advantage of all the information and experience that is readily available.

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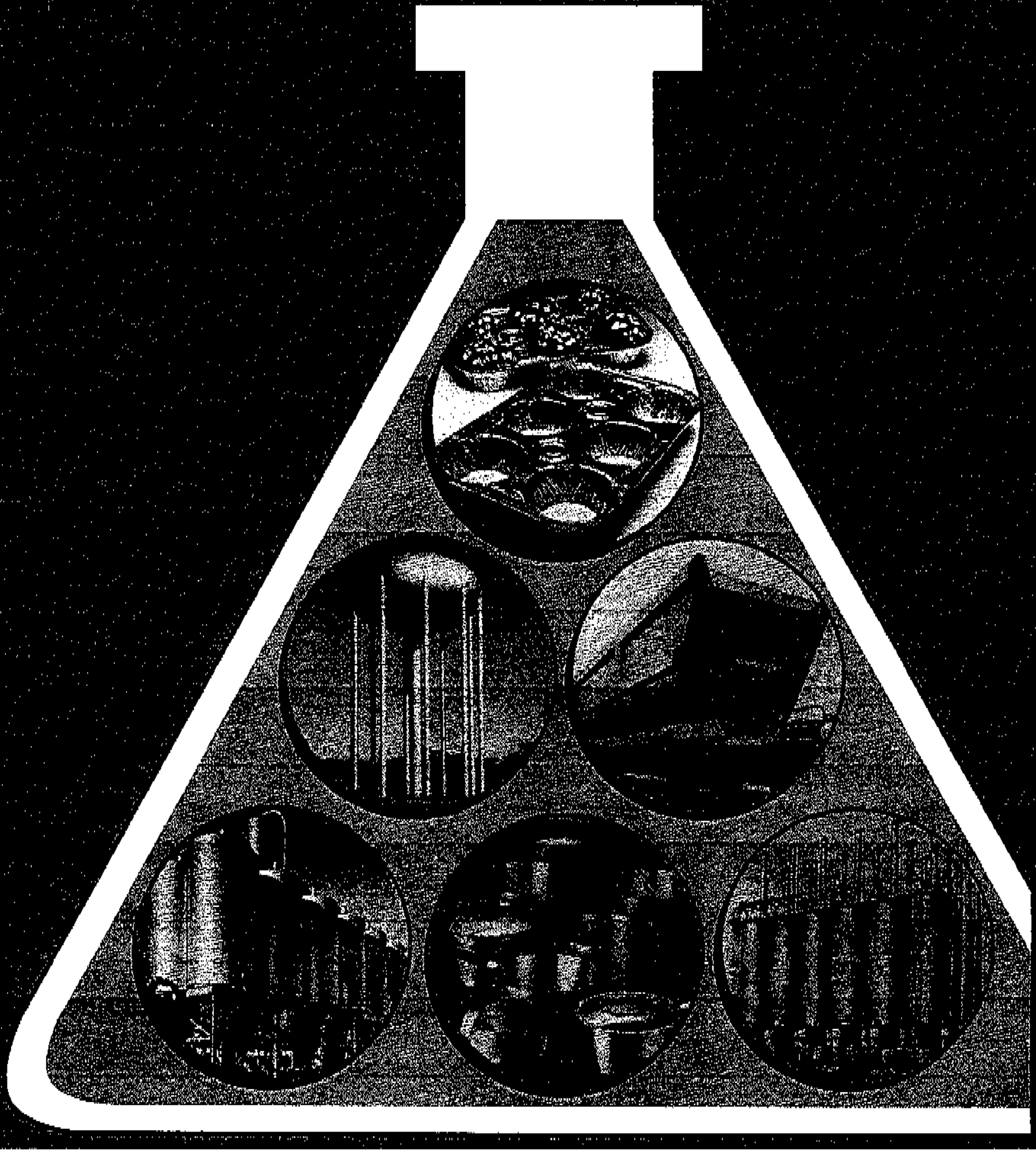
Guidelines for the use of Aluminum with food and chemicals

60



Guidelines for the use of Aluminum with food and chemicals

NOTICE: The data and suggestions in this book are based on information believed to be reliable and are offered in good faith but without guarantee. Since much of the information contained herein is based on limited data and since the endless varieties of conditions and possible methods of use cannot be accurately predicted and adequately covered, the prospective user should determine the suitability of the materials for a particular application based upon the specific conditions to be encountered in service. Accordingly, the Aluminum Association and its member companies assume no responsibility or liability for the use of these data and suggestions. No warranty express or implied, is made of this information by the Aluminum Association or by any of its member companies.

GUIDELINES for the use of ALUMINUM with FOOD and CHEMICALS

FOREWORD: Paralleling the growth of our industrial society are mounting corrosion losses and costs of corrosion control systems. The soaring cost of maintenance labor, alone, demands increased attention to low cost, corrosion resistant materials such as aluminum.

There is equal incentive for the use of processing, handling and storage equipment basically compatible with sensitive products.

Frequently, the materials engineer is faced with a choice of technically suitable, available materials for a given application. Where aluminum is suitable, it usually offers the lowest total costs.

This publication is intended to assist in determining the suitability of aluminum alloys for specific applications and in achieving their potential economy through proper specification and use.

TYPICAL CORROSION-RESISTANT APPLICATIONS: Aluminum alloys can be readily fabricated and welded into storage tanks, tank trailers, tank cars, covered hopper cars, reaction vessels, heat exchangers, process piping, distillation equipment and related process equipment.

Distilled water, condensate and demineralized water have been handled in laboratories, hospitals, chemical plants, paper plants, and power plants using aluminum alloy tanks and piping. Seawater and brine have been handled in aluminum alloy desalination equipment. Seawater applications for aluminum alloys include offshore drilling platforms, crude oil piping, gas piping, barges, boats and submarines. Natural water supplies have been piped in aluminum alloy irrigation pipe.

Nitrogen fertilizer solutions, ammonium nitrate, urea, ammonia and 98% nitric acid have been handled in aluminum alloy tanks, piping, heat exchangers, tank cars, covered hopper cars, prilling towers, drums and containers. High concentration, high purity nitric acid has been processed in high purity aluminum equipment. Ammonium nitrate and urea prills have been stored in aluminum alloy warehouses and aluminum alloy bins.

Sulfur, hydrogen sulfide and mercaptans have been processed and handled in aluminum alloy bins, piping and tanks. Sulfur dioxide in low concentrations and as dry gas refrigerant has been used in aluminum alloy food processing and refrigeration systems. Concentrated 95% sulfuric acid has been stored in aluminum alloy tanks in textile industries to avoid iron contamination in the textile fiber. Amine scrubbers for the removal of sulfur dioxide and carbon dioxide in petroleum refineries have often been made of aluminum alloys. Sulfite paper mills have used aluminum alloy conduit, drying machine rolls, hoods, vents and stacks. Tall oil has been distilled in aluminum alloy columns, condensers and receivers.

Paper and pulp mills have used aluminum alloy building materials.

Organic chemicals such as alcohols, acetic and other organic acids, solvents, glycols, glycerin, aspirin, rosin, turpentine, nitro paraffins, phenols and aromatic compounds may be handled in aluminum alloy equipment. Pharmaceuticals, penicillin, cosmetics, drugs, latex, vitamins and related materials have been processed and shipped in aluminum alloy containers. The use of aluminum alloy containers avoids toxicity, discoloration, rancidity and metal contamination. Hypodermic hubs have been made of aluminum alloys.

Foods, vegetable oils, fatty acids, sugar solutions, corn syrup, sucrose, dextrose, candy, starch, confections and many related products have been handled in aluminum alloys. Cookware and tableware have been made from aluminum alloys. Many aluminum alloy cans and containers have been used for such products as orange juice, beer, soft carbonated drinks, cheese, butter, frozen foods and bakery products. Beer and wine have been transported in aluminum alloy barrels or drums.

Cryogenic liquids have been handled in aluminum alloy Dewar flasks and insulated double-wall tanks. Oxygen, nitrogen, argon, hydrogen, helium, methane, natural gas, fluorine are some of the cryogenic liquids that have been handled in vessels and piping of aluminum alloys. Aluminum powder has been used as an infrared radiation barrier when added to powder insulation. Multilayer "Super Insulation" has used aluminum foil or aluminized mylar. Liquid methane tanks and liquid natural gas tanks in ships have been welded of aluminum alloys. Propane and butane are borderline cryogenic liquids which have used aluminum alloy materials.

Hydrogen peroxide in 30%, 50% and 90% concentration has been handled in high purity aluminum tanks and equipment. Rocket fuels such as hydrazine compounds, nitrogen tetroxide and related materials have utilized aluminum alloy tanks and piping. Jet fuel, JP4, gasoline, kerosene and lubricating oil have been handled in aluminum alloy piping and tanks to reduce metallic contamination.

Building materials of aluminum alloys have been successfully used in the paper and pulp, fertilizer, phosphate, potash, chlor-alkali, food, pharmaceutical and electrical power generating industries. Textile and plastic plants have been users of aluminum alloy siding, roofing and other building materials.

Textiles such as nylon, polyethylene, dacron, cellulose acetate have been processed and handled in aluminum alloy equipment. The plastic pellets of polyethylene, polypropylene, cellulose acetate, polyvinyl chloride, polyvinylidene chloride, nylon, polyester and polycarbonate have been transferred in aluminum alloy pneumatic lines, containers and covered railroad hopper cars.

Water desalination plants, sewage treatment plants and air pollution control equipment have been recent users of aluminum alloys. Aluminum alloy heat exchanger tubes and components have been used for seawater distillation units at a fraction of the cost for other materials. The use of aluminum alloys in sewage tanks, settling basins, weirs, grating, ladders, aerators and piping has existed for a number of years. Air pollution control has required the use of alumina chemicals, aluminum alloy towers, ductwork, water washers and electrostatic precipitators.

Swimming pools have been fabricated from aluminum alloys coated for protection and appearance. The pools have been installed in concrete, sand, gravel or inside of such buildings as hotels, schools, and motels. Ladders and diving boards, likewise, have been made of aluminum alloys as have light poles, fixtures and chain link fence. Culvert pipe and drains have been other aluminum applications.

USE OF THIS BOOK: This book provides a concise and up-to-date guide to the behavior of aluminum alloys with a wide variety of foods and chemicals. Unless otherwise specified, the entries in this book describe the action of aluminum alloys in direct contact with the pure material in its normal state (solid, liquid, or gas); aqueous or other solutions are specified.

In cases where specific laboratory test data are cited, the alloy tested has been listed. It must be recognized that all aluminum alloys do not perform in the same manner when exposed to the same environment, i.e. 2024 alloy will generally exhibit lower resistance to corrosion in a given environment than will alloy 3003. While the low and medium strength alloys usually have similar resistance to corrosion in most environments, it is desirable to conduct tests prior to proceeding with the use of aluminum alloys for a specific application. It must also be recognized that the conditions of use in a specific application may differ sufficiently from the ideal conditions of laboratory tests or from the conditions of previous service experience to change the performance of aluminum alloys in the anticipated application. Again, the need for testing and/or supplemental corrosion protection should be considered.

The information contained herein applies to massive aluminum surfaces as exist in typical processing equipment, such as storage tanks, heat exchangers, pressure vessels, piping and valves, etc. The information may not be applicable to finely divided aluminum such as powder.

The term "handling" refers to the use of piping, drums, tanks, tank cars and the like for transportation and storage of a product.

The phrases such as "have been used for," or "have been handled in" indicate known applications of aluminum with the substance. However, the complete history and longevity of the applications are not known.

The terms "elevated temperature" and "low temperature" refer to any temperature above or below ambient encountered in normal production or use of the chemical product.

TYPES OF CORROSION: Corrosion is defined as the deterioration of a metal by chemical or electrochemical reaction with its environment. This deterioration takes place in different ways, depending upon the corrosive media, temperature, presence of other metals, and other factors.

Uniform Corrosion: Uniform corrosion is the term applied when the metal surface corrodes evenly over the entire area.

Pitting: Pitting is a localized form of corrosion that usually occurs randomly in the form of small pits or craters, roughly hemispherical in shape. Pits usually become covered with a mound or nodule of corrosion product which tends to stifle further corrosion. As a result, the rate of penetration of a pit tends to diminish with time. Some pitting usually can be tolerated if the wall thickness is adequate.

Galvanic Corrosion: Galvanic or dissimilar metal corrosion is the corrosion that takes place when different metals or alloys are coupled together electrically in the presence of an electrolyte. The severity of corrosion depends upon several factors, one being the position of the dissimilar metals in the galvanic series in the table below.

Galvanic Series

magnesium alloys
zinc
aluminum-zinc alloys
aluminum-magnesium alloys
aluminum, 1100, 3003, Al-Mg-Si alloys
Cadmium
Aluminum-copper alloys
mild steel, cast and wrought iron
chromium
lead-tin solders
lead
tin
brasses
copper
bronzes
monel
nickel
stainless steels

In this series, any material tends to be corroded by contact with any other metal beneath it. The extent of corrosion also depends upon the conductivity of the electrolyte; it can become negligible in solutions of low conductivity such as high purity water. Despite its low position in the series, stainless steel can be safely coupled to aluminum in many environments because the steel is highly polarized. In high chloride environments, stainless steel can cause substantial corrosion of contacting aluminum.

Deposition Corrosion: Deposition corrosion is a form of corrosion in which ions of heavy metals, such as copper, lead, mercury, tin, nickel and cobalt are electroplated onto aluminum; the resulting couple of dissimilar metals leads to further corrosion. Copper is the heavy metal most commonly encountered in practice because of the use of copper equipment. Mercury ions are less common, but even more detrimental.

Poultice Corrosion: Poultice corrosion is a form of corrosion that takes place when moisture is absorbed by porous materials, such as insulation, wood, cloth, cork and paper in contact with aluminum. The corrosion reaction is the result of differences in oxygen concentration in the electrolyte in adjacent regions of the material. These differences lead to a concentration cell and the region on the aluminum which is oxygen-starved corrodes.

CORROSION RATE UNITS: The most commonly accepted unit for expressing the rate of corrosion of a metal is mils per year, abbreviated mpy. One mil is equal to 0.001". In this book, the following terminology is used to indicate corrosion rates.

Resistant = less than 1 mpy attack
Mild action = 1-5 mpy attack
Moderate action = 5-20 mpy attack
Corrosive or corroded by = greater than 20 mpy

It must be recognized that these ranges of corrosion rates may provide insufficient information for a particular application. However, they should provide at least general information on the compatibility of the food or chemical with aluminum alloys. In some cases the actual value for corrosion rate as well as the range has been included for the reader's assistance. In any case, advice and/or testing are desirable before proceeding to use aluminum alloys in any application.

ALUMINUM ALLOYS: Systems of four digit numerical designations are used to identify wrought and cast aluminum alloys.

Designations for Wrought Alloy Groups

		Alloy No.
Aluminum—99.00% minimum and greater		1xxx
	Major Alloying Element	
Aluminum alloys grouped by major alloying elements	Copper	2xxx
	Manganese	3xxx
	Silicon	4xxx
	Magnesium	5xxx
	Magnesium and Silicon	6xxx
	Zinc	7xxx
	Other Element	8xxx
	Unused Series	9xxx

The first digit of the designation as shown in the table serves to indicate the alloy group. The last two digits identify the aluminum alloy or indicate the aluminum purity. The second digit indicates modifications of the original alloy or impurity limits. For more specific details, refer to the Aluminum Association publication entitled "Aluminum Standards and Data."

In this book the term "aluminum," when unqualified by an alloy designation, implies all the more corrosion resistant aluminum alloys, e.g. 1xxx, 3xxx, 5xxx, 6xxx, and the copper-free 7xxx series alloys.

Commercial purity aluminum is designated alloy 1100. It contains a minimum of 99% aluminum, with small amounts of copper, iron, and silicon and lesser amounts of other metals. Alloy 1100 and other 1xxx series alloys are not used where strength is a major consideration. These alloys do, however, possess excellent resistance to corrosion, weldability, and formability and are suitable for numerous applications.

Stronger aluminum alloys having the characteristics desired for process equipment are obtained by additions of such elements as manganese, magnesium, and silicon. The well known aluminum alloy, 3003, has very good corrosion resistance and is somewhat superior to alloy 1100 in applications where additional strength is required. The 5xxx series group combines very good corrosion resistance with much greater strength. However, several of these alloys having magnesium contents in excess of 3% are limited to 150°F maximum sustained operating temperature. Other common 5xxx series alloys that are not so limited are 5050, 5052, and 5454. Alloys 6063 and 6061 exhibit good general corrosion resistance and are used widely in the chemical and food industry. The 2xxx and copper containing 7xxx series alloys, in spite of their high strengths, are seldom used in the chemical and food industry because they do not have the high degree of corrosion resistance generally required.

Designations for Casting Alloy Groups

		Alloy No.
Aluminum—99.00% minimum and greater		1xx.x
	Major Alloying Element	
Aluminum alloys grouped by major alloying elements	Copper	2xx.x
	Silicon, with added Copper and/or Magnesium	3xx.x
	Silicon	4xx.x
	Magnesium	5xx.x
	Zinc	7xx.x
	Tin	8xx.x
	Other Element	6xx.x
	Unused Series	9xx.x

The first digit of the designation indicates the alloy group. The second two digits identify the specific alloy or indicate the aluminum purity. The last digit, separated from the first three by a decimal point, identifies the product form; i.e., castings or ingot. A modification of the original alloy is indicated by a letter prefix before the numerical designation.

Aluminum sand and permanent mold casting alloys have been widely used in the chemical and food industry. Applications which include dairy and food handling equipment, cooking utensils and fittings for chemical and sewage use have been most common. Alloys 356.0, B443.0 and 514.0 have good corrosion resistance and have been used for valves, fittings and other components. The 2xx.x, high copper containing 3xx.x, 7xx.x and 8xx.x series alloys are less resistant to corrosion and are not normally used in the food and chemical industry.

Alclad aluminum alloys have been commonly used to minimize the possibility of perforation by corrosion in aggressive environments. They consist of a relatively thick core of one alloy for strength and a relatively thin layer of a second alloy metallurgically bonded to one or both surfaces. A cladding alloy is selected to provide cathodic protection to the core alloy. As a result, any corrosion that takes place penetrates only to the cladding-core interface. The corrosion then spreads out laterally with substantially complete consumption of the cladding as it spreads.

SYNONYMS: A chemical or material that cannot be found in the alphabetical listing should be sought in the index of synonyms in the back of the handbook. It may appear in the alphabetical section under another name.

INHIBITORS: An inhibitor is a substance which, when added to a liquid or chemical, reduces or prevents the corrosion of a metal which would otherwise occur. Some of the common inhibitors for aluminum and the media in which they have been used are listed in Appendix II.

OTHER SOURCES OF INFORMATION: Additional information on the corrosion performance of aluminum alloys with various foods and chemicals exists in the literature. Some of the more prominent sources of information are listed below. While this list is not all inclusive, most of these references list many other sources of information which the reader can pursue if necessary. No attempt has been made to assess the validity of the data included in these references. They have been included as additional information sources only. The references in the text are listed by number together with the appropriate page number in the specific reference.

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In addition to these references, others specific to a particular food or chemical are listed in the text where appropriate.

ADVANTAGES OF ALUMINUM AS A BUILDING MATERIAL

ATTACHMENT 2

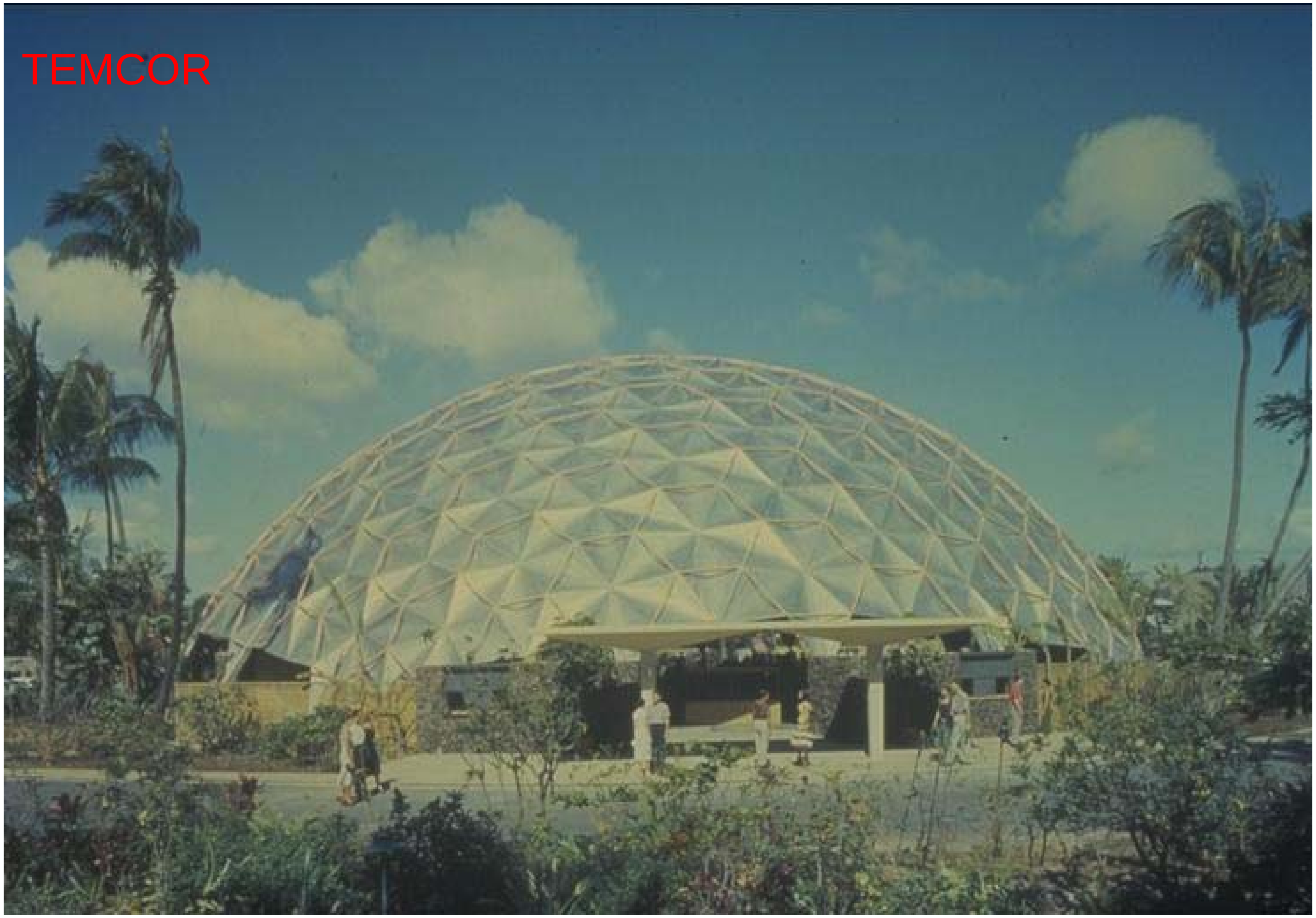
ALUMINUM DOME IN MARINE ENVIROMENT

Aluminum Dome in a Marine Environment

Aluminum Dome in a Marine Environment

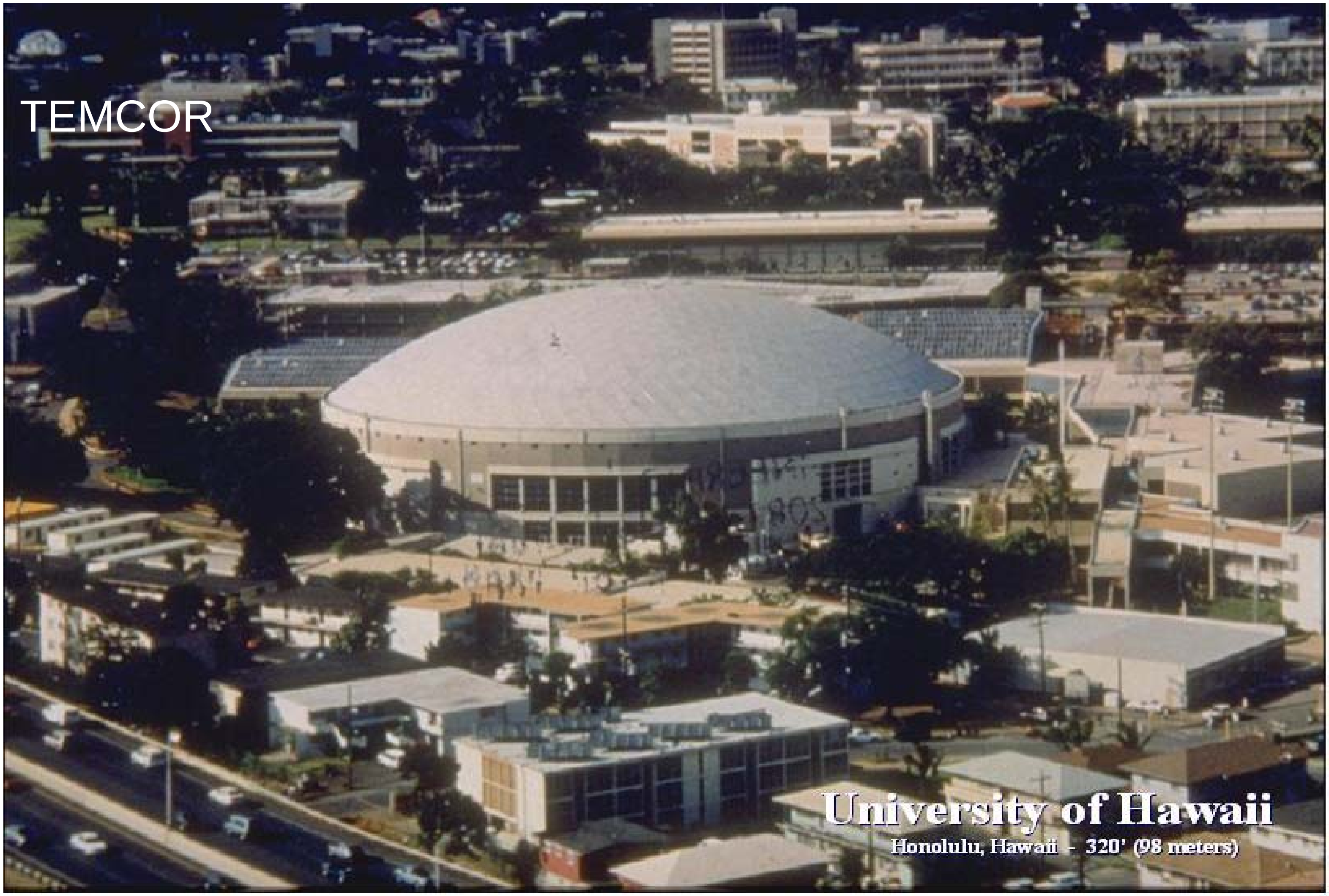
- The alloys that Temcor uses, 3003-H16 and 6061-T6, in its domes perform well. Aluminum, many times has been given a bad name due to the use of aluminum copper alloys which do not perform well in marine atmospheres, as well as the low-end aluminum market, that uses re-melted scrap which develops adequate physical properties but not chemical properties. Such products are used commonly in screens, door frames, window frames, etc.

Temcor's oldest aluminum dome resides at what is now called Hilton Hawaiian Village in Honolulu, Hawaii. It was an all aluminum, mill finish dome, used as a theater and built in 1956 very near the ocean at Waikiki Beach. The dome is still in place and being used nightly for various performances by entertainers. It has also been declared an historic landmark.



In order to make it better blend in to the surrounding area, the dome was painted in about 1977 with a camouflage coating. But the over 20 years of performance prior to painting showed no corrosion had taken place

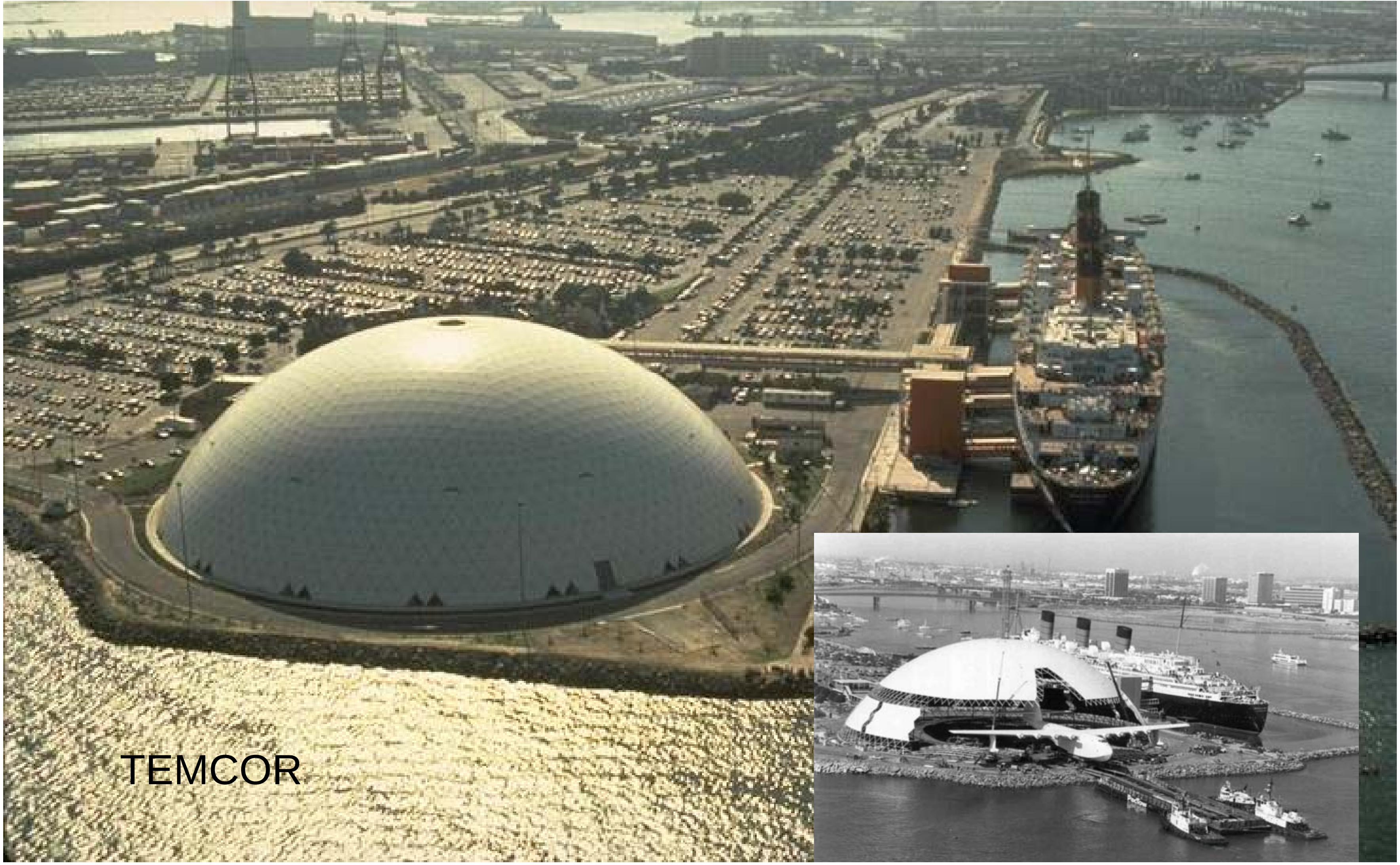
Another good example in Hawaii is The University of Hawaii Sports Arena which has a 98 meter Temcor Aluminum Dome covering it. The University chose to purchase an Aluminum Dome without paint or coatings because of the well known corrosion resistance of the Aluminum alloys used for marine environments. Built in 1993



Temcor has installed over 7000 aluminum domes in a variety of environments throughout the United States, and the world. In every case, the all aluminum construction has not been affected by marine atmospheres In February 1982, Temcor completed a 126.5 meter aluminum dome in Long Beach, California that was used for a time to house the “Spruce Goose”, Howard Hughes’ large airplane. The dome is still as maintenance free as the day it was built. In addition, aluminum was preferred as the airplane had been housed in a hanger skinned with 3003 aluminum sheet, the same alloy Temcor uses, for over 35 years in a nearby area. There was no evidence of corrosion despite Long Beach's heavy marine and industrial atmosphere.

LONG BEACH, CA

After the Spruce Goose was removed, the dome was used as a giant movie set for films such as "*Batman*“ and “Pirates of the Caribbean” (see http://www.seeing-stars.com/imagepages/QueenMaryDomePhoto1.shtml The dome is currently use as Terminal for the Carnival Cruise Line’s. See http://california.construction.com/features/archive/0305_CvrQueenMaryDome.asp

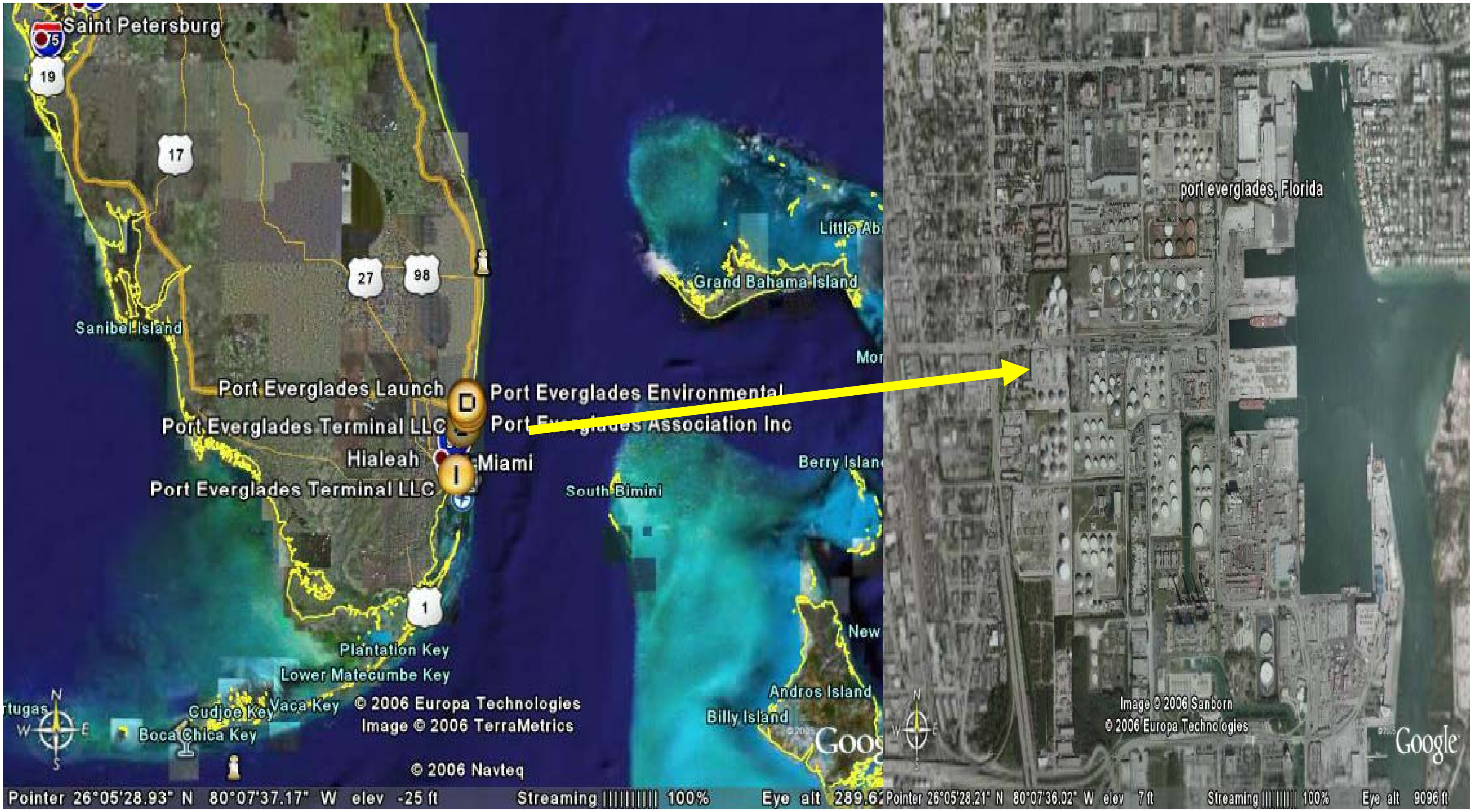


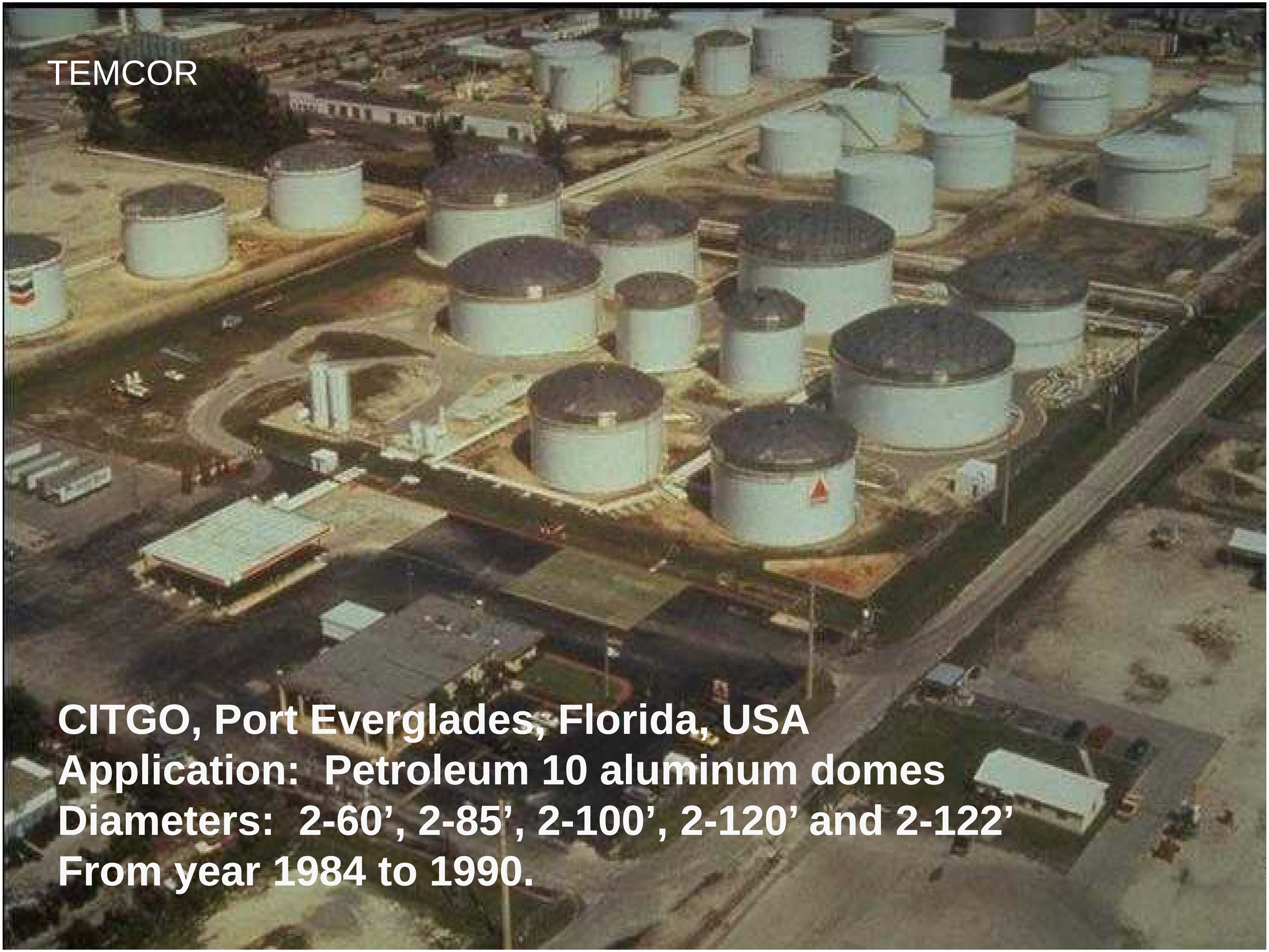
SEE SOME OF THE DOMES INSTALLED IN MARINE ATMOSPHERES. Satellite images from Google Earth

TANK WITH ALUMINUM DOME ROOF, 32 m (105 pies) DIAMETER. Cardon Refinery Venezuela. Year: 1996


Cardon Refinery, Venezuela

CITGO, Port Everglades Terminal
Fort Lauderdale, Florida USA



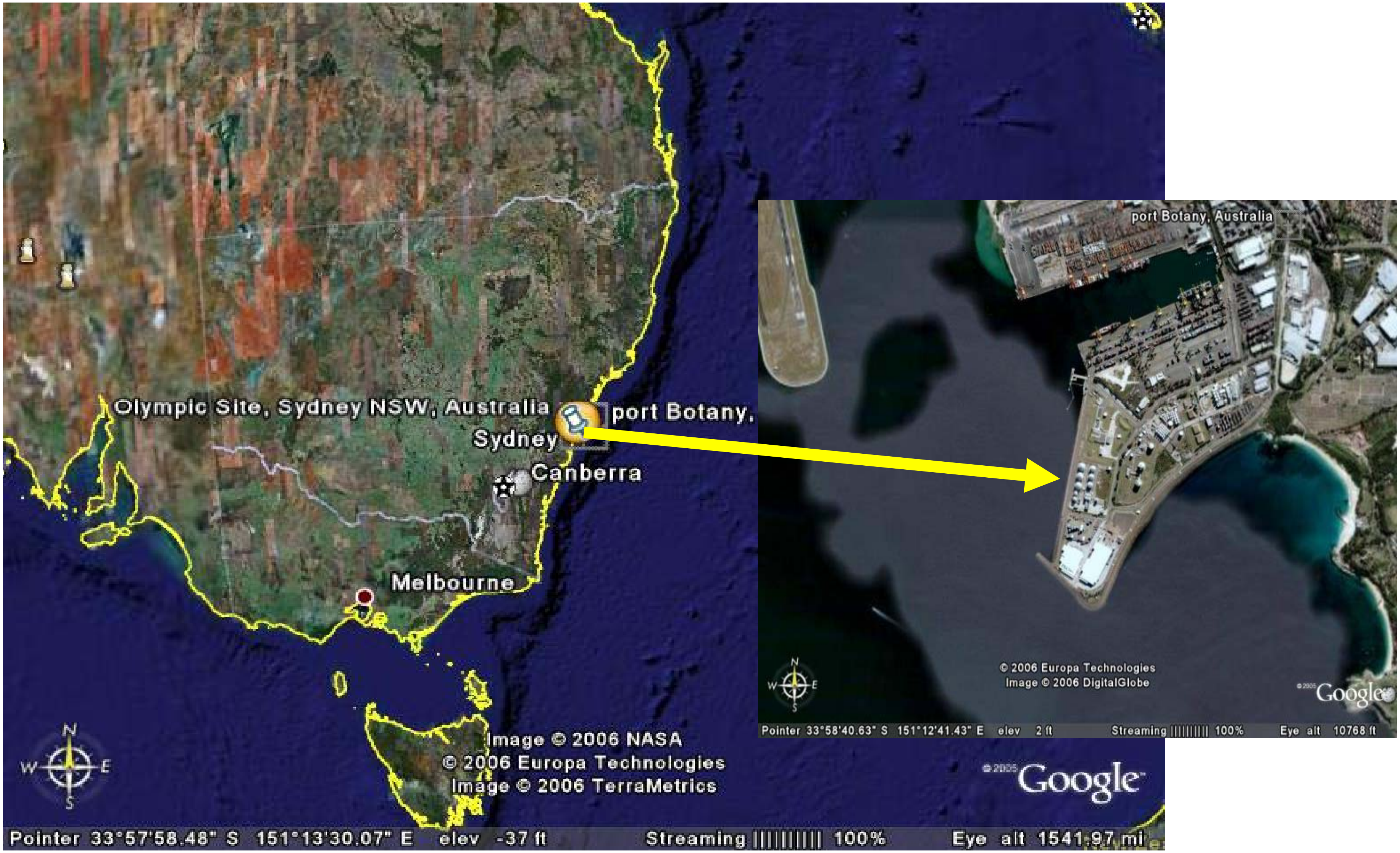


TEMCOR

CITGO, Port Everglades, Florida, USA
Application: Petroleum 10 aluminum domes
Diameters: 2-60’, 2-85’, 2-100’, 2-120’ and 2-122’
From year 1984 to 1990.

Van Ommeren Terminals

Port Botany, near Sidney, Australia

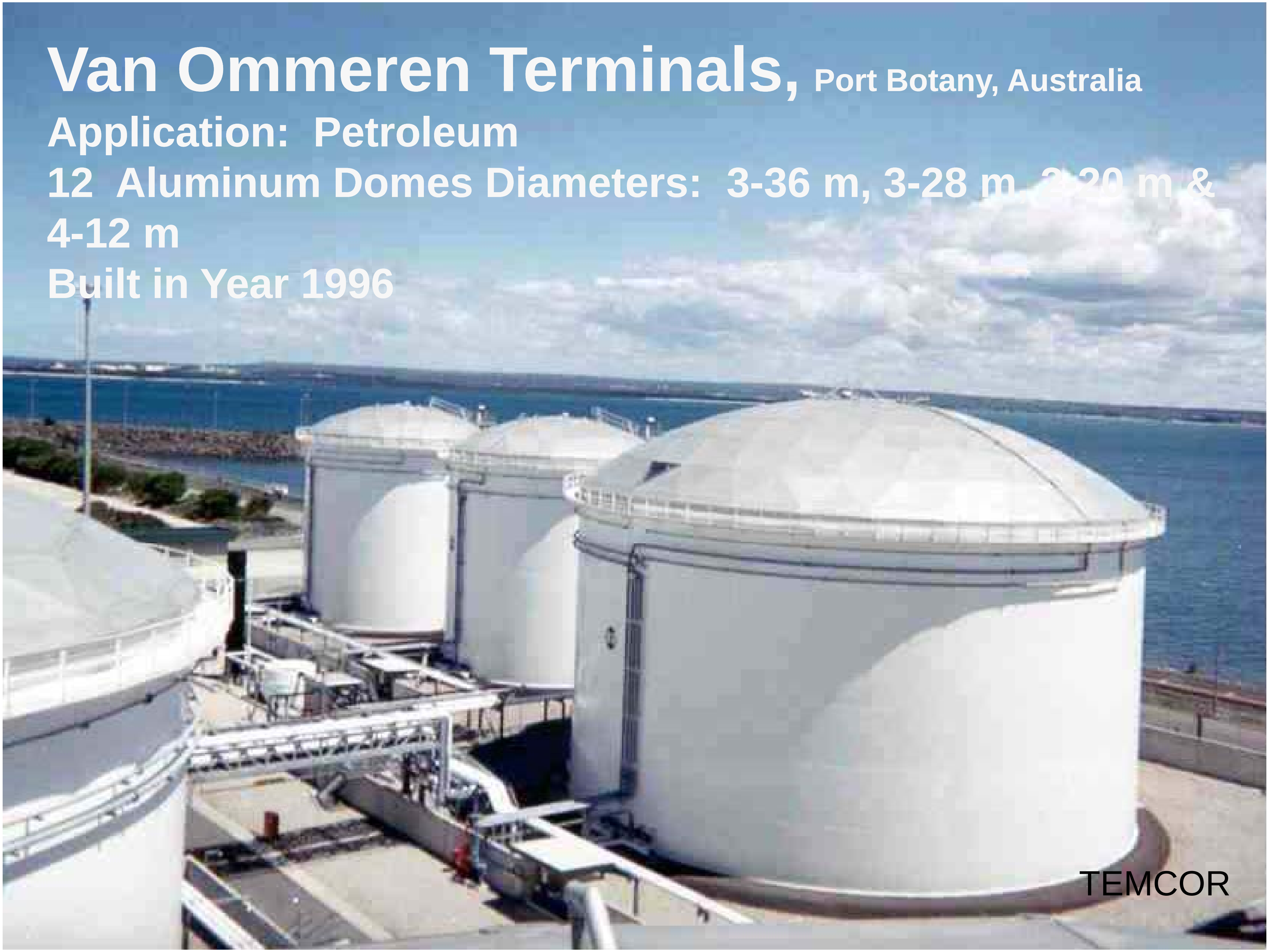


Van Ommeren Terminals, Port Botany, Australia

Application: Petroleum

12 Aluminum Domes Diameters: 3-36 m, 3-28 m, 2-20 m & 4-12 m

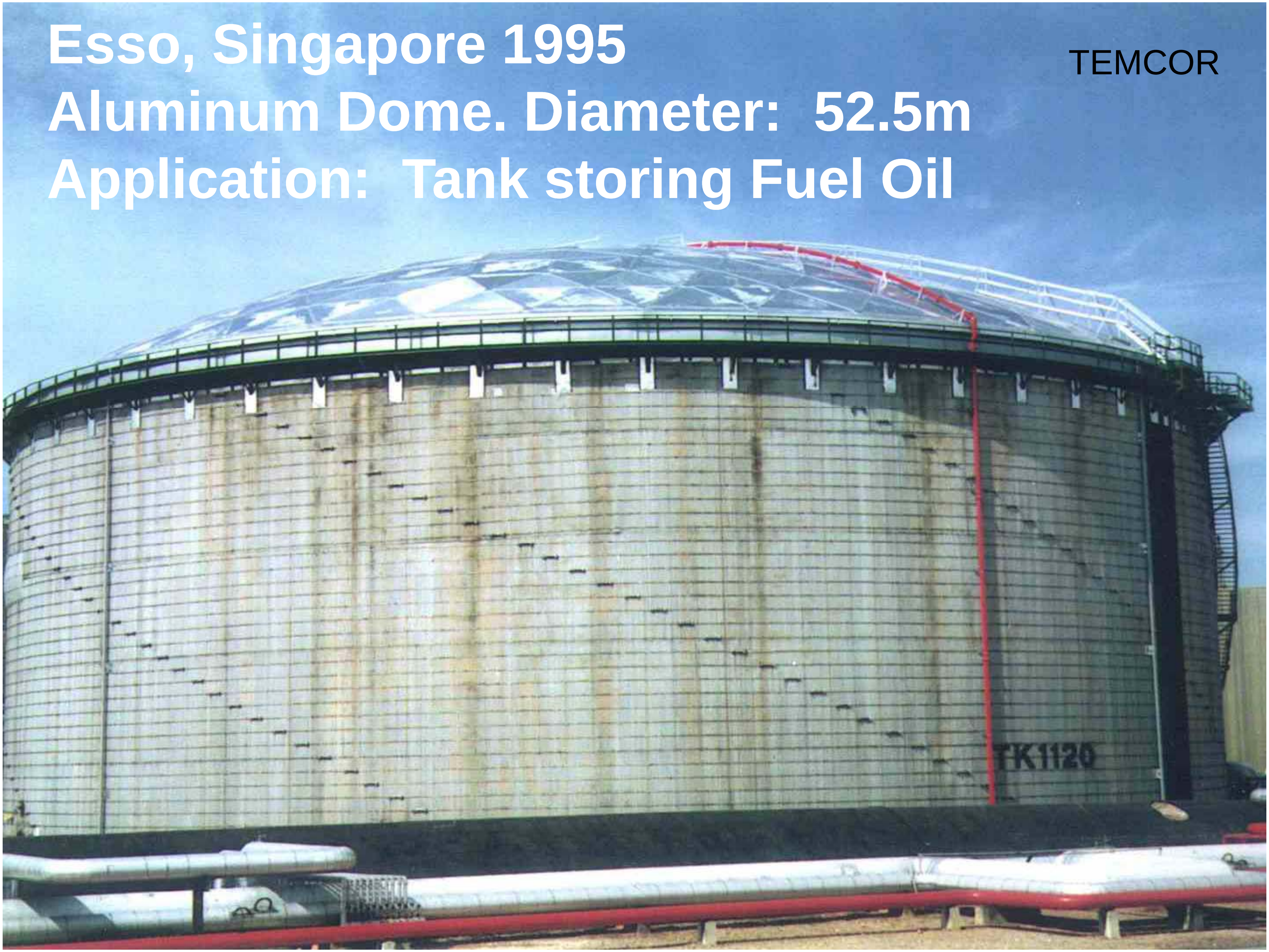
Built in Year 1996



TEMCOR

ESSO Pulau Ayer Chawan SINGAPORE

Esso Singapore 45.4m Fuel Oil Storage Tank;
conversion from steel cone roof to aluminum dome;
completed January, 1997.



Esso, Singapore 1995

Aluminum Dome. Diameter: 52.5m

Application: Tank storing Fuel Oil

TEMCOR

DECAL. TERMINAL IN RECIFE, BRAZIL

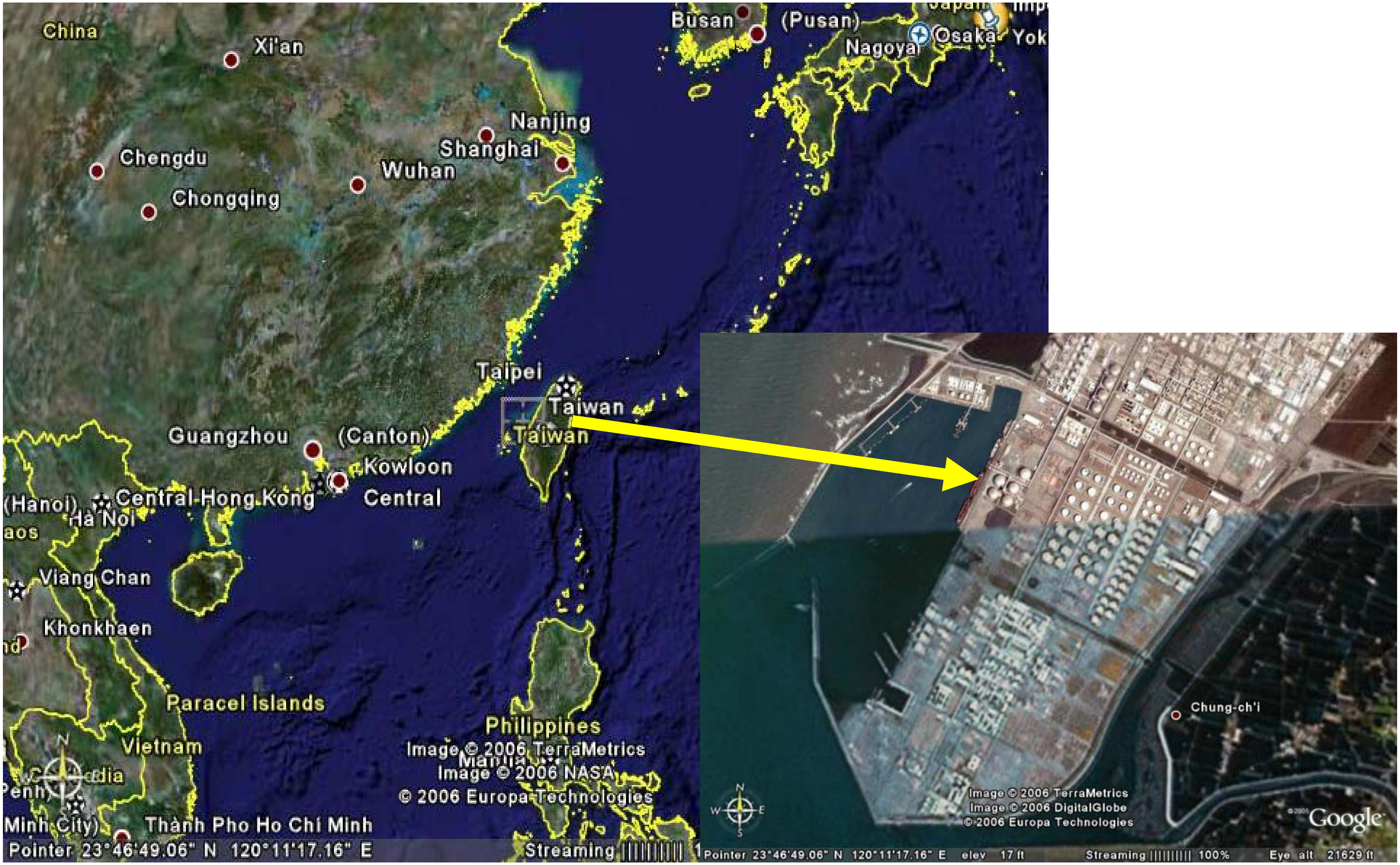
PICTURE DURING CONSTRUCTION. YEAR 2OO3

DECAL. TERMINAL IN RECIFE, BRAZIL. Storing Diesel, alcohol & gasoline

13 ALUMINUM DOMES: 1-45.6 M, 2-41.7 M, 2-40.3 M, 2-30.4 M, 2-27.4 M, 1-24.8 M, 2-21.3 M & 1-8.0 M

TEMCOR

MAI LIAO, YUN LIN, TAIWAN



Formosa Plastics Corp, Taiwan

Application: Coal (9) / Salt (2)

Diameter: 120m (394')

Capacity: 180,000 t

台塑重工(股)公司規劃

龜鼎工程有限公司承造

TEMCOR

TEMCOR

TAIWAN, FORMOSA
PLASTIC CORPORATION

11 ALUMINUM DOMES STORING SALT & COAL

6-120 M Built in 1996, 4-120 m Built in 1998 & 1-120 m Built in 2002

Aluminum Dome in a Marine Environment

- There is considerable literature that can be provided, including test studies, reports and actual certifications by institutes such as Battelle Memorial Institute, as to the performance of test panels of the same alloys Temcor uses in it’s covers.
- In summary, the alloys that Temcor utilizes in its products are well documented for use in industrial applications. The net result should be a permanent maintenance-free installation for your operation. This performance is certainly superior to that of steel in a marine environment.

ADVANTAGES OF ALUMINUM AS A BUILDING MATERIAL

ATTACHMENT 3

ALUMINUM INCOMBUSTIBILITY TEST

file

LABORATORY CERTIFICATE

SIGNET TESTING LABORATORIES, INC.

TESTING AND INSPECTION OF CONSTRUCTIONAL AND INDUSTRIAL MATERIALS

ENGINEERS
CHEMISTS
METALLURGISTS

REPLY TO
1428 WEST WINTON AVENUE
HAYWARD, CALIFORNIA 94545
782-7919 AREA CODE 415

September 30, 1968

P.O. # 90-90404

LAB NO.: 4342
SAMPLES: Two (2) Samples of Aluminum Alloy
MARK: 3004 Alloy and 8112 Alloy
DATE TESTED: August 23, 1968 and September 17, 1968
REPORT TO: Kaiser Aluminum and Chemical Corporation
300 Lakeside Drive
Oakland, California 94604
Attention: Mr. R.A. Edgren

REPORT

TEST

The submitted samples of aluminum alloys were tested for noncombustibility property as prescribed by ASTM Designation: E136-65, "Standard Method of Test for Determining Noncombustibility of Elementary Materials".

TEST SPECIMENS AND PROCEDURES

The prepared test specimens were 1½" wide by 1½" thick by 2" long. The test was performed in accordance with the procedure specified in ASTM Designation: E136-65. Temperature Specification: 1382 ± 10°F. Exposure period specification: After 5 minutes of exposure, test continued until thermocouples on specimens reached maxima.

TEST RESULTS

	EXPOSURE TEMPERATURE, °F		
3004 Alloy Specimen	Initial Temperature	Final Temperature	Observation
1	1390	1380	Noncombustible
2	1390	1380	Noncombustible
3	1390	1380	Noncombustible
4	1385	1380	Noncombustible
8112 Alloy Specimen			
1	1390	1380	Noncombustible
2	1385	1380	Noncombustible
3	1390	1380	Noncombustible
4	1390	1380	Noncombustible

Respectfully submitted,
SIGNET TESTING LABORATORIES, INC.

By Wilbur Chinn

ESTABLISHED 1880

United States Testing Company, Inc.

HOBOKEN, N. J. 07030
201-792-2400

REPORT

RECEIVED
JUL 24 1967
W. W. PRITSKY

NUMBER
10107
(Refer to this number)

July 19, 1967

Client: The Aluminum Association
420 Lexington Avenue
New York, New York 10017

Subject: Two (2) samples of aluminum alloy, sampled and identified by Client for specification tests. Letter dated 7-11-67.

Sample Identification:*

1. 6061-T6 Aluminum Alloy (1" cubes)
2. 6063-T5 Aluminum Alloy (1" cubes)

Test Performed:

The submitted samples were tested for conformance to the requirements of "Incombustible Material" as defined in Section 410 Volume I of the Uniform Building Code 1961 Edition, published by the International Conference of Building Officials.

Test Procedure:

Testing for conformance to the above stated requirement was performed in accordance with the procedures specified in the Uniform Building Code Standard No. 4-1-61 Volume III-1961 Edition.

*Certification of material as supplied by Client is appended to this report.

Test Results:

	Exposure Temperature, °F. 5 minute duration		
6061-T6	Start	Finish	Observations
Specimen			
1	1205	1200	Conforms
2	1205	1205	Conforms
3	1205	1205	Conforms
6063-T5			
Specimen			
1	1205	1210	Conforms
2	1205	1210	Conforms
3	1210	1210	Conforms

Supervised By John Carroll
John Carroll
Metallurgist

United States Testing Company, Inc.
BY F. Razzuoli

File

LABORATORY CERTIFICATE

SIGNET TESTING LABORATORIES, INC.

TESTING AND INSPECTION OF CONSTRUCTIONAL AND INDUSTRIAL MATERIALS

ENGINEERS
CHEMISTS
METALLURGISTS

REPLY TO
1428 WEST WINTON AVENUE
HAYWARD, CALIFORNIA 94545
782-7919 AREA CODE 415

May 17, 1972

LAB NO.: 10263 P.O. No.; 395M909727

SAMPLES: Three (3) Samples of Aluminum Alloy

MARK: 3003 Alloy, 3105 Alloy and 5005 Alloy

DATE TESTED: May 5, 1972

REPORT TO:
Kaiser Aluminum and Chemical Corporation
300 Lakeside Drive #7730B
Oakland, California 94604
Attention: R.A. Edgren

REPORT

TEST

The submitted samples of aluminum alloys were tested for noncombustibility property as prescribed by ASTM Designation: E136-65, "Standard Method of Test for Determining Noncombustibility of Elementary Materials".

TEST SPECIMENS AND PROCEDURES

The prepared test specimens were 1 1/2" wide by 1 1/2" thick by 2" long. The test was performed in accordance with the procedure specified in ASTM Designation: E136-65. Temperature Specification: 1382 ± 10°F. Exposure period specification: after 5 minutes of exposure, test continued until thermocouples on specimens reached maxima.

TEST RESULTS	EXPOSURE TEMPERATURE, 0°F		
	Initial Temperature	Final Temperature	Observation
3003 Alloy Specimen			
1	1390	1385	Noncombustible
2	1390	1388	Noncombustible
3	1390	1385	Noncombustible
4	1390	1390	Noncombustible
3105 Alloy Specimen			
1	1390	1390	Noncombustible
2	1390	1385	Noncombustible
3	1390	1390	Noncombustible
4	1390	1390	Noncombustible
5005 Alloy Specimen			
1	1390	1380	Noncombustible
2	1390	1385	Noncombustible
3	1390	1385	Noncombustible
4	1390	1390	Noncombustible

Respectfully submitted,
SIGNET TESTING LABORATORIES, INC.

By

2cc: Kaiser Aluminum
s

ADVANTAGES OF ALUMINUM AS A BUILDING MATERIAL

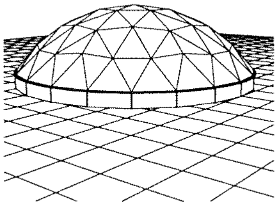
ATTACHMENT 4

ALUMINUM TEMPERATURE STRENGTH

TEMCOR

Phone:(310) 549-4311 • Fax:(310) 549-4588

24724 S. Wilmington Avenue, Carson, CA 90745
P.O. Box 6256, Carson, CA 90749



FAX COVER SHEET

DATE: August 27, 1999

COMPANY: Formosa Heavy Industries

FROM: G. Clark Margolf

ATTN: Chien-Sung Wang
Marketing and Planning Manager

FAX NO: 011 886 7 3717476

REF: Aluminum Tables

ATTACHED: - Total number of pages including transmittal - 10

Dear Mr. Wang,

As requested, attached please find aluminum temperature information previously sent to Mr. Tseng as well as additional information on the performance of steel at elevated temperatures.

As the preliminary heat transfer analysis report (attached) from Parson's shows, when aluminum reaches 400 degrees F from a heat source, steel reaches 950 degrees F from exposure to the same heat source. This will deform the steel and steel's properties do not allow the return of strength as do aluminum. For example at 400 degrees F for one half hour, aluminum per Alcoa's table reduces to 80% of original or to 32 ksi yield and after cooling back to room temperature it returns to 100% or 40 ksi. Steel according to MIL-HDBK-5G (Military Handbook) for the same period of one half hour at 950 degrees F (equivalent to aluminum being 400 degrees F) goes to about 50% of its original room temperature yield strength. In other words under coal fire conditions the aluminum will perform better than steel due to its superior conductivity and specific heat properties.

I hope this information will be of assistance to you. Please let me know if I can be of further help.

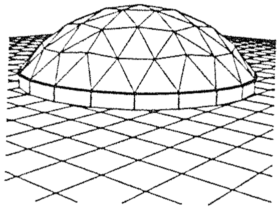
Very truly yours,

G. Clark Margolf
Executive Vice President

cc: J.C. Tseng - Kingtech ✓

TEMCOR

Phone:(310) 549-4311 • Fax:(310) 549-4588
24724 S. Wilmington Avenue, Carson, CA 90745
P.O. Box 6256, Carson, CA 90749



FAX COVER SHEET

DATE: August 27, 1999

COMPANY: Kingtech Engineering Corp.

FROM: G. Clark Margolf

ATTN: J.C. Tseng

FAX NO: 011-886-7-3369124

REF: Temperature Reports

ATTACHED: - Total number of pages including transmittal - 6

Dear Mr. Tseng,

Attached please find the following:

1. Kaiser Aluminum report (2 pages) showing tensile properties of 6061-T6 aluminum ***after*** being exposed to elevated temperatures for different lengths of time. These are the values discussed in my July 19th fax.
2. The Aluminum Association Table 8 for tensile properties ***at*** an elevated temperature for 10,000 hours (see footnote 1).
3. An Alcoa report for 6061-T6 showing both ***at*** and ***after*** for various temperatures for different lengths of time.

As you will note there are some variances between the data due to test sample differences. In any event, none of these values will have any impact on the dome to support itself as only about 10% of its design capacity is required to support its dead load. Of course, wind or live load might have to be considered.

I hope to have the dust as well as the temperature studies by early next week which will provide a more definite response to the unfounded statements by a competitor.

Regards,

RECEIVED DEC 17 1979

KAISER
ALUMINUM

KAISER ALUMINUM & CHEMICAL SALES, INC.

December 13, 1979

Mr. Clark Margoff
Temcor
2825 Toledo Street
Torrance, CA 90503

Dear Clark:

The lab sent me the attached chart showing room temperature tensile properties of 6061-T6 rod and extruded bar after exposure to elevated temperatures.

I thought this might be useful to you for the dome you are designing which is exposed to elevated temperatures. The data given should be fairly typical for sheet also. If you require any further information, please advise.

Yours truly,

KAISER ALUMINUM AND
CHEMICAL SALES, INC.

Bob Beran

R. J. Beran
Regional Field Engineer

RJB/slb
Enc.

cc: Mr. R. Weatherford, Kaiser
Mr. P. Sydow, Jr., Kaiser

P.O. BOX 22100, 6250 E. BANDINI BLVD., LOS ANGELES, CALIFORNIA 90040, 213/726-7762

Table I. Room-temperature Tensile Properties of 6061-T6 After Exposure to Elevated Temperature

Alloy Designation: 6061 Data Sheet No: 1
Heat Treatment T6 Form 3/4-in. Dia. rod

Chemical	Al	Bal.	Cu	0.23	Zn	0.02	Cr	0.22	Bi		Th	
Analysis	Mg	0.88	Fe	0.38	Ni	0.03	Zr		Pb		Be	
% by Wt	Si	0.57	Mn	0.04	Ti	0.07	Co		Misch Metal			

SHORT-TIME TENSILE PROPERTIES

Prior Exposure (1) Temp °F	Prior Exposure (1) Time, hr.	Test Temp °F	Elastic Modulus 10^6 psi	Yield (2) Strength 1000 psi	Tensile Strength 1000 psi	Elong % (3)	R. A. %
		Room		38.2	44.3	19.8	50.0
212	1/2	Room		38.6	44.7	18.5	48.0
212	1/2	Room		32.9	44.3	19.0	47.0
212	1/2	Room		37.8	44.2	19.5	48.0
212	100	Room		33.3	44.4	18.0	48.0
212	100	Room		38.1	44.1	19.0	48.0
212	1000	Room		39.9	45.2	18.5	50.0
212	1000	Room		39.1	45.0	18.5	49.0
212	5000	Room		39.7	45.1	18.0	47.0
212	10000	Room		39.7	45.0	19.0	46.0
300	1/2	Room		38.5	44.8	20.0	50.0
300	1/2	Room		32.8	44.1	19.0	49.0
300	1/2	Room		38.0	44.3	19.5	49.0
300	1	Room		38.2	44.0	18.5	50.0
300	16	Room		38.6	44.5	18.5	44.0
300	100	Room		39.5	44.4	18.0	47.0
300	1000	Room		39.4	43.2	17.0	49.0
300	5000	Room		36.8	41.0	18.0	52.0
300	10000	Room		36.0	40.4	18.0	52.0
400	1/12	Room		37.3	42.4	17.5	50.0
400	1/6	Room		37.8	42.8	17.0	50.0
400	1/3	Room		38.3	43.1	16.5	50.0
400	1/2	Room		38.5	43.0	17.5	48.7
400	1/2	Room		38.2	42.9	17.5	50.0
400	4	Room		37.6	41.8	16.0	51.0
400	16	Room		34.9	39.7	16.5	52.0
400	20	Room		34.3	39.1	17.0	53.0
400	100	Room		31.3	37.1	17.5	55.0
400	1000	Room		22.9	31.4	18.0	56.0
400	5000	Room		17.1	26.7	20.0	60.0
400	10000	Room		16.2	26.1	21.0	60.0
500	1/2	Room		35.9	40.7	16.5	51.0
500	4	Room		24.4	32.3	17.5	55.0
500	100	Room		14.8	25.2	21.0	64.0
500	1000	Room		12.1	22.4	23.0	62.0
500	5000	Room		8.1	18.5	31.0	65.0
500	10000	Room		7.9	17.9	32.0	65.0
600	1/2	Room		15.5	25.9	20.0	62.0
600	4	Room		14.5	24.9	21.5	63.0
600	20	Room		11.7	22.5	23.5	61.0
600	100	Room		9.2	19.9	29.5	65.0
600	500	Room		8.1	18.7	32.5	66.0
600	1000	Room		8.2	18.5	32.0	66.0
600	10000	Room		7.7	17.8	32.0	69.0
700	1/2	Room		12.4	23.4	22.5	61.0
700	1/2	Room		10.4	21.9	24.0	63.0
700	4	Room		9.1	20.6	28.0	64.0
700	20	Room		8.3	19.3	31.0	65.0
700	100	Room		8.3	18.9	30.0	67.0
800	1/2	Room		8.8	21.6	30.0	64.5
900	1/2	Room		9.8	22.7	29.5	63.0
1000	1/2	Room		10.3	22.8	26.5	62.0

Alloy Designation 6061 Data Sheet No
Heat Treatment T6 Form Extruded bar

Chemical	Al	Bal.	Cu	0.36	Zn	—	Cr	0.25	Bi	—	Th	
Analysis	Mg	0.83	Fe	0.45	Ni	—	Zr	—	Pb	—	Be	
% by Wt	Si	0.59	Mn	0.03	Ti	0.03	Co	—	Misch Metal			

SHORT-TIME TENSILE PROPERTIES

Prior Exposure (1) Temp °F	Prior Exposure (1) Time, hr.	Test Temp °F	Elastic Modulus 10^6 psi	Yield (2) Strength 1000 psi	Tensile Strength 1000 psi	Elong % (3)	R %.
—	—	Room	—	39.5	43.0	16.5	4
—	—	Room	—	39.3	42.4	16.5	4
—	—	Room	—	32.8	45.2	12.0	3
212	1/2	Room	—	40.0	42.1	18.0	47
212	360	Room	—	40.6	43.5	17.0	45
212	2400	Room	—	41.5	44.1	17.0	45
212	10000	Room	—	41.5	43.8	17.0	45
300	1/2	Room		39.6	42.6	17.5	47
300	16	Room		40.5	43.3	17.0	45
300	96	Room		41.3	43.3	16.0	46
300	480	Room		40.9	43.2	16.5	49
300	1920	Room		39.8	42.5	17.0	49
300	5000	Room		37.3	40.1	15.5	46
300	10000	Room		36.6	39.4	16.0	46
400	1/2	Room		39.4	42.0	17.0	47
400	6	Room		38.7	40.9	15.5	47
400	30	Room		35.3	38.3	16.5	48
400	96	Room		35.4	36.9	16.0	48
400	480	Room		30.4	35.3	16.0	51
400	2400	Room		24.1	31.6	17.0	55
400	7392	Room		23.7	31.3	17.0	56
400	10000	Room		19.2	28.3	17.5	52
500	1/2	Room		35.3	38.4	17.0	48
500	16	Room		16.9	26.6	18.5	56
500	72	Room		12.4	23.2	20.5	60
500	360	Room		13.6	24.1	19.5	57
500	960	Room		9.0	20.2	25.5	60
500	3600	Room		6.9	18.5	31.0	60
600	1/2	Room		19.1	28.1	18.0	56
600	4	Room		14.2	24.6	19.5	58
600	30	Room		10.3	21.4	23.5	59
600	96	Room		7.6	19.5	29.0	58
600	480	Room		6.2	17.9	34.5	62
600	1440	Room		6.1	17.6	34.5	61
600	5000	Room		5.9	17.3	44.0	63
600	16800	Room		3.9	17.0	34.0	61
700	1/2	Room		13.3	24.3	20.0	32
700	4	Room		7.9	19.9	27.5	57
700	16	Room		6.4	18.6	33.0	61
700	960	Room		6.3	17.7	34.0	62
700	10000	Room		6.3	17.4	33.5	61
800	1/2	Room		7.3	20.4	30.5	59
900	1/2	Room		8.2	21.7	30.0	57
1000	1/2	Room		9.1	23.5	26.0	53

KAiser AL.

Aluminum Associat.

TABLE 8
TYPICAL TENSILE PROPERTIES AT VARIOUS TEMPERATURES ① (Continued)

The following typical properties are not guaranteed, since in most cases they are averages for various sizes, product forms and methods of manufacture and may not be exactly representative of any particular product or size. These data are intended only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes.

ALLOY AND TEMPER	TEMP.	TENSILE STRENGTH, ksi		ELONGATION IN 2 IN., PERCENT
	°F	ULTIMATE	YIELD ②	
5454-H32	-320	59	36	32
	-112	42	31	23
	-18	41	30	20
	75	40	30	18
	212	39	29	20
	300	32	26	37
	400	25	19	45
	500	17	11	80
	600	11	7.5	110
	700	6	4.2	130
5454-H34	-320	63	41	30
	-112	46	36	21
	-18	44	35	18
	75	44	35	16
	212	43	34	18
	300	34	28	32
	400	26	19	45
	500	17	11	80
	600	11	7.5	110
	700	6	4.2	130
5456-O	-320	62	26	32
	-112	46	23	25
	-18	45	23	22
	75	45	23	20
	212	42	22	31
	300	31	20	50
	400	22	17	60
	500	17	11	80
	600	11	7.5	110
	700	6	4.2	130
5652-O	-320	44	16	46
	-112	29	13	35
	-18	28	13	32
	75	28	13	30
	212	28	13	30
	300	23	13	50
	400	17	11	60
	500	12	7.5	80
	600	7.5	5.5	110
	700	5	3.1	130
5652-H34	-320	55	36	28
	-112	40	32	21
	-18	38	31	18
	75	38	31	16
	212	38	31	18
	300	30	27	27
	400	24	15	45
	500	12	7.5	80
	600	7.5	5.5	110
	700	5	3.1	130
5652-H38	-320	60	44	25
	-112	44	38	18
	-18	42	37	15
	75	42	37	14
	212	40	36	16
	300	34	28	24
	400	25	15	45
	500	12	7.5	80
	600	7.5	5.5	110
	700	5	3.1	130
6053-T6, T651	75	37	32	13
	212	32	28	13
	300	25	24	13
	400	13	12	25
	500	5.5	4	70
	600	4	2.7	80
	700	2.9	2	90
6061-T6, T651	-320	60	47	22
	-112	49	42	18
	-18	47	41	17
	75	45	40	17
	212	42	38	18
	300	34	31	20
	400	19	15	28
	500	7.5	5	60
	600	4.6	2.7	85
	700	3	1.8	95
6063-T1	-320	34	16	44
	-112	26	15	36
	-18	24	14	34
	75	22	13	33
	212	22	14	18
	300	21	15	20
	400	9	6.5	40
	500	4.5	3.5	75
	600	3.2	2.5	80
	700	2.3	2	105
6063-T5	-320	37	24	28
	-112	29	22	24
	-18	28	22	23
	75	27	21	22
	212	24	20	18
	300	20	18	20
	400	9	6.5	40
	500	4.5	3.5	75
	600	3.2	2.5	80
	700	2.3	2	105
6063-T6	-320	47	36	24
	-112	38	33	20
	-18	36	32	19
	75	35	31	18
	212	31	28	15
	300	21	20	20
	400	9	6.5	40
	500	4.5	3.5	75
	600	3.3	2.5	80
	700	2.3	2	105

For all numbered footnotes, see last page of this Table.

TABLE 8
TYPICAL TENSILE PROPERTIES AT VARIOUS TEMPERATURES ① (Concluded)

The following typical properties are not guaranteed, since in most cases they are averages for various sizes, product forms and methods of manufacture and may not be exactly representative of any particular product or size. These data are intended only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes.

ALLOY AND TEMPER	TEMP. °F	TENSILE STRENGTH, ksi ULTIMATE	TENSILE STRENGTH, ksi YIELD ②	ELONGATION IN 2 IN., PERCENT
6101-T6	-320	43	33	24
	-112	36	30	20
	-18	34	29	19
	75	32	28	19
	212	28	25	20
	300	21	19	20
	400	10	7	40
	500	4.8	3.3	80
	600	3	2.3	100
	700	2.5	1.8	105
6151-T6	-320	57	50	20
	-112	50	46	17
	-18	49	45	17
	75	48	43	17
	212	43	40	17
	300	28	27	20
	400	14	12	30
	500	6.5	5	50
	600	5	3.9	43
	700	4	3.2	35
6262-T651	-320	60	47	22
	-112	49	42	18
	-18	47	41	17
	75	45	40	17
	212	42	38	18
	300	34	31	20
6262-T9	-320	74	67	14
	-112	62	58	10
	-18	60	56	10
	75	58	55	10
	212	53	52	10
	300	38	37	14
	400	15	13	34
	500	8.5	6	48
	600	4.6	2.7	85
	700	3	1.8	95
7075-T6, T651	-320	102	92	9
	-112	90	79	11
	-18	86	75	11
	75	83	73	11
	212	70	65	14
	300	31	27	30
	400	16	13	55
	500	11	9	65
	600	8	6.5	70
	700	6	4.6	70
7075-T73, T7351	-320	92	72	14
	-112	79	67	14
	-18	76	65	13
	75	73	63	13
	212	63	58	15
	300	31	27	30
	400	16	13	55
	500	11	9	65
	600	8	6.5	70
	700	6	4.6	70
7175-T74	-320	106	98	13
	-112	90	83	14
	-18	87	80	16
	212	72	69	17
	300	35	31	30
	400	18	13	65
7178-T6, T651	-320	106	94	5
	-112	94	84	8
	-18	91	81	9
	75	88	78	11
	212	73	68	14
	300	31	27	40
	400	15	12	70
	500	11	9	76
	600	8.5	7	80
	700	6.5	5.5	80
7178-T76, T7651	-320	106	89	10
	-112	91	78	10
	-18	88	76	10
	75	83	73	11
	212	69	64	17
	300	31	27	40
	400	15	12	70
	500	11	9	76
	600	8.5	7	80
	700	6.5	5.5	80
7475-T61 (SHEET)	-320	99	87	10
	-112	88	79	12
	-18	84	75	12
	75	80	72	12
	212	70	65	14
	300	30	26	28
	400	14	11	55
	500	9.5	7	70
	600	6.5	5.5	80
	700	5	3.8	85
7475-T761 (SHEET)	-320	95	82	11
	-112	84	73	12
	-18	80	70	12
	75	76	67	12
	212	64	61	14
	300	30	26	38
	400	14	11	55
	500	9.5	7	70
	600	6.5	5.5	80
	700	5	3.8	85

① These data are based on a limited amount of testing and represent the lowest strength during 10,000 hours of exposure at testing temperature under no load; stress applied at 5,000 psi/min to yield strength and then at strain rate of 0.05 in./in./min to failure. Under some conditions of temperature and time, the application of heat will adversely affect certain other properties of some alloys.

② Offset equals 0.2 percent.

6061-T6**

ALCOA

ALCOA RESEARCH LABORATORIES
TYPICAL MECHANICAL PROPERTIES AT VARIOUS TEMPERATURES

NOT RELEASED FOR PUBLICATION

TENSILE PROPERTIES

Temperature	Time at Temp, hr	At Temperature Indicated: Tensile Strength, ksi	At Temperature Indicated: Yield Strength, ksi	At Temperature Indicated: Elong. in 4D, %	At Temperature Indicated: Modulus of Elas*, 10³ ksi	At Room Temp After Heating: Tensile Strength, ksi	At Room Temp After Heating: Yield Strength, ksi	At Room Temp After Heating: Elong. in 4D, %
-452°F		74	53	27				
-423°F		74	53	27				
-320°F		58	46	23	11.1			
-112°F		49	42	19	10.4			
- 18°F		47	41	18	10.1			
75°F		45	40	17	9.9	45	40	17
212°F	0.1	41	38	19		45	40	17
	0.5	41	38	19		45	40	17
	10	41	38	18		45	40	17
	100	41	38	18	9.5	45	40	17
	1 000	42	39	18		46	41	17
	10 000	42	39	18		46	42	17
	100 000	42	39	17		45	41	17
300°F	0.1	38	36	20		45	40	17
	0.5	38	36	20		45	40	17
	10	38	36	19		46	41	16
	100	38	36	18	9.1	45	41	16
	1 000	38	36	18		43	40	16
	10 000	33	31	19		39	35	17
	100 000	29	27	21		35	30	17
350°F	0.1	36	35	21		45	40	17
	0.5	35	35	21		45	40	17
	10	36	35	18		44	40	15
	100	34	32	18	8.9	41	38	16
	1 000	30	28	19		38	34	16
	10 000	24	22	22		33	27	18
	100 000	20	17	28		28	21	19
400°F	0.1	34	32	20		44	39	18
	0.5	34	32	19		44	40	17
	10	30	30	18		40	36	16
	100	27	25	19	8.6	35	30	17
	1 000	22	20	23		31	24	17
	10 000	17	14	28		26	18	19
	100 000	13	9	40		21	11	24
450°F	0.1	29	28	19		43	38	16
	0.5	29	28	17		42	38	16
	10	24	23	18		34	28	17
	100	19	18	23	8.3	29	21	18
	1 000	15	13	30		25	15	19
	10 000	12	8.5	40		20	11	24
	100 000	9	6.5	70		18	8	30
500°F	0.1	25	24	17		41	36	15
	0.5	23	22	16		39	33	16
	10	18	16	20		29	20	18
	100	13	11	29	7.9	25	14	20
	1 000	10	8	45		21	10	24
	10 000	8	6	65		18	8	30
	100 000	7	5.5	80		18	8	30
600°F	0.1	14	13	18		32	25	17
	0.5	12	11	23		27	17	19
	10	9	8	30		23	12	22
	100	6	4.5	65	6.3	20	8.5	29
	1 000	5	4.2	80		18	8	30
	10 000	5	4.2	90		18	8	30
	100 000	5	4.2	80		18	8	30
700°F	0.1	8.5	5	35		27	17	20
	0.5	7	6.5	35		23	12	22
	10	3.8	3	80		19	8	30
	100	3.6	3	80	5.5	19	8	30
	1 000	3.6	3	80		18	8	30
	10 000	3.6	3	80		18	8	30
	100 000	3.6	3	80		18	8	30
800°F	0.1	3.8	3.2	65				
	0.5	3	2.4	80				
900°F		2.2	1.6	80				
1000°F		1.6	1.2	60				

CREEP-RUPTURE AND CREEP PROPERTIES / STRESS-RELAXATION / FATIGUE PROPERTIES†

Temperature	Time Under Stress, hr	Stress, ksi, for Rupture and Creep In Time Indicated: Rupture	1.0% Creep	0.5% Creep	0.2% Creep	0.1% Creep	Stress-Relaxation: Time Under Strain‡, hr	Stress-Relaxation: Loss in Stress, %	Fatigue: No. of Cycles	Fatigue: Stress, ksi
75°F	0.1	45	45	44	43	42	0.1			
	1	45	45	43	42	42	1		10⁴	44
	10	45	44	43	42	42	10		10⁵	31
	100	45	44	42	42	41	100		10⁶	23
	1 000	45	43	42	41	41	1 000		10⁷	17
	10 000						10 000		10⁸	15
	100 000						100 000		5x10⁸	14
212°F	0.1	41	40	40	39	38	0.1			
	1	40	39	39	38	37	1		10⁴	
	10	39	38	38	37	36	10		10⁵	
	100	38	37	37			100		10⁶	
	1 000	37					1 000		10⁷	
	10 000						10 000		10⁸	
	100 000						100 000		5x10⁸	
300°F	0.1	37	36	36	35	34	0.1			
	1	36	34	34	32	31	1		10⁴	
	10	34	32	32	30	28	10		10⁵	
	100	31	30	29	27	24	100		10⁶	
	1 000	27	26	25	21	17	1 000		10⁷	
	10 000						10 000		10⁸	
	100 000						100 000		5x10⁸	
350°F	0.1	34	33	33	32	30	0.1			
	1	32	31	31	29	27	1		10⁴	
	10	30	29	28	25	23	10		10⁵	
	100	26	25	24	22	17	100		10⁶	
	1 000	20	19	18	15	12	1 000		10⁷	
	10 000						10 000		10⁸	
	100 000						100 000		5x10⁸	
400°F	0.1	31	30	29	28	26	0.1			
	1	28	27	26	24	22	1		10⁴	
	10	24	24	23	20	17	10		10⁵	
	100	20	19	18	15	10	100		10⁶	
	1 000	14	13	12	8.5	6.5	1 000		10⁷	
	10 000	10					10 000		10⁸	
	100 000						100 000		5x10⁸	
450°F	0.1	25	24	24	23	20	0.1			
	1	22	21	21	19	16	1		10⁴	
	10	17	16	15	13	11	10		10⁵	
	100	13	12	11	8.5	6	100		10⁶	
	1 000	9.5	8.5	7			1 000		10⁷	
	10 000						10 000		10⁸	
	100 000						100 000		5x10⁸	
500°F	0.1	20	19	19	18	16	0.1			
	1	17	16	15	14	12	1		10⁴	
	10	12	11	11	9	7	10		10⁵	
	100	8.5	8	7	5.5	4.2	100		10⁶	
	1 000	6.5	5.5	4.7			1 000		10⁷	
	10 000						10 000		10⁸	
	100 000						100 000		5x10⁸	
600°F	0.1	11	10	9.5	9	8	0.1		10⁴	
	1	9.5	8	8	7	6	1		10⁵	
	10	7	6	5.5	4.3	3.2	10		10⁶	
	100	3.6	3.0	2.8	2.2	2.0	100		10⁷	
	1 000	2.3	2.2	2.1	1.9	1.7	1 000		10⁸	
	10 000	1.7					10 000		5x10⁸	
700°F	0.1						0.1		10⁴	
	1						1		10⁵	
	10						10		10⁶	
	100						100		10⁷	
	1 000						1 000		10⁸	
									5x10⁸	

* The modulus of elasticity in compression is about 2 per cent greater than in tension.

† Based on results of rotating-beam tests at room temperature and cantilever-beam (rotating-load) tests at elevated temperatures.

‡ Stressed in tension to 60% of the tensile yield strength at the stressing temperature. Strain held constant during exposure.

** Sheet and rolled-and-drawn products.

June 18, 1970

PARSONS

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September 3, 1999

Mr. G. Clark Margolf, Executive Vice President
TEMCOR
24724 S. Wilmington Ave.
Carson, CA 90749

Subject: Heat Transfer Analysis Status Report

Dear Mr. Margolf:

The following is a preliminary heat transfer analysis of the effects of a heat event to a dome. The setting is coal storage covered by (1) an aluminum dome, and (2) a sheet metal dome. The analysis applies a heat source of one million Btu/hr.

At this point in time, the analysis is modeled after two horizontal plates with the heat source facing upward. A more refined analysis is being considered and would therefore modify the results.

Results

Based on a constant heat source of 1,000,000 Btu/hr applied under the dome, an aluminum skin would have an average temperature of approximately 400°F (~2,000 ft^2) and a galvanized steel dome skin would have an average temperature of 950°F (362 ft^2). The 400°F temperature was picked because it is aluminum's deformation temperature. The primary reason for the large temperature difference between aluminum and steel is the difference in thermal conductivities.

This preliminary analysis is somewhat simplistic in that the skin temperature was assumed constant over the whole area. In reality, a gradient would exist with a temperature spike at the center and lower temperatures at the extreme. Aluminum, because of its high thermal conductivity would have a much lower thermal gradient. The temperature spike for steel would be very high. The 950°F average steel skin temperature is already well above steel's 800°F deformation temperature.

Thank you for the opportunity to prepare the preliminary and future refined analyses. We look forward to working with TEMCOR on future projects. Should you have any questions, please contact me at x6216. We will be happy to provide any additional information promptly at your request.

Sincerely,

PARSONS ENGINEERING SCIENCE, INC.

Charles W. Botsford

Charles W. Botsford, P.E.
Senior Engineer

2.2 Carbon Steels

2.2.0 COMMENTS ON CARBON STEELS

2.2.0.1 *Metallurgical Considerations.*— Carbon steels are those steels containing carbon up to about 1 percent and only residual quantities of other elements except those added for deoxidation.

The strength that carbon steels are capable of achieving is determined by carbon content and, to a much lesser extent, by the content of the residual elements. Through cold working or proper choice of heat treatments, these steels can be made to exhibit a wide range of strength properties.

The finish conditions most generally specified for carbon steels include hot-rolled, cold-rolled, cold-drawn, normalized, annealed, spheroidized, stress-relieved, and quenched-and-tempered. In addition, the low-carbon grades (up to 0.25 percent C) may be carburized to obtain high surface hardness and wear resistance with a tough core. Likewise, the higher carbon grades are amenable to selective flame hardening to obtain desired combinations of properties.

2.2.0.2 *Manufacturing Considerations*

Forging.—All of the carbon steels exhibit excellent forgeability in the austenitic state provided the proper forging temperatures are used. As the carbon content is increased, the maximum forging temperature is decreased. At high temperatures, these steels are soft and ductile and exhibit little or no tendency to work harden. The resulfurized grades (free-machining steels) exhibit a tendency to rupture when deformed in certain high-temperature ranges. Close control of forging temperatures is required.

Cold Forming.—The very low-carbon grades have excellent cold-forming characteristics when in the annealed or normalized conditions. Medium-carbon grades show progressively poorer formability with higher carbon content, and more frequent annealing is required. The high-carbon grades require special softening treatments for cold forming. Many carbon steels are embrittled by warm working or prolonged exposure in the temperature range from 300 to 700 F.

Machining.—The low-carbon grades (0.30 percent C and less) are soft and gummy in the annealed condition and are preferably machined in the cold-worked or the normalized condition. Medium-carbon (0.30 to 0.50 percent C) grades are best machined in the annealed condition, and high-carbon grades (0.50 to 0.90 percent C) in the spheroidized condition. Finish machining must often be done in the fully heat-treated condition for dimensional accuracy. The resulfurized grades are well known for their good machinability. Nearly all carbon steels are now available with 0.15 to 0.35 percent lead, added to improve machinability. However, resulfurized and leaded steels are not generally recommended for highly stressed aircraft and missile parts because of a drastic reduction in transverse properties.

Welding.—The low-carbon grades are readily welded or brazed by all techniques. The medium-carbon grades are also readily weldable but may require preheating and postwelding heat treatment. The high-carbon grades are difficult to weld. Preheating and postwelding heat treatment are usually mandatory for the latter, and special care must be taken to avoid overheating. Furnace brazing has been used successfully with all grades.

Heat Treatment.—Due to the poor oxidation resistance of carbon steels, protective atmospheres must be employed during heat treatment if scaling of the surface cannot be tolerated. Also, these steels are subject to decarburization at elevated temperatures and, where surface carbon content is critical, should be heated in reducing atmospheres.

2.2.0.3 *Environmental Considerations.*— Carbon steels have poor oxidation resistance above about 900 to 1000 F. Strength and oxidation-resistance criteria generally preclude the use of carbon steels above 900 F.

Carbon steels may undergo an abrupt transition from ductile to brittle behavior. This transition temperature varies widely for different carbon steels depending on many factors. Cautions should be exercised in the application of carbon steels to assure that the transition temperature of the selected alloy is below the service temperature. Additional information is contained in References 2.2.0.3(a) and (b).

2.3.0.3 *Environmental Considerations.*—Alloy steels containing chromium or high percentages of silicon have somewhat better oxidation resistance than the carbon or other alloy steels. Elevated-temperature strength for the alloy steels is also higher than that of corresponding carbon steels. The mechanical properties of all alloy steels in the heat-treated condition are affected by extended exposure to temperatures near or above the temperature at which they were tempered. The limiting temperatures to which each alloy may be exposed for no longer than approximately 1 hour per inch of thickness or approximately one-half hour for thicknesses under one-half inch without a reduction in strength occurring are listed in Table 2.3.0.3. These values are approximately 100 F below typical tempering temperatures used to achieve the designated strength levels.

Low-alloy steels may undergo a transition from ductile to brittle behavior at low temperatures. This transition temperature varies widely for different alloys. Caution should be exercised in the application of low-alloy steels at temperatures below -100 F. For use at a temperature below -100 F, an alloy with a transition temperature below the service temperature should be selected. For low temperatures, the steel should be heat treated to a tempered martensitic condition for maximum toughness.

Heat-treated alloy steels have better notch toughness than carbon steels at equivalent strength levels. The decrease in notch toughness is less pronounced and occurs at lower temperatures. Heat-treated alloy steels may be useful for subzero applications, depending on their alloy content and heat treatment. Heat treating to strength levels higher than 150 ksi F_{ty} may decrease notch toughness.

The corrosion properties of the AISI alloy steels are comparable to the plain carbon steels.

TABLE 2.3.0.3. *Temperature Exposure Limits for Low-Alloy Steels*

	Exposure Limit, F						
F_{tu}, ksi	125	150	180	200	220	260	270 & 280
Alloy:							
AISI 4130 and 8630	925	775	575	. . .	. . .	. . .	. . .
AISI 4140 and 8740	1025	875	725	625	. . .	. . .	. . .
AISI 4340	1100	950	800	700	. . .	350	. . .
AISI 4135 and 8735	975	825	675	. . .	. . .	. . .	. . .
D6AC	1150	1075	1000	950	900	500	. . .
Hy-Tuf	875	750	650	550	450	. . .	. . .
4330V	925	850	775	700	500	. . .	. . .
4335V	975	875	775	700	500	. . .	. . .
300M	. . .	. . .	. . .	. . .	. . .	. . .	475

[a] Quenched and tempered to F_{tu} indicated. If the material is exposed to temperatures exceeding those listed, a reduction in strength is likely to occur.

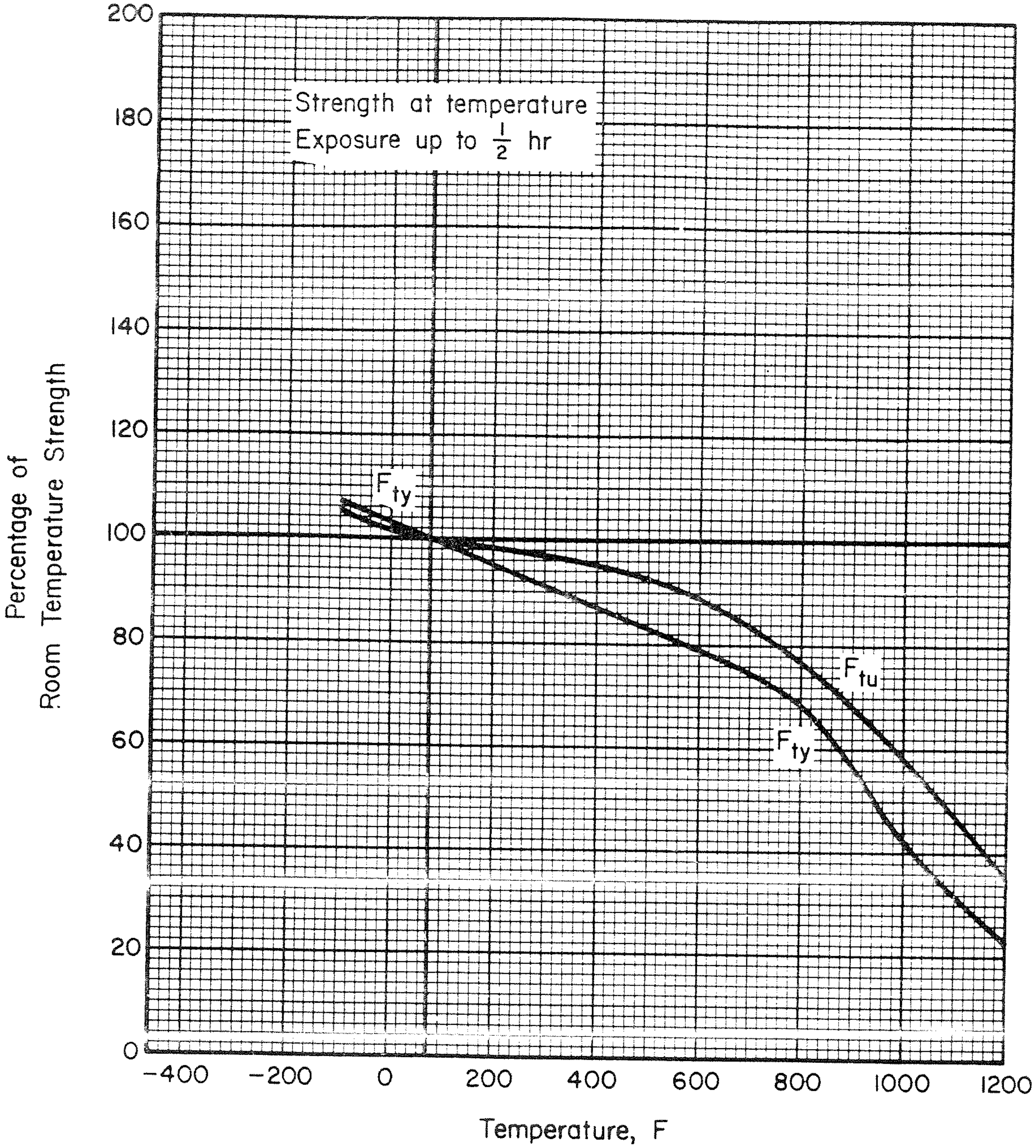

FIGURE 2.3.1.1.1. *Effect of temperature on the tensile ultimate strength (F_{tu}) and tensile yield strength (F_{ty}) of AISI low-alloy steels (all products).*