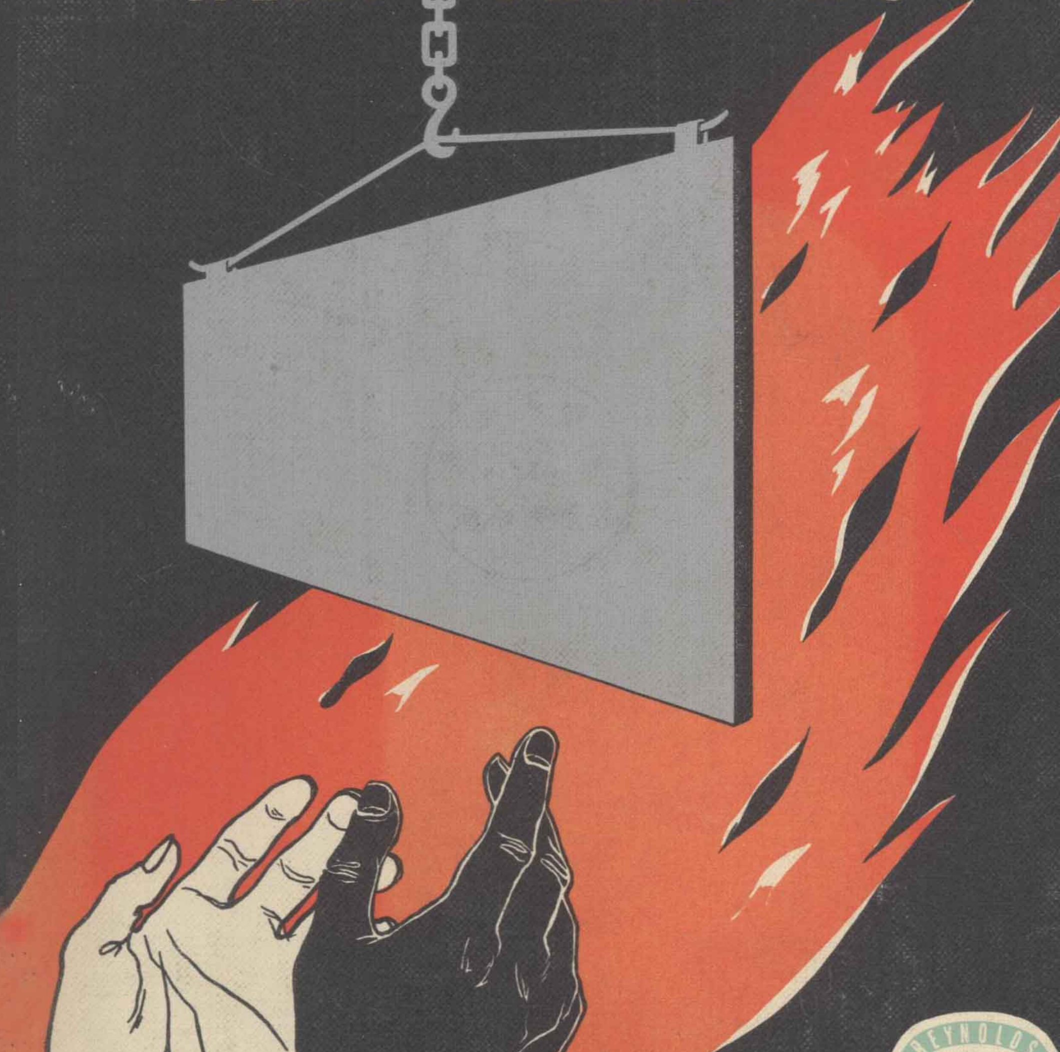
# Aluminum

## HEAT TREATING



REYNOLDS ALUMINUM

REYNOLDS METALS COMPANY

# HEAT TREATING ALUMINUM ALLOYS

**Foreword:** This book explains, on two different levels, the principles and procedure for heat treating the aluminum alloys. The first, in easily understandable concepts, enables the non-technical reader to obtain a basic understanding of aluminum heat-treating metallurgy. . . . The second is a more technical discussion for the highly trained engineer and metallurgist.

## CONDENSED CONTENTS

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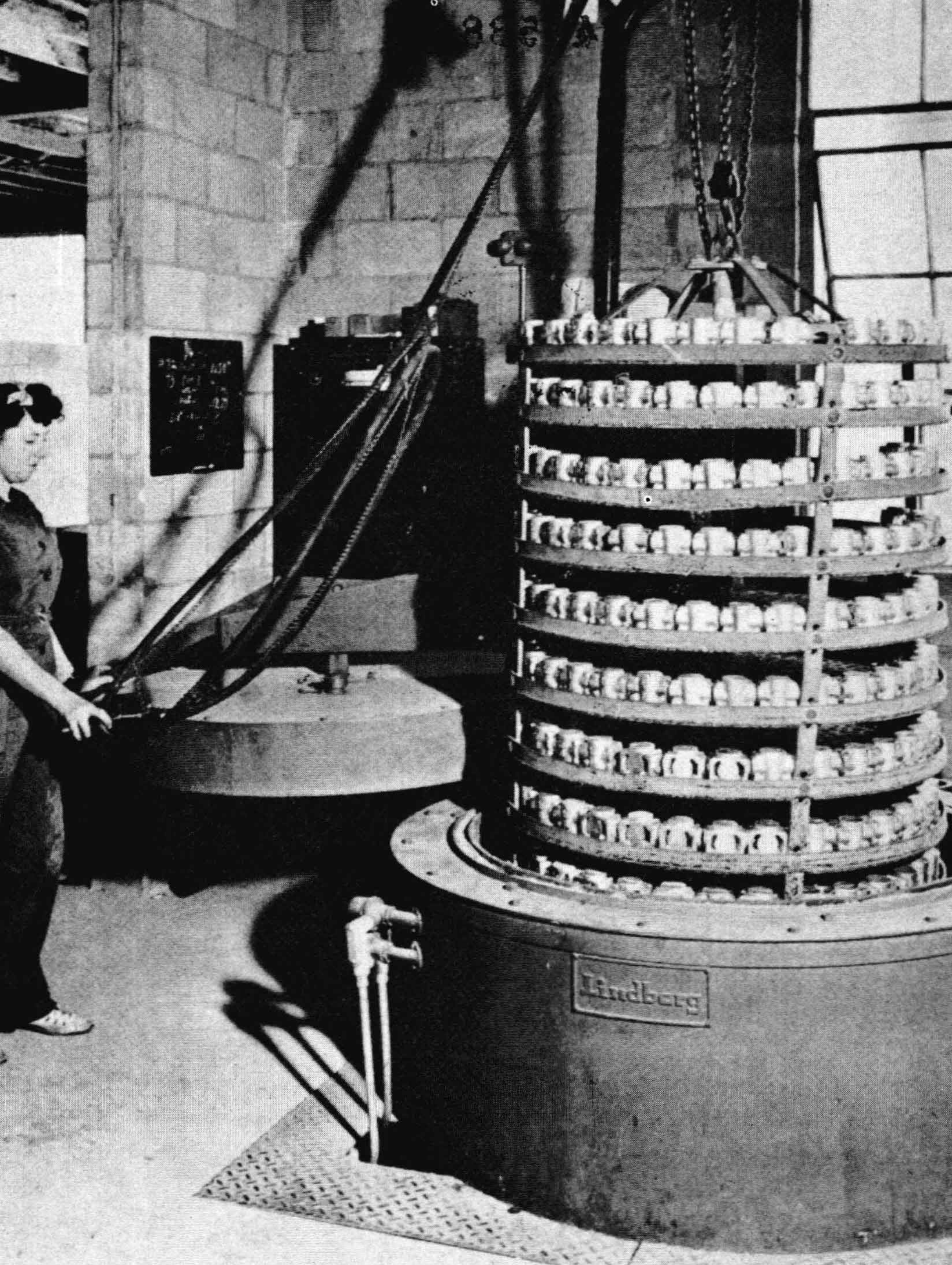



**Pit-type forced-air Lindberg Cyclone electric furnace for solution and aging treatments. Work chamber is 38″ diameter, 48″ deep. Cover swings to one side for loading and unloading by electric hoist. Waukesha Foundry photo.**

# SECTION ONE

Presented here is a simplified non-technical discussion of the underlying principles having to do with the metallurgy and heat treatment of aluminum.

## METALLURGY, HEAT TREATMENT OF ALUMINUM ALLOYS

**METALLURGY** is an exceedingly complex subject, because the metal structures involved are themselves quite complex. Where electricity lends itself to simple analogies (electricity flowing in a wire being similar to water flowing in a pipe, etc.), there are very few such analogies that can be used in explaining metallurgical reactions. So the reader can be forewarned that the subject is not easy to master.

However, if we disregard for the moment some of the fine technical details, it is possible to present a few comparatively simple concepts that may enable the reader to obtain a little better understanding of what goes on in producing and heat treating aluminum alloys. Production is included with heat treatment because the two are so closely allied.

The following discussion is not for the metallurgist–he should turn on to Section Two – but is intended for the non-technical reader. The metallurgist will recognize we have taken certain liberties with the subject to enable the non-technical reader to more easily understand some of the "reasons why" in the metallurgy and heat treatment of the aluminum alloys.

Combinations of metals like those found in the aluminum alloys may have an exceedingly complex structure. A molten aluminum alloy will be composed of six to nine different metals, some dissolved in others (like ink in water) and some not dissolved but just mixed in (like oil in water). As the molten alloy is allowed to cool, it will reach a point where solidification begins.

At this point "crystals" begin to form. With continued cooling, additional crystals form, building up on the first ones, in turn producing "grains". Thus, for our purpose, we will say that the solidified metal is composed of grains, in turn composed of crystals.

In addition, certain compounds are formed by the various combinations of metals. These compounds may solidify out separately, either between the grains along the grain boundaries, or in the grains between the crystals. Too, certain other elements may separate out during cooling to room temperature. Obviously, the resulting structure is quite complex, as previously mentioned.

## Work Hardening

For the moment, let's disregard some of these additional particles and say that in general, aluminum alloys are composed of "grains", in turn composed of "crystals". Adjoining crystals can "slip" against each other in many different directions; that is, they are said to have many different "slip planes". A metal is called "soft" when its crystals have a "fresh" set of slip planes that have "not been used".

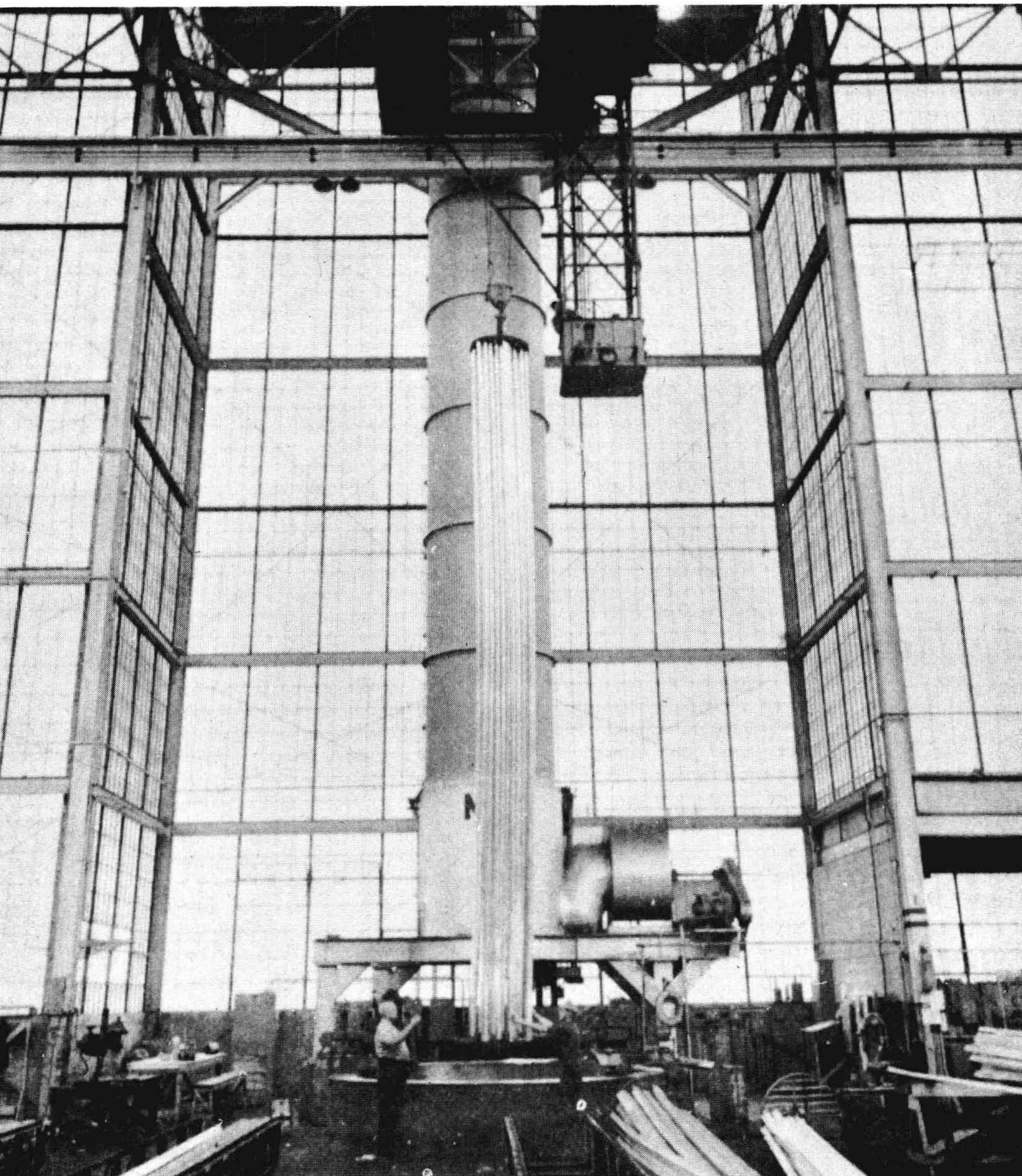
We say "not been used" because application of mechanical force will cause crystals to slip along any given slip plane only a certain amount. When a soft metal is hammered or stretched out or has its dimensions changed mechanically by any other method of applying force at room temperature, the adjoining crystals move along a slip plane. But because only a certain amount of slippage can occur along any one slip plane, the limit of movement on that plane is quickly reached and further working then requires slippage along other planes.

However, the planes along which subsequent slippage then occurs may not be so favorably positioned with respect to the applied force. The result is that the application of the same amount of force as before produces much less change in shape. Or saying it in another way – to produce the same amount of change in shape, much more force must be applied. As further work is done on the piece, this resistance increases greatly and the metal is said to "work harden".

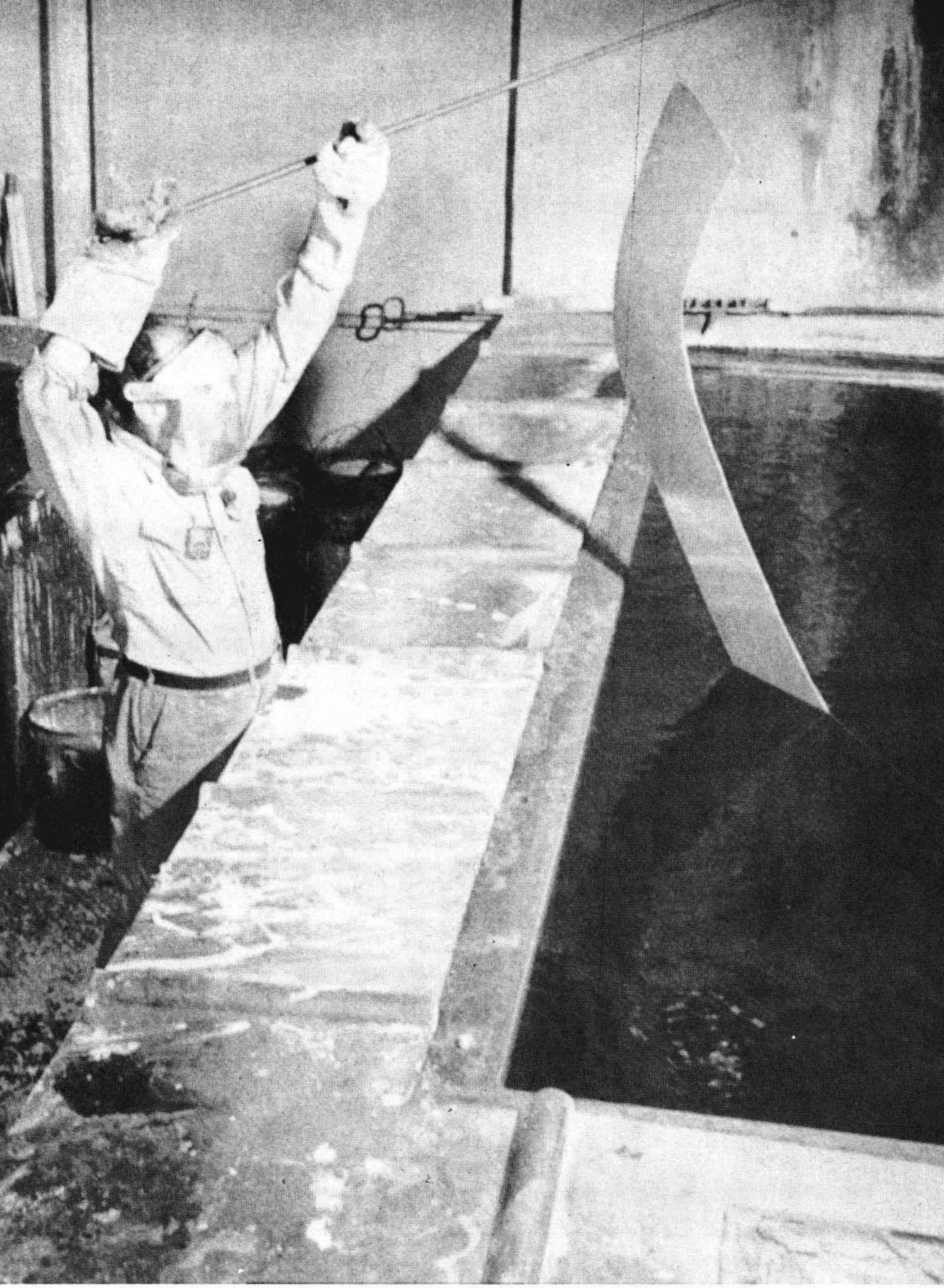
Thus as the shape of the metal piece is changed by working it mechanically, more and more slip planes are used up and the metal becomes progressively harder and less capable of further working. It is evident that metals possessing few slip planes quickly reach a point where excessive force is required for further working or where the metal structure may even break down if all available slip planes have been "used up".

## Annealing

However, the original workability of the metal can be restored by producing a "fresh" set of crystals having an entirely new set of slip planes. This is done by heating the previously worked metal to a point where a new crystal structure is produced.



**Huge vertical heat-treating furnace takes 50-foot extrusions easily. Water quench tank directly under furnace permits fast quenching from furnace temperature. Reynolds Metals photo. Serial 41N288.**



**Quench tank directly back of operator allows him to merely turn to make a fast quench from this salt bath. Kaiser-Fleetwings photo.**

This temperature is called the "recrystallization" point or "temperature of recrystallization". Aluminum alloys require comparatively low temperatures, in the neighborhood of 650-750° F. This operation is easy to control and reliable results can be had with little difficulty on most of the aluminum alloys. (Note specific recommended treating cycles in Section Three, page 94.

Suppose we are forming a deep drawn aluminum cup from a flat circle. Instead of attempting to produce the cup from the flat in a single forming operation, the final shape may be attained in steps or stages, annealing the part between successive operations wherever necessary to correct work hardening. In this manner it is possible to keep each step within the practical working limits of the material and not draw the sheet past the point where excessive work hardening would cause cracks or breaks. This is why many articles formed from aluminum alloy sheet involve a sequence of press operations with a series of intermediate annealing treatments.

## The Time Element

It is important to understand the influence of time in heat treating metals. For instance, if in the above described annealing process, the work is not held above the recrystallization temperature long enough, the new crystals will not have a chance to form completely. It takes a certain amount of time to form the new grain structure. In fact, most changes in the structure of the metal require a certain amount of time for completion.

Also time is required for the heat to soak thoroughly throughout all portions of the metal piece being treated. This is necessary in order that sufficient temperature rise be produced in all sections to provide the change in metallurgical structure that we desire. While a fast treatment in a furnace operated at a higher temperature might bring the interior of the work up to temperature quicker, it would be sure to heat the edges and corners of the work to excessive temperatures and probably damage those portions.

For these reasons, allowance for proper time "at temperature" is essential in any heat treatment.

The time element enters into heat treatment in another important manner. Because a certain period of time is required for structural or metallurgical changes (such as solid diffusion, page 12) to reach a completed or stable stage, it is possible to quickly change the temperature of the metal and thereby obtain at room temperature certain desired types of structures that could not otherwise be had at room temperature.

But before getting into heat-treating cycles and structures of

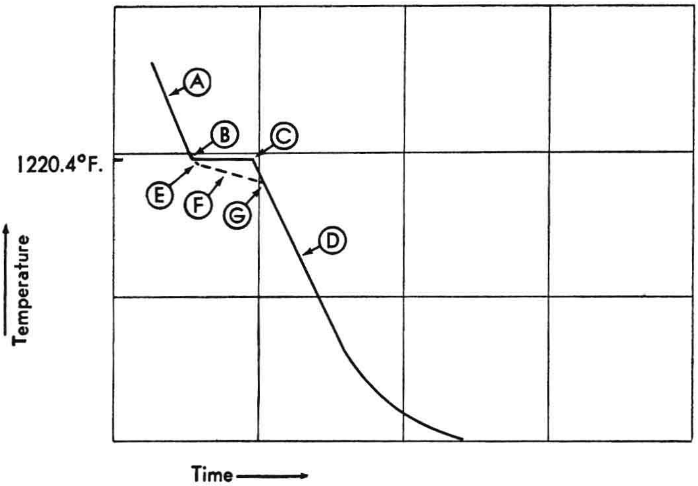



**Chart 1—Time versus Temperature for a pure metal. See text.**

aluminum alloys, let's start out with a pure metal for the sake of simplicity and see how this time element influences the structure. Chart 1, page 8, indicates the relation between time and temperature as a pure metal is allowed to cool from the molten state, represented by point "A". As its temperature falls, it reaches a point "B" where the metal begins to solidify or freeze. For pure aluminum, this freezing point is 1220.4°F.

Note that the curve indicates the temperature remains at this value for a period of time. This is because the change from a liquid to a solid is accompanied by the release of heat, the mechanism of the operation being such that just enough heat is released to balance that being lost, thus retaining the temperature of the metal constant during the period this solidification is taking place. So the curve is level from "B" to "C".

As soon as the metal has completely solidified, its temperature again falls gradually as it is allowed to cool, represented by the sloping line "D".

It should be noted that only a pure metal follows this type of curve . . . and each different metal has a different solidification or freezing point; that is, the level portion of the curve or "plateau" will come at a different temperature.

Now let's see what happens when we melt two pure metals together – let's say aluminum and copper – and allow them to cool. We find that we have a curve of an entirely different shape because the combination of the two metals has a freezing "range" instead of a freezing "point"; that is, the material begins to freeze at one temperature and continues to freeze while the temperature falls to a lower value before all of it has solidified. This is shown by the dotted portion of the curve at "F" in Chart 1 where the curve slopes from "E" to "G".

The combination of aluminum and copper does not freeze or solidify completely at a single temperature because the mixture formed by the two metals behaves in an entirely different manner than a pure metal like copper or aluminum (alone). Suppose we examine this freezing action for a moment, tracing the new curve on Chart 1.

## Differential Freezing

At "E", Chart 1, the crystals forming out as the molten metal is just beginning to solidify will consist of an alloy of almost pure aluminum. As the temperature falls, crystals with appreciable amounts of copper will begin forming. With continued dropping temperature, the crystals forming will contain more and more copper. Thus at "E", the alloy particles freezing out may contain 99.9% aluminum, 0.1% copper. Just below "E", the particles freezing out of solution may contain 98% aluminum, 2% copper. Similarly, particles containing 97% aluminum, 3% copper will freeze out at a lower temperature, and so on.

*Thus as the temperature falls, the material freezing out of solution at any particular moment corresponds to the alloy of aluminum and copper that freezes at that particular temperature.*

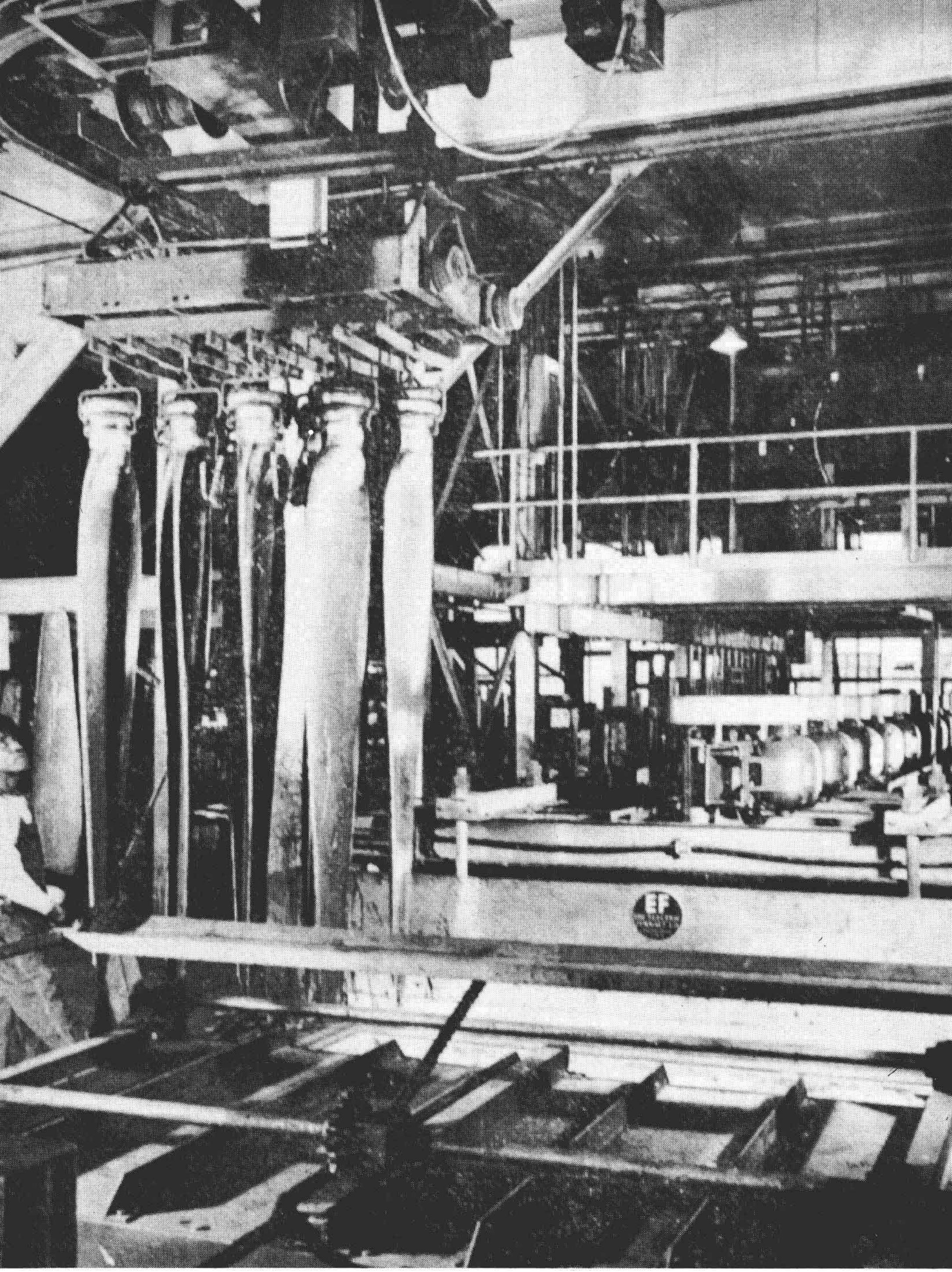
This accounts for the fact that as the temperature curve traverses the "F" portion, Chart 1, the alloy particles or crystals forming out of the molten metal contain more and more copper. At "G", the entire mass becomes solidified and the temperature drops along the same type of curve as before.

When the molten metal contains more than two elements, this curve changes considerably and the freezing action becomes increasingly complicated. It is evident, that in an aluminum alloy where we may have six to nine different elements, the action may be extremely complicated. Especially because the many different elements in turn form various mixtures or compounds which may behave in still different ways to further complicate the situation.

## Precipitation

One of the complications that results from having these many different elements in the aluminum alloy is that certain combinations of elements may form mixtures or compounds which may freeze out of solution or separate out in small independent particles before or even after most of the other material has solidified.

These particles may be extremely small and may exist between



**Special 600-kw continuous furnace setup for solution treatment of forged aluminum propeller blades up to 10′ in length. Blades are hung from small cars which are lowered into the furnace and automatically pushed through heating chamber, rapidly removed, and quenched. The Electric Furnace Co. photo.**

the surfaces of adjoining crystals in such a manner as to "lock" the crystals by hindering them from sliding and thus increasing the resistance to mechanically working the material. This in turn may make the metal hard, tough, brittle, etc. Depending upon circumstances, the result may be desirable or undesirable.

This precipitation or separating out from the molten metal can be demonstrated in this manner: Place several spoonfuls of salt in a glass of boiling water, adding salt until no more will dissolve and some remains in the bottom of the glass even after repeated stirring. Pour this solution into another glass, leaving behind the extra salt. We now have a "saturated" solution of salt in water.

Then place this glass in a basin of cold water and stir the solution. As it cools, the temperature will drop to a point where the water can not hold all of the salt in solution. We now have a "supersaturated" solution in which the extra salt will immediately form salt crystals as it "precipitates" out of the solution.

**Cooling:** The same thing happens when a molten aluminum alloy is allowed to cool. Various elements and combinations of elements will precipitate out of the molten alloy as the temperature falls to a point where they can no longer be held in solution. Certain compounds may precipitate out after solidification.

When a constituent precipitates out, it may accumulate between grains along grain boundaries, or in the form of minute particles between crystals inside the grains. These particles may thus be present in the slip planes between adjacent crystals. If the same particle is partially imbedded in both surfaces of adjoining crystals, it is evident that it will tend to lock those surfaces together and prevent them from sliding freely one on the other. Thus such particles will tend to increase the resistance to slippage between crystals because of this "keying" effect.

With slippage made more difficult, the metal acts like it had fewer slip planes, is harder to work and may be considerably stronger. So the end result may be that the mechanical properties of the metal are greatly improved. As we will see, this is the aim of certain heat-treating cycles.

Remember, we have not only solids precipitating out of a liquid (the molten metal), but also solids precipitating out of solids, because just as a solid metal can diffuse into another solid metal (described under "homogenizing" page 12), so can a solid precipitate out from another solid. To illustrate this latter action, however, there is no simple analogy like that of the salt and water previously mentioned.

At this point, the picture becomes increasingly difficult to follow. So before getting any deeper in this direction, let's look at some other factors.

## Segregation

When molten aluminum alloys are poured into molds and allowed to cool to form ingots (casting), the surfaces of the ingot that contact the mold naturally cool faster. So the first crystals to be formed are in the ingot surfaces contacting the mold walls. Then as the temperature of the metal continues to fall and more crystals are formed, the new ones form on top of the older ones, causing the metal grains to "grow" toward the center of the ingot in a direction at right angles to the mold walls.

At the same time the rapid extraction of heat through the mold walls is causing the grains to grow inwardly from the ingot surface, the temperature difference existing between the solidifying outer layers of the ingot and the still molten inner portion produces another important action.

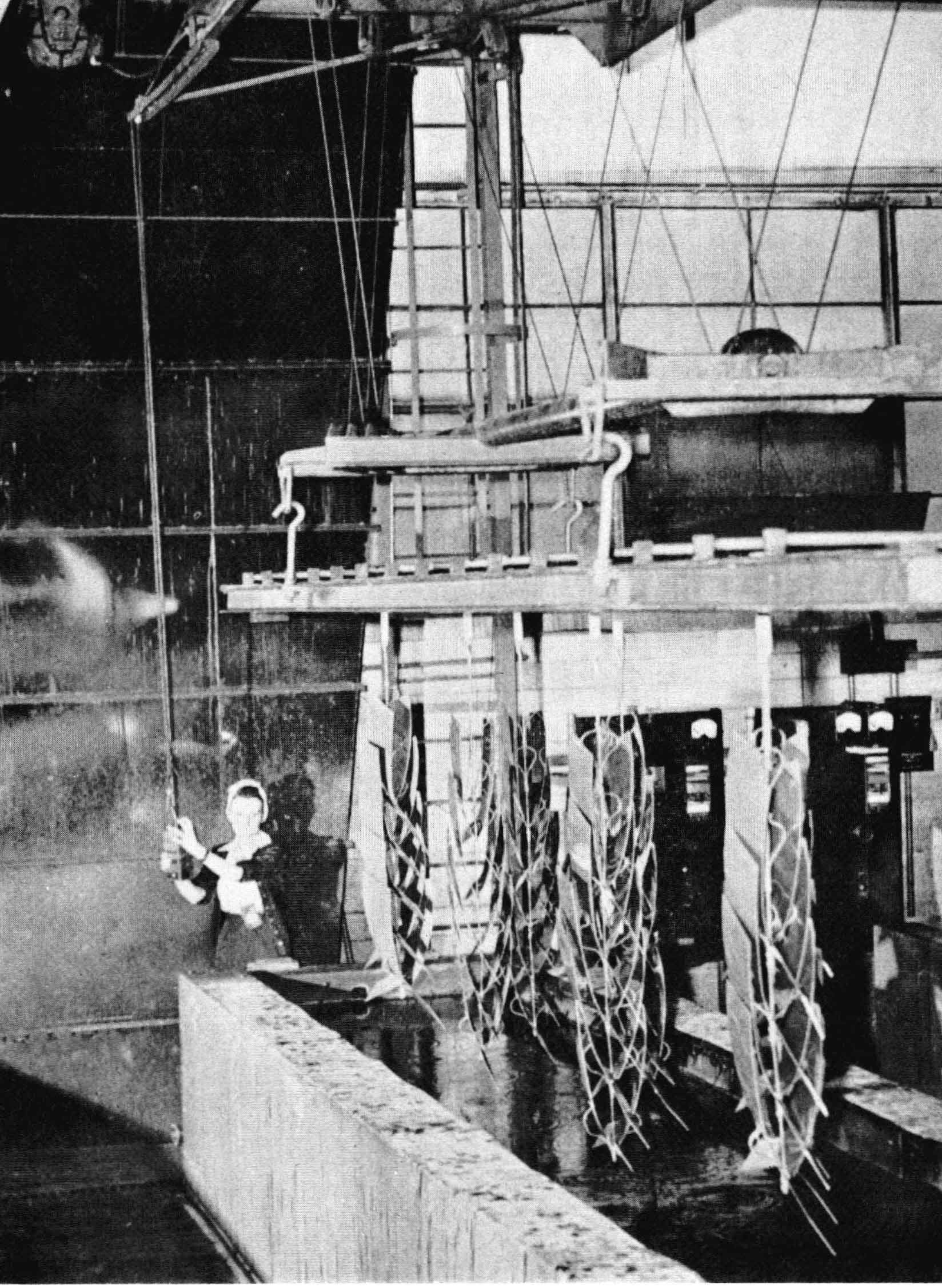
We have seen how certain constituents of the metal may precipitate or separate out from the remainder as the temperature drops. Now with uneven temperatures throughout the ingot, it becomes evident that precipitation will occur unevenly. This in turn results in an uneven distribution of the precipitate (the material that precipitates out).

Since these precipitates may have an exceptionally important influence on the characteristics of the metal, it is essential that they be uniformly distributed throughout the entire body of the metal. This is done by mechanically working or "kneading" the ingot, supplemented by the heat treatment called "homogenizing".

## Homogenizing

Let's go back for a moment to where all the metal had just solidified. Note that the crystals forming first were almost pure aluminum and that succeeding crystals contained more and more copper in the form of a richer copper-aluminum alloy. Thus the grains in the solidified metal have what is termed a "cored" structure; that is, the inside crystals near the core are much different than the outer crystals of a grain. As the metal freezes and cools to room temperature, the resultant "cast" metal possesses this undesirable cored structure. So it becomes necessary to change this structure to a more desirable one.

To do this, we resort to "solid diffusion"— a term used to denote the diffusion or spreading out or dissolving of one metal into another when both are in the solid state. It is well known that some liquids will readily dissolve into others, such as ink into water. Likewise certain liquids will readily dissolve certain solids, as water dissolves salt. But it is not so well known that certain solids can dissolve other solids.



**Overhead monorail system with traveling bridge and electric hoist easily handles frame from which parts are suspended for quenching from a salt bath. Curtiss-Wright photo.**

It is a fact, however, that if a gold block and a silver block are cleaned carefully and pressed tightly together, the dividing line will gradually disappear, one metal blending or dissolving into the other. While this action will occur at room temperature, it is greatly speeded by heating both metals.

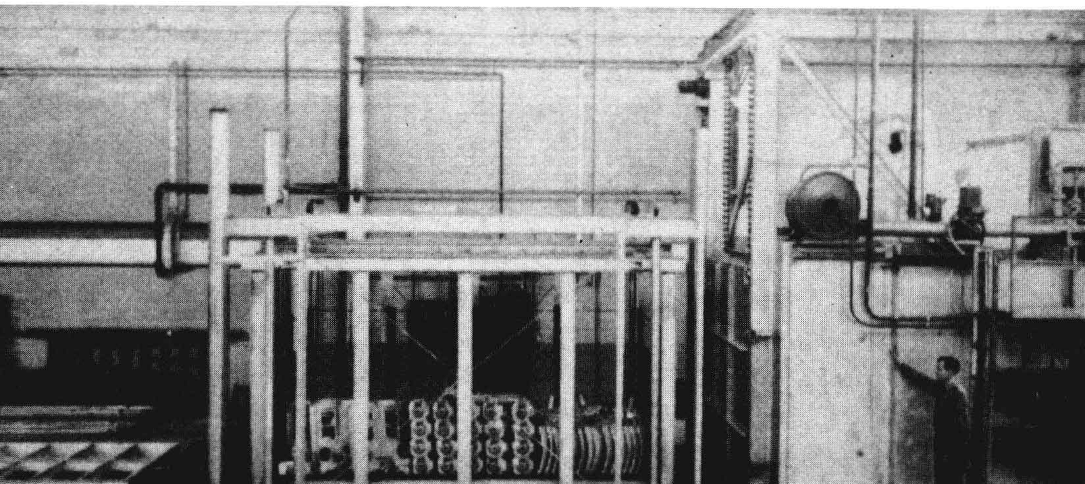
In a similar manner, the copper is caused to diffuse throughout the metal structure by heating the metal to a temperature just under its melting point, followed by slow cooling. This treatment is known as "homogenizing". For many aluminum alloys it is done in the temperature range of 900-1000° F. By this means it is possible to overcome the tendency of certain constituents to segregate or separate to form thin and dense areas. Homogenizing thus is an aid in bringing about proper uniform distribution of the alloying elements and other constituents, and so helps in producing the desired homogeneous structure.

## Strengthening Aluminum Alloys by Heat Treatment

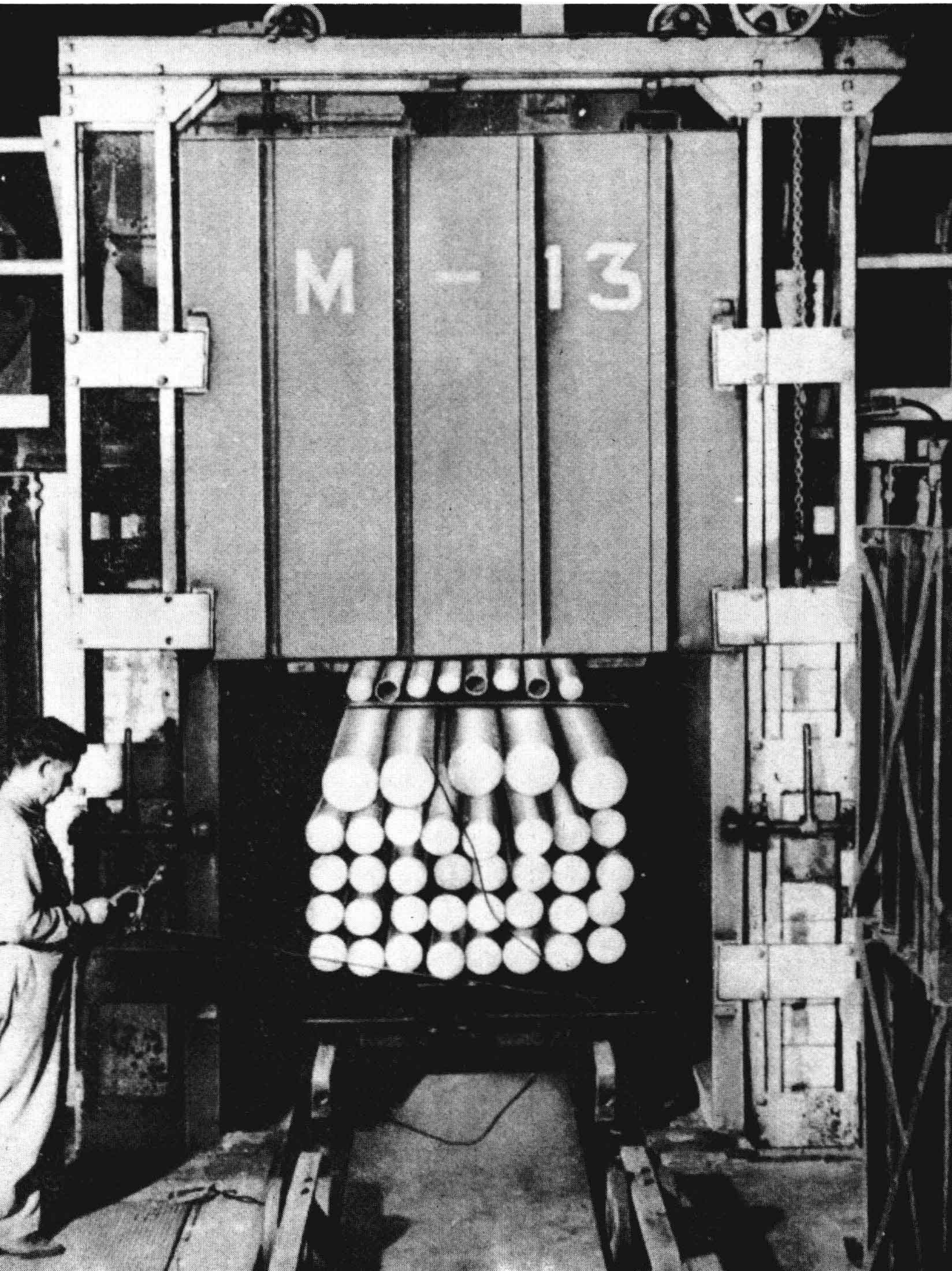
As was explained briefly under "precipitation," page 9, it is possible to strengthen the aluminum alloys by causing certain constituents to precipitate out inside the grains along the crystal boundaries or in the slip planes between crystals in such a manner as to lock or key the crystals, thus hindering slippage and so producing a "harder" and stronger material.

Also resistance to slippage can be increased by controlling the material that is precipitated between the crystals so that it acts like a "sharp grit" instead of like a "ball bearing". It is evident

**Gas-fired Despatch furnace measures 15′ long, 7′ high, 7′ wide inside. Heated load is run out on elevator which lowers it into the quench tank. Rails on top of elevator cage then allow a second car platform with its load to be run into furnace. Thus one platform can be reloaded while the other is in furnace. Aluminum Industries, Inc., photo.**



A 30,000-pound capacity McCann soaking furnace for handling billets in an extrusion plant. Note connections to thermocouples embedded at various points in the load for checking temperatures. Reynolds Metals photo. Serial 8C481.



that a material that tends to aid free movement of one crystal on another will produce a softer, weaker alloy, whereas a precipitate that tends to prevent such movement will in turn produce a harder and stronger structure.

Section Three, page 94, details typical times and temperatures for controlling both of the above factors. Of course the different aluminum alloys require slightly different treatments because of the cumulative effect of the different combinations of elements in them.

Let's examine Chart 2, page 17, to see why these particular temperature ranges are required and to find out about the "aging" treatment – either natural or artificial – that is necessary to develop maximum strength in the aluminum alloys.

The vertical scale in Chart 2 represents temperature, starting with a low temperature at the bottom and going up above the melting point of the aluminum alloys. Since the alloys we are going to look at have aluminum and copper as the principle constituents, we can make the horizontal or base scale a double scale. Going from left to right, the upper scale measures per cent of copper from zero to 40%. Disregarding other constituents, we can say that remainder at any point is aluminum. So we can put in another scale immediately below the copper one reading 100-90-80-70-60% aluminum for the same points designated as 0-10-20-30-40% copper respectively.

For our purpose, we have selected an alloy containing 3% copper at room temperature (97% aluminum), represented by Point 8 on the chart. Now let's see what happens when we heat and cool this alloy.

First the temperature of the material will be raised along the vertical dotted line to Point 1—say 1300° F. At this temperature all the material is molten and the copper has dissolved in the aluminum.

Now the material is allowed to cool to 1190° F—Point 2 lying on Curve A. This curve represents the temperature at which the molten metal starts to solidify. The first crystals that start to form here will be almost pure aluminum. These crystals will serve as the nuclei or center points around which the grains will form by solidification of other crystals on them as cooling continues.

## Solid Solution

Now we will allow the material to cool to 1160°F—Point 3—and hold it at this temperature while we see what is happening here. Since solidification began at Point 2, the material is now partly solidified and partly molten. Because the aluminum has been