MAGNESIUM ALLOY RESEARCH STUDIES

A. Jones
J. H. Lennon
R. R. Nash
W. H. Chang
E. G. MacPeek

Rensselaer Polytechnic Institute

September 1952

Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report was prepared by the Rensselaer Polytechnic Institute, Troy, New York, under Supplemental Agreement Number 2 (S-51-1012) of Contract Number W33-038-ac-22542 and Research and Development Order Number 605-230, "Improved Magnesium Alloys". The administration of this work was under the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Mr. J. C. McGee acting as project engineer. This report summarizes the progress on magnesium alloy research up to 31 January 1952 under the above contract.

WADC TR 52-169

ABSTRACT

Diagrams are presented to show the constitution at 500° and 700°F for the magnesium-lithium-aluminum and magnesium-lithium-zinc alloy systems. These diagrams were determined mainly by microscopic examination of alloys quenched from elevated temperatures. Corrosion and loss of lithium prevented the successful use of x-ray diffraction and electrical resistivity measurements at elevated temperatures. The solubility for aluminum and for zinc was less at 500° than at 700°F but the solubility for lithium was almost the same at these two temperatures.
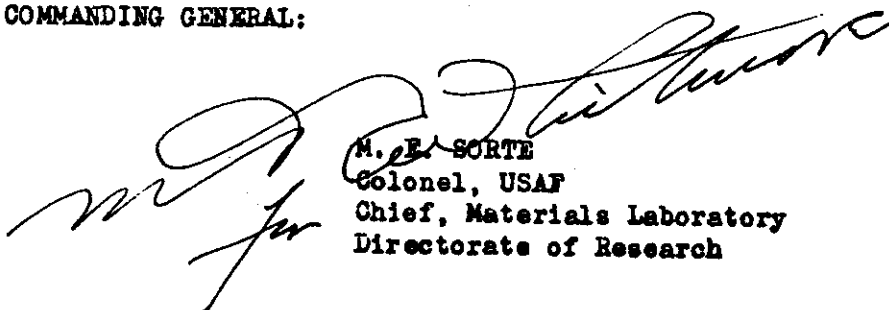
The study of dilute magnesium alloys found a good combination of properties for magnesium-1.0% zinc-0.4% cerium. The addition of cerium refined the grain structure and introduced a small amount of a second constituent. The best properties were obtained with a fine equiaxed grain structure produced by warm rolling and annealing just above the recrystallization range. These conditions of structure and properties were not obtainable by a single cycle of cold rolling and annealing.

Single crystals of high purity magnesium were grown by controlled solidification in a gradient furnace. The furnace and the mold remained stationary and only the temperature gradient moved. The conditions of growth were found to be more critical for single crystals of magnesium-aluminum and magnesium-zinc alloys. No alloy single crystals were produced but favorable conditions for their growth were approached. Causes and remedies are discussed for the failure to produce magnesium alloy single crystals.

PUBLICATION REVIEW

Manuscript Copy of this report has been reviewed and found satisfactory for publication.

FOR THE COMMANDING GENERAL:

M. E. SORTE
Colonel, USAF
Chief, Materials Laboratory
Directorate of Research

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

This program was devoted to a study of three different types of magnesium alloy research:

I Constitution of alloys in the solid state in the magnesium corner of the magnesium-lithium-aluminum and magnesium-lithium-zinc alloy systems.

II Development of magnesium alloys with a low alloy content for high ductility sheet.

III Study of single crystals of magnesium alloys.

Therefore, the experimental work and results are reported in three separate sections.

The objectives in the constitutional diagram study were the identification of the phases and the locations of the phase boundaries at 500° and 700°F in the magnesium-lithium-aluminum and magnesium-lithium-zinc alloy systems. The methods chosen for this study were microscopic examination, x-ray diffraction studies at room and elevated temperatures and electrical resistivity measurements at high temperatures. Oxidation and loss of lithium could not be prevented at high temperatures so that microscopic examination of quenched alloys was more useful than the other methods.

The objective of the dilute alloy study was to develop magnesium alloys with a good combination of strength, toughness and formability but with a total alloy content of about one percent. Various combinations of hot, warm, straight and cross rolling were to be tried but limitations of the rolling equipment prevented an investigation of the effects of cross rolling. It was believed that the optimum properties of magnesium alloys would result from such mechanical treatments followed by a heat treatment to produce an extremely fine equiaxed grain structure.

The development of a method for growing large single crystals of magnesium alloys was the first objective in the third portion of this program. Crystals, free from surface and internal defects and of large size, were desired for a fundamental study of the behavior of individual alloying elements in strengthening magnesium. After these studies with elements of high solid solubility such as aluminum, zinc and cadmium, it was planned to extend the work to other elements.

SECTION I

TERNARY MAGNESIUM-LITHIUM BASE CONSTITUTIONAL DIAGRAMS
MAGNESIUM-LITHIUM-ALUMINUM AND MAGNESIUM-LITHIUM-ZINC

INTRODUCTION

Considerable interest in the constitution of magnesium
-lithium base alloys was stimulated even before Jackson[1] and
his associates published their results on the general
characteristics of these alloys. The purpose of this study was
to obtain data for the preparation of the phase diagrams for
magnesium-lithium base alloys in order to aid the further
development of magnesium alloys with a high strength-weight
ratio and with good stability. This initial work was concentrated
on the constitution of alloys in the magnesium corner of the
magnesium-lithium-aluminum and the magnesium-lithium-zinc alloy
systems and to temperature levels of 500° and 700°F.

PREPARATION OF MAGNESIUM-LITHIUM TERNARY ALLOYS

Selection of Alloy Compositions

The compositions of the first series of these alloys were
chosen arbitrarily since no equilibrium data were available for
these ternary systems when this work was started. These first
compositions represented increasing amounts of aluminum or of
zinc added to the chosen magnesium-lithium ratios. The study of
these alloys showed the approximate location of the phase
boundaries and guided the choice of additional alloys. As the
knowledge of these alloy systems increased, compositions were
chosen closer and closer to the phase boundaries in order to
locate their position as accurately as possible.

A total of 306 alloys was prepared for this work. The
intended composition of these alloys, the chemical analysis of
alloys near phase boundaries and their constitution are given
in Appendix I in Table XXI   for magnesium-lithium-aluminum
alloys and in Table XXII for magnesium-lithium-zinc alloys.

------

1. References are listed in the bibliography.

Chemical Analysis of Selected Alloys

The actual compositions were determined by analysis for those alloys which were found to be near phase boundaries at 500° or at 700°F. The methods for these chemical analyses were in accordance with those recommended by The Dow Chemical Company. Initial determinations of lithium were made by the gravimetric method but a majority of the lithium analyses were made by a flame photometer. Occasional gravimetric analyses were made to maintain close agreement between the two methods. Analyses for aluminum and zinc were by gravimetric and volumetric methods, respectively. The actual chemical compositions are listed in Appendix I as stated in the preceding paragraph.

Alloy Charging Components

The purest available metals were used in the preparation of these alloys. Redistilled magnesium crystals and purified lithium ingots were obtained from The Dow Chemical Company, high purity aluminum ingots from the Aluminum Research Laboratories and Horse Head Special slab zinc from the New Jersey Zinc Company through the Belmont smelting and Refining Works, Inc. The analyses for these metals were given in the Summary Report for 1950.[2]

Melting and Casting Technique

The melting of magnesium-lithium-aluminum alloys in an open steel crucible with a flux of lithium chloride and lithium fluoride resulted in considerable loss of lithium. Difficulties were also experienced when the alloys were melted and allowed to solidify in closed steel containers which had been charged with the alloy components and then flushed with argon. Oxidation occurred and the ingots adhered firmly to the walls of the container. Such ingots were unsound and contained a large quantity of inclusions. Therefore, equipment was constructed for melting and casting 250 gram charges of the alloys in a closed container under an atmosphere of argon or helium.

An assembly drawing of this equipment was shown in the Summary Report for 1949.[3] It consists of four main parts:- the housing, the crucible, the mold and the stirring rod which also served as a thermocouple protection tube. Plain carbon steel was used for these parts in the original construction but crucibles, molds and stirring rods were made later from a ferritic stainless steel. For melting, the crucible portion of the assembly was heated in an electric resistance furnace. When melting had occurred, the alloy was mixed thoroughly by the stirring rod and then cast into the ingot mold by lifting the equipment from the furnace and tilting the entire assembly. A more detailed description of the construction and operation of this melting equipment was given in the Summary Report for 1949.[3]

Argon was used during melting as the protective atmosphere at first but improved results were obtained by using the XX Welding Grade* of helium. Ingots of excellent cleanliness were also obtained in this equipment by melting in an argon atmosphere with a flux of lithium chloride and lithium fluoride but the use of high purity helium gave such good ingots that flux melting was not considered necessary. The resulting ingots were approximately 5 inches in length and 1-1/2 inches in diameter. They were free from porosity and pipe for 60 – 75% of their length and had a clean bright surface.

Some lithium was lost during the melting and subsequent thermal treatment to prepare the ingots for extrusion. Therefore, the alloying addition of lithium was calculated from the following equation:—

$$\text{Intended \% Lithium} = 0.9\ (\text{\% Lithium Added})\ -0.2\%$$

More disconcerting than this loss during melting was the loss of lithium in extruded alloys during their storage in a normal laboratory atmosphere. Examples are shown in Table I for this loss of lithium from binary magnesium-lithium alloys during storage.

Extrusion of Magnesium-Lithium Ternary Alloys

Extrusion was selected as the best method for the thorough working of cast structures under controlled conditions and for the working of any complex structures too brittle for working by any other method. Also, uniformity of structure and rapid approach to equilibrium should be aided by the high reductions in area which can be obtained in extrusion. A reduction in area of more than 99% was obtained in this work by extruding 1/8 inch diameter rod from a 1-1/2 inch diameter container.

All ingots were homogenized for 48 hours at 500°F in an electric muffle furnace and then air cooled prior to machining for extrusion. At first, several coats of Dow-Corning #993 silicone resin were used to protect the ingots during the treatment at 500°F but this method was not completely successful. Much better protection was obtained by coating the ingots with Keepbryte** which was applied to the ingots after they had been heated for about 10 minutes at 500°F. The ingots were then returned to the

---

* The XX Welding Grade of helium was supplied by the Air Reduction Company.
** Keepbryte is the trade name of a powder supplied by Kasenit Ltd., 7 Holyrood Street, London S.E.1. It is reported to consist mainly of boric acid and ferric oxide.

furnace for the 48 hour treatment at 500°F. Keepbryte produced
a very adherent, glass-like coating at 500°F and gave excellent
protection to all alloys except those containing more than about
10% of both lithium and zinc. Ingots containing over 10% lithium
were coated with Keepbryte and then given additional protection
by placing each ingot in a close fitting and tightly capped steel
pipe nipple.

The homogenized ingots were machined to produce extrusion
charges 1-7/16 inches in diameter and 3/4 to 1 inch in length.
These charges were extruded to 1/8 inch diameter rod by the
direct method in a small laboratory extrusion press with a
container diameter of 1-1/2 inches. This equipment was described
in the Summary Report for 1947 and 1948.[4] The extrusion equip-
ment was used originally in a Southwark-Emery testing machine
of 50 tons capacity but it was modified later for operation with
a Watson-Stillman hydraulic press of 125 tons capacity. The
general procedure was to extrude at the lowest container
temperature at which the available force of 125 tons was
considered sufficient to permit extrusion to 1/8 inch diameter
rod. The extrusion process was accelerated by preheating the
charges for 10 minutes in an electric muffle furnace controlled
at 500°F. This extrusion from a 1-1/2 inch diameter container
to 1/8 inch diameter rod gave an extrusion ratio of 144 to 1 and
a reduction in area of more than 99%.

After extrusion, the early procedure was to store the bare
1/8 inch rods in a normal laboratory atmosphere. This resulted
in considerable corrosion of the pitting type and also considerable
loss of lithium. Examples are shown in Table I for this loss of
lithium from magnesium-lithium alloys during storage.

TABLE I

CHEMICAL ANALYSES OF MAGNESIUM-LITHIUM ALLOYS
SHOWING LOSS OF LITHIUM

Alloy Number	% Lithium	Date
L-21	12.25	19 April 1949
	11.85	3 January 1950
L-43	15.15	10 May 1949
	13.3	7 March 1950
L-44	19.25	10 May 1949
	15.3	7 March 1950

After this serious loss of lithium was noticed, the extruded
rods were stored in glass tubes with a cork at each end and
these tubes were placed in capped steel pipes for added
protection.

MICROSCOPIC STUDY OF MAGNESIUM-LITHIUM TERNARY ALLOYS

Relative Value of the Microscopic Method

The microscopic method for locating phase boundaries in the magnesium-lithium ternary alloys was finally used almost to the exclusion of the x-ray diffraction and electrical resistivity methods. It was found to be the most rapid, adaptable and informative of the three methods which were used. The principal use for the other two methods was to confirm microscopic data and to identify the phases found in the microstructure. The application of the x-ray diffraction and electrical resistivity methods at elevated temperatures was hindered by the extreme reactivity of these alloys and the difficulties of providing perfect protection of the surface during long runs at 500° and 700°F. Very slight surface contamination completely invalidated x-ray diffraction data but did not destroy the core structure which could be evaluated by microscopic examination. However, core structures in equilibrium at elevated temperatures may transform to other structures at a lower temperature regardless of the rapidity of quenching.

Heat Treatment of Alloys for Microscopic Examination

Four methods were tried to protect these alloys during long periods of treatment at elevated temperatures. These methods were:

1. Treatment in fused salt baths of lithium nitrate and of lithium stearate

2. Treatment of the samples protected by a coating of Keepbryte

3. Treatment of a large number of samples in an aluminum block with an atmosphere of argon or helium

4. Treatment of samples supported by graphite bushings at each end and individually sealed in Pyrex tubes with an atmosphere of helium

The first method was not satisfactory because the nitrate bath reacted violently with the high lithium alloys and the stearate bath decomposed at temperatures slightly above its melting point. The use of Keepbryte gave considerable but not complete protection to samples heated for 24 hours at 700°F. It was found that the coating broke down at some points and that the attack spread inward from these points. Good protection was obtained by treating a large number of samples in an aluminum container with an atmosphere of helium as described in the Summary Report for 1950.[2] However, this method was discarded in favor

of sealing individual samples in Pyrex tubes because of troubles
due to imperfect sealing of the aluminum container. Sealing
individual samples with an atmosphere of helium in Pyrex was more
tedious than treating a group of samples in the aluminum container
but the results were nearly always perfect and imperfect sealing
destroyed only one rather than a large number of samples. No
detrimental reaction occurred between the sample and the glass
as the graphite bushings supported the sample out of contact
with the glass.

The Summary Report for 1950[2] gave a description of the
procedure used for sealing the samples in Pyrex tubes for protec-
tion during all heat treatments at elevated temperatures. A
sample length of 3 inches was used to provide material for
transverse and longitudinal sections for microscopic examination
and for chemical analysis after heat treatment. Analysis of the
original extruded rods was not considered satisfactory because
of possible volatilization of lithium from the sample and its
deposition elsewhere in the sealed glass tube.

These samples sealed in Pyrex tubes were treated for 24 hours
at 700°F or for 72 hours at 500°F in an electric resistance
furnace in which temperature gradients were minimized by the use
of aluminum blocks. An auxiliary microscopic and electrical
resistivity investigation showed that 24 hours at 700°F and 72
hours at 500°F were sufficient to obtain a close approach to
conditions of equilibrium. At the conclusion of the heat treat-
ment, the Pyrex tube was quickly transferred and fractured at
the quenching bath so that the bare specimen was cooled as
rapidly as possible. Water could not be used for quenching
because it reacted with the specimens. Kerosene did not react
with the specimens but it did not prevent the formation of a
feathery structure near grain boundaries in alloys containing a
high percentage of lithium and zinc.

Preparation of Samples for Microscopic Examination

Longitudinal and transverse sections of each heat-treated
specimen of 1/8 inch rod were mounted in Selectron 5003* in order
to avoid the elevated temperatures needed with Lucite and
bakelite. Selectron 5003 does not require any pressure during
the mounting and it polymerizes to a solid in two or three days
at room temperature. The disadvantage of this long curing time
was more than offset by the ease of mounting a large number of
specimens at the same time.

---

* Selectron 5003 is obtainable from Pittsburgh Plate Glass
Company, 2 Chester Avenue, Newark, N. J.

The low hardness and the reactivity of these alloys required more than the usual care in finishing them for microscopic examination. Some alloys were slightly etched during the final polishing in spite of rapid drying and the most reactive complex alloys were badly pitted. Kerosene was necessary as the carrier for the abrasive in the final polishing of such alloys.

The etching method for these alloys was similar to that described by George[5] and the most useful single etchant consisted of 100 parts of 6% picral, 10 parts of water and 5 parts of glacial acetic acid. Modifications of this solution, other important etchants and a more detailed discussion of the preparation of these alloys for microscopic examination were given in the Summary Report for 1950.[2] An additional etchant recently used for some alloys consisted of 0.7 ml. 85% orthophosphoric acid, 4 grams picric acid and 100 ml. ethyl alcohol.

Evaluation of the Microstructure

The usual procedure in the microscopic study of these alloys was to estimate the relative quantities of each phase in the structure and to identify each by its etching characteristics and by x-ray diffraction as described later. The success of this method depended on the preparation of a properly polished and etched structure but this was exceedingly difficult for some of the complex alloys. The acetic-picral etchant revealed grain boundaries and darkened the beta solid solution more than the other phases but it did not produce a clear distinction between the alpha solid solution and the intermediate phases. The structure developed by this etchant and its modifications are shown and discussed at a later point in this report. Tables **XXI** and **XXII** in Appendix I give the phases and the relative amount of each phase present at 500° and 700°F in the structure of alloys which were examined.

X-RAY DIFFRACTION STUDY OF MAGNESIUM-LITHIUM TERNARY ALLOYS

X-ray Diffraction Equipment

The design, construction and initial operation of the apparatus for elevated temperature x-ray diffraction was described in the Summary Report for 1949.[3] A small removable furnace surrounded the specimen in a 57 mm. diameter camera which was designed for operation with a vacuum or with an inert atmosphere. The intended use for this equipment was to provide a means of identifying the phases present and to supplement microscopic examination by x-ray diffraction studies at elevated temperatures. The two major difficulties in this work were the surface

oxidation of the powder specimens and the progressive loss of
lithium from these specimens. These conditions were very
serious with alloys of high lithium content when studied at
high temperature. High purity helium gave better protection
than argon but the many uncertainties caused the abandonment
of nearly all high temperature diffraction work so that more
effort could be devoted to microscopic studies.

X-ray Diffraction Patterns of Phases

X-ray diffraction patterns were prepared from powders for
a series of alloys corresponding to the phases whose presence
was expected in the magnesium-lithium-aluminum and magnesium
-lithium-zinc alloy systems. The purpose of these patterns was
to permit identification of phases by direct comparison of
diffraction patterns. The composition and identity of these
phases are given in Table II.

Specimens for x-ray diffraction were prepared by filing
the alloys and using the fraction passing through a 325 mesh
screen. This powder was mixed with collodion or Duco cement to
form a viscous paste and then extruded through a 0.5 mm. diameter
orifice to make a specimen about one inch long. The K-alpha
radiation from copper was used and the exposure time was from
three to four hours.

The method for identification[6] of the phases was to compare
values of interplanar spacings and relative diffraction line
intensities from these patterns with standard diffraction data
available in the ASTM publications[7] and with diffraction data
supplied by the Dow Chemical Company for Al Li, Mg Li_2 Al,
Mg Li Zn and Mg Li_2 Zn. The values of the interplanar spacings
for these latter compounds are listed in Appendix II. The
values of interplanar spacings and relative line intensities of
pure magnesium were considered representative of the alpha phase
and data from the binary alloy L-21 were taken as representative
of the beta phase. Variations in the nature of the solute and
its concentration in the alpha and beta phases would alter the
values of the interplanar spacings but the extent of this
variation would not be sufficient to prevent the use of the
patterns for visual comparison with those of multiphase alloys.
Photographs of diffraction patterns for these alloys are shown
in Figs. 1 and 2.

TABLE II

PHASES IN MAGNESIUM-LITHIUM TERNARY ALLOYS

Alloy Number	Intended Composition and (Chemical Analysis)				Phase
*	99.95+%Mg	---	---	---	alpha
L-21	88.00	12.00%Li (11.85)	---	---	beta
L-62	55.00 ---	--- ---	45.0%Al (44.0)	--- ---	$Mg_{17}Al_{12}$
L-63	--- ---	21.0 (26.6)	79.0 (73.4)	--- ---	Al Li
L-177	37.3 ---	21.3 (20.2)	41.4 (43.1)	--- ---	$MgLi_2Al$
L-93	25.3 ---	7.2 (5.9)	--- ---	67.5%Zn (68.4)	MgLiZn
L-178	23.4 ---	13.4 (12.9)	--- ---	63.2 (63.5)	$MgLi_2Zn$
L-95	27.1 ---	--- ---	--- ---	72.9 (72.5)	MgZn

* Redistilled magnesium crystals containing at least 99.95%Mg
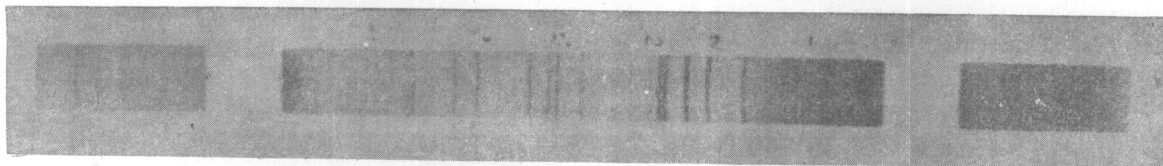
(a)   Alpha phase.   High purity magnesium.
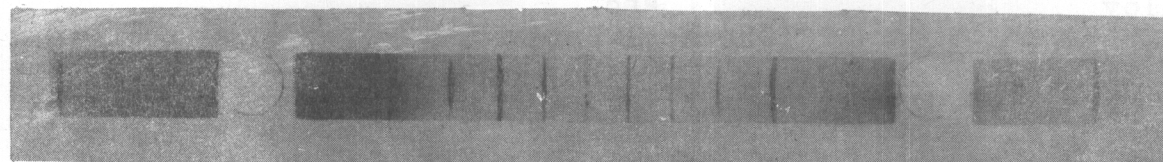
(b)   Beta phase.   Alloy L-21 (magnesium
      - 11.85 lithium).
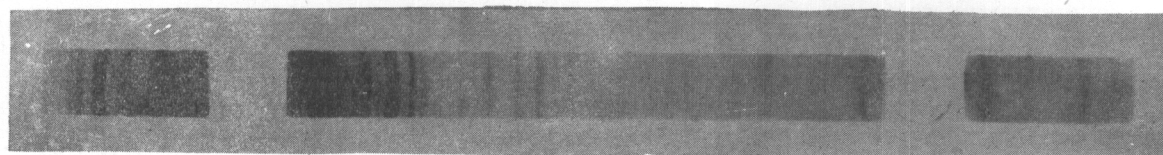
(c)   AlLi phase.   Alloy L-63 (73.4 aluminum
      - 26.6 lithium). Specimen was not stored.
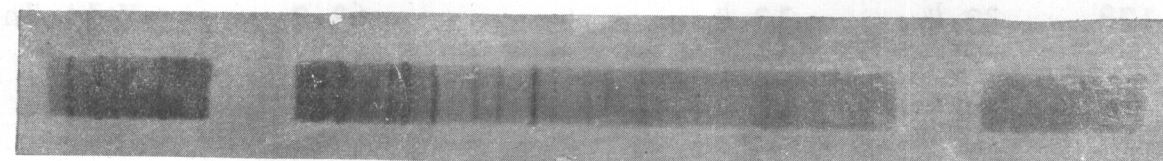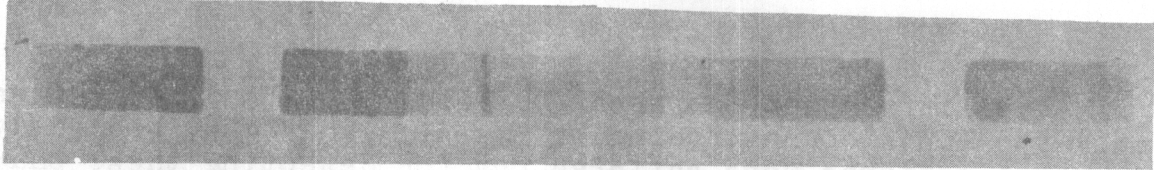
(d)   AlLi phase. Alloy L-63. Specimen
      stored three hours before exposure
      was started.
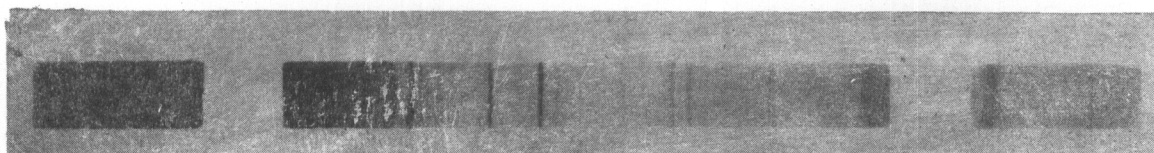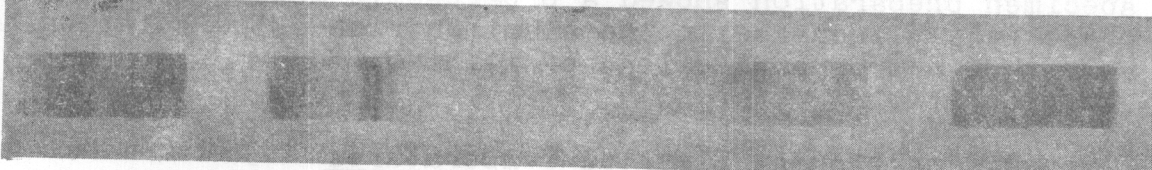
(e)   AlLi phase. Alloy L-63. Specimen
      stored 24 hours before exposure was
      started.

Figure 1
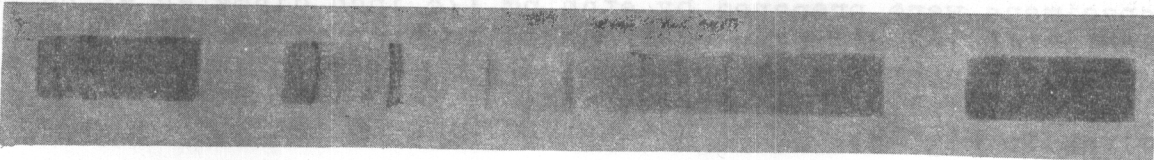
X-ray Diffraction Patterns of the Alpha
Beta and AlLi Phases.
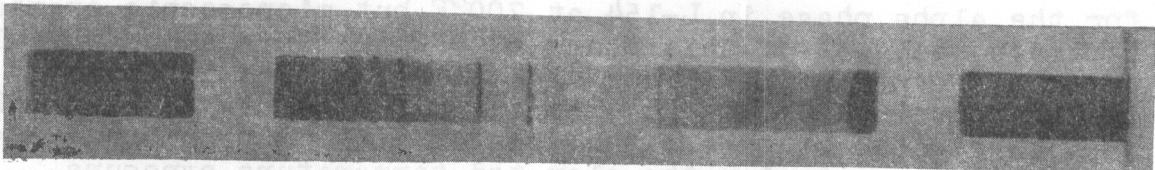
(a) $Mg_{17}Al_{12}$ phase. Alloy L-62 (magnesium 44.0 aluminum).

(b) MgZn phase. Alloy L-95 (magnesium - 72.5 zinc).

(c) MgLiZn Phase. Alloy L-93 (magnesium - 5.9 lithium - 68.4 zinc)

(d) $MgLi_2Zn$ phase. Alloy L-178 (magnesium, 12.9 lithium, 63.5 zinc).

Figure 2

X-ray Diffraction Patterns of the $Mg_{17}Al_{12}$, MgZn, MgLiZn and $MgLi_2Zn$ Phases.

The diffraction patterns for alloys L-62 and L-95 showed only the lines corresponding to $Mg_{17}Al_{12}$ and MgZn, respectively, so these patterns were satisfactory for detecting these phases in multiphase alloys. The pattern for alloy L-93 was useful for confirming the presence of MgLiZn although there was one beta line in this pattern as a result of its low lithium content. Considerable lithium was lost during the powdering of alloys L-63 and L-178 so the analyses of the homogenized ingots were not correct for the diffraction specimens and the diffraction patterns were not correct for AlLi and $MgLi_2Zn$. Also, diffraction patterns for L-63 taken immediately, 3 hours and 24 hours after specimen preparation showed a progressive decrease in the AlLi phase and an increase in the aluminum rich solid solution as a result of a progressive loss of lithium.

X-ray Diffraction at Elevated Temperatures

Three alloys in the multiphase fields of the magnesium -lithium-aluminum system were studied by x-ray diffraction to check the microscopic observations of phases present at 700°F. Diffraction patterns were made at 700°F and also at room temperature on alloys quenched from 700°F. These diffraction specimens were prepared by etching 1/8 inch diameter extruded rod until its diameter was reduced to approximately 0.30 mm. The composition of the alloys studied and the results obtained are listed in Table III. Photographs of the diffraction patterns are given in Fig. 3.

Thermal expansion caused slightly greater interplanar spacings for the high temperature patterns but otherwise there was complete agreement between the results from the room temperature exposure and from the 700°F exposure for alloys L-145 and L-61 but not for L-154. There was a strong diffraction pattern for the alpha phase in L-154 at 700°F but microscopic examination indicated only 5% of this phase at 700°F. This amount of alpha would not explain the strong alpha lines on the diffraction pattern obtained at 700°F. The large amount of the alpha phase was believed to be due to the loss of lithium from the surface of the specimen during the elevated temperature exposure.

TABLE III

PHASES FOUND BY X-RAY DIFFRACTION
AT 700°F IN SOME
MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

Alloy Number	Film Number	Intended Composition and (Chemical Analysis)		Phases Present	Temperature of Exposure
L-145	219	5.0%Li (4.5)	20.0%Al (21.7)	Alpha + $Mg_{17}Al_{12}$	Room Temperature
	225			Alpha + $Mg_{17}Al_{12}$	700°F
L-61	218	11.4 (11.5)	20.0 (19.7)	Alpha + Beta + $Mg_{17}Al_{12}$	Room Temperature
	216			Alpha + Beta + $Mg_{17}Al_{12}$	700°F
L-154	213	15.0 (12.9)	20.0 (21.5)	Beta + Al Li	Room Temperature
	229			Alpha + Beta + Al Li	700°F
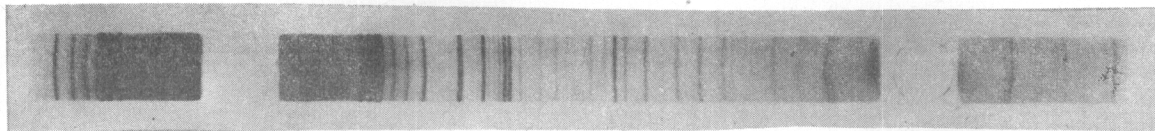
(a) L-145 (magnesium-4.5 lithium-21.7 aluminum) heat treated 24 hours at 700°F, kerosene quenched and exposed at room temperature. Alpha and $Mg_{17}Al_{12}$ phases are present.
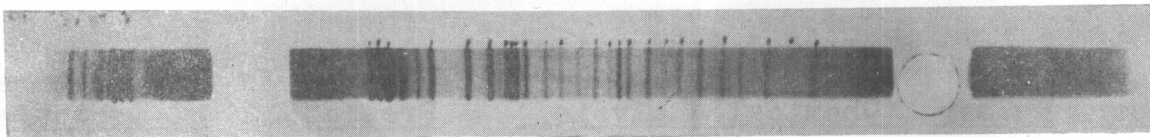
(b) L-145, exposed at 700°F. Alpha and $Mg_{17}Al_{12}$ phases are present.
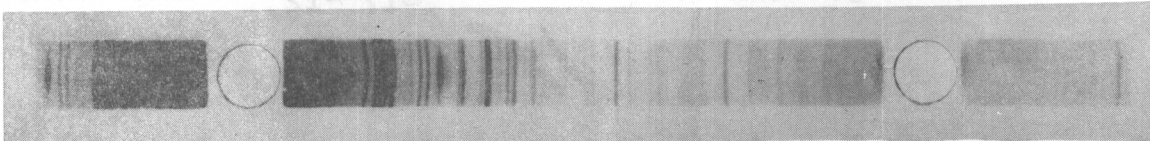
(c) L-61 (magnesium-11.5 lithium-19.7 aluminum) heat treated 24 hours at 700°F kerosene quenched and exposed at room temperature. Alpha, beta and AlLi phases are present.

(d) L-61, exposed at 700°F. Alpha, beta and AlLi phases are present.
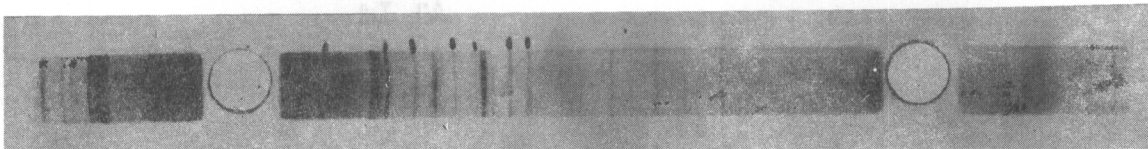
(e) L-154 (magnesium-12.9 lithium-21.5 aluminum) heat treated 24 hours at 700°F, kerosene quenched and exposed at room temperature. Beta and AlLi phases are present.
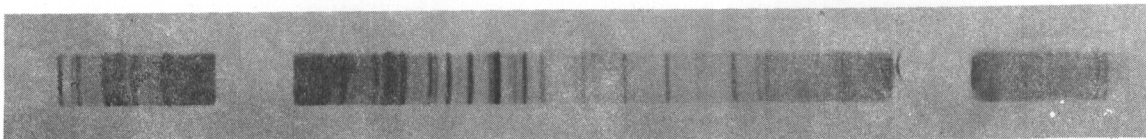
(f) L-154, exposed at 700°F. Alpha, beta and AlLi phases are present.

Figure 3

X-ray diffraction patterns for multiphase magnesium-lithium-aluminum alloys exposed at room temperature after quenching from 700°F and exposed at 700°F.

ELECTRICAL RESISTIVITY STUDY OF MAGNESIUM-LITHIUM TERNARY ALLOYS

Electrical Resistivity Equipment

The effect of temperature and of composition on electrical resistivity has been used by many investigators to locate phase boundaries. Equipment for use with magnesium-lithium base alloys followed the basic design described by Fink and Willey[6] in their work on aluminum-zinc alloys but the rapid corrosion of magnesium -lithium alloys prevented corresponding success. Considerable effort was devoted to the construction and modification of this equipment but completely satisfactory results were not obtained. The details of the construction and modifications of this equipment were given in previous Summary Reports.[2,3]

In this equipment, a hexagonal aluminum block was used with mounts for six samples of 1/8 inch diameter rod with a distance of 2 inches between the potential contacts on each specimen. This block was enclosed in an aluminum container which was sur-rounded by an electrical resistance furnace. Provision was made for leading thermocouple, potential and current connections through the cover of the container and for the entrance and exit of helium. Originally, a single potentiometer was used for measuring the potential drops across the individual specimens and across a standard resistance. Later, it was found much more convenient and accurate to use two potentiometers and to make simultaneous measurements of the potentials.

Specimen Protection During Measurements

Disastrous corrosion of the specimens of magnesium-lithium ternary alloys occurred during electrical resistivity measurements unless very careful precautions were taken. Surface oxidation interrupted the electrical circuits in many cases and, in severe cases of oxidation, the specimens were completely destroyed. Argon with a purity of 99.85% was not satisfactory under either static or flow conditions but helium with a purity of 99.99% (XX Welding Grade) gave reasonably good results with a steady flow. The low steady flow of helium carried away all contamina-ting agents as they were evolved and maintained an atmosphere of higher purity than that obtained under static conditions. The best surface conditions were maintained by using a low steady flow of high purity helium and by careful polishing of the extruded specimens. Careful cleaning and polishing of the specimens were necessary to remove all foreign material absorbed on the surface or mechanically held in the longitudinal die marks.

Resistivity of Magnesium-Lithium Alloys

After the correct operating procedure had been established, resistivity measurements were made on a number of alloys with compositions corresponding to the alpha, alpha plus beta and beta solid solution fields in the magnesium-lithium alloy system. This work showed the time necessary to achieve equilibrium at 500°F., established the value of various treatments previous to resistivity measurements and permitted a comparison with the results of Grube[9] on magnesium-lithium alloys.

The data in Table IV and the curves in Fig. 4 show the results of the experimental work to determine the time to reach equilibrium at 510°F. These data show that from 30 to 36 hours were required to reach stable values of resistivity at this temperature.

The effect of different preliminary treatments on the time to attain equilibrium at 700°F are shown in Table V. These results show that the higher lithium alloys required a longer time to reach equilibrium and that the precipitation treatment at 200°F was quite effective in speeding the attainment of equilibrium. Deep corrosion pits and further corrosion during the resistivity run at 700°F prevented a more accurate evaluation of these preliminary treatments.

Experimental results are shown in Table VI and in Fig. 5 for the resistivity measurements over a period of 13 days for six binary magnesium-lithium alloys up to 715°F. The compositions of these alloys corresponded to the alpha, alpha plus beta and beta solid solution fields in the magnesium-lithium alloy system. Data from the work of Grube as plotted in Fig. 5 show good agreement with the present work for alpha and alpha plus beta solid solution alloys. However, there is a great difference between the curves for alloys near the boundary between the alpha plus beta and the beta solid solution fields. Data from Grube give smooth curves but the present data show definite breaks above 500°F and a marked increase in slope. These breaks and the increase in slope may be the result of the order-disorder reaction suggested by Hume-Rothery.[10] The discrepancy between the present work and that of Grube may be due to the high heating rates -- 10°C in 6-10 minutes -- used by him compared to the slow heating and the long time at temperature used in the present investigation. Thirteen days were used in the present investigation to obtain the data plotted in Fig. 5.

TABLE IV

EFFECT OF TIME AT 510°F ON
ELECTRICAL RESISTANCE OF MAGNESIUM-LITHIUM ALLOYS

Time in Hours	Resistance in Ohms x 10^3 for Lithium Contents of					
	2.6%	3.2%	4.9%	7.77%	10.5%	11.85%
0	0.821	0.833	0.936	0.988	1.003	1.072
5	1.092	1.095	1.239	1.371	1.475	1.549
29	1.182	1.173	1.333	1.498	1.633	1.698
46	1.188	1.180	1.329	1.500	1.634	1.698
76	1.186	1.177	1.338	1.502	1.640	1.696
94	1.182	1.173	1.333	1.496	1.629	1.694
101	1.185	1.179	1.340	1.500	1.633	1.699
119	1.183	1.173	1.332	1.498	1.624	1.693

TABLE V

EFFECT OF PRELIMINARY TREATMENT ON
ELECTRICAL RESISTANCE OF MAGNESIUM-LITHIUM ALLOYS

Alloy	Observations from Measurements at 700°F		
	Treatment* A	Treatment* B	Treatment* C
Mg-3.2%Li	Equilibrium attained after 24 hours	Equilibrium attained after 25 3/4 hours	Equilibrium attained after 23 hours
Mg-7.77%Li	Equilibrium attained after 32 hours	Resistivity still changing at 55 3/4 hrs.	Equilibrium attained after 48 hours
Mg-11.85%Li	Resistivity still changing at 55 3/4 hrs.	Equilibrium attained after 48 hours	Equilibrium attained after 23 hours

* Details of preliminary treatments of alloys sealed in glass tubes with a slight pressure of helium

    Treatment A:- Heat 24 hours at 700°F; age 1 week at 200°F

    Treatment B:- Heat 24 hours at 700°F; cool by dropping temperature 100°F each day

    Treatment C:- Age extruded alloys 2 weeks at 200°F
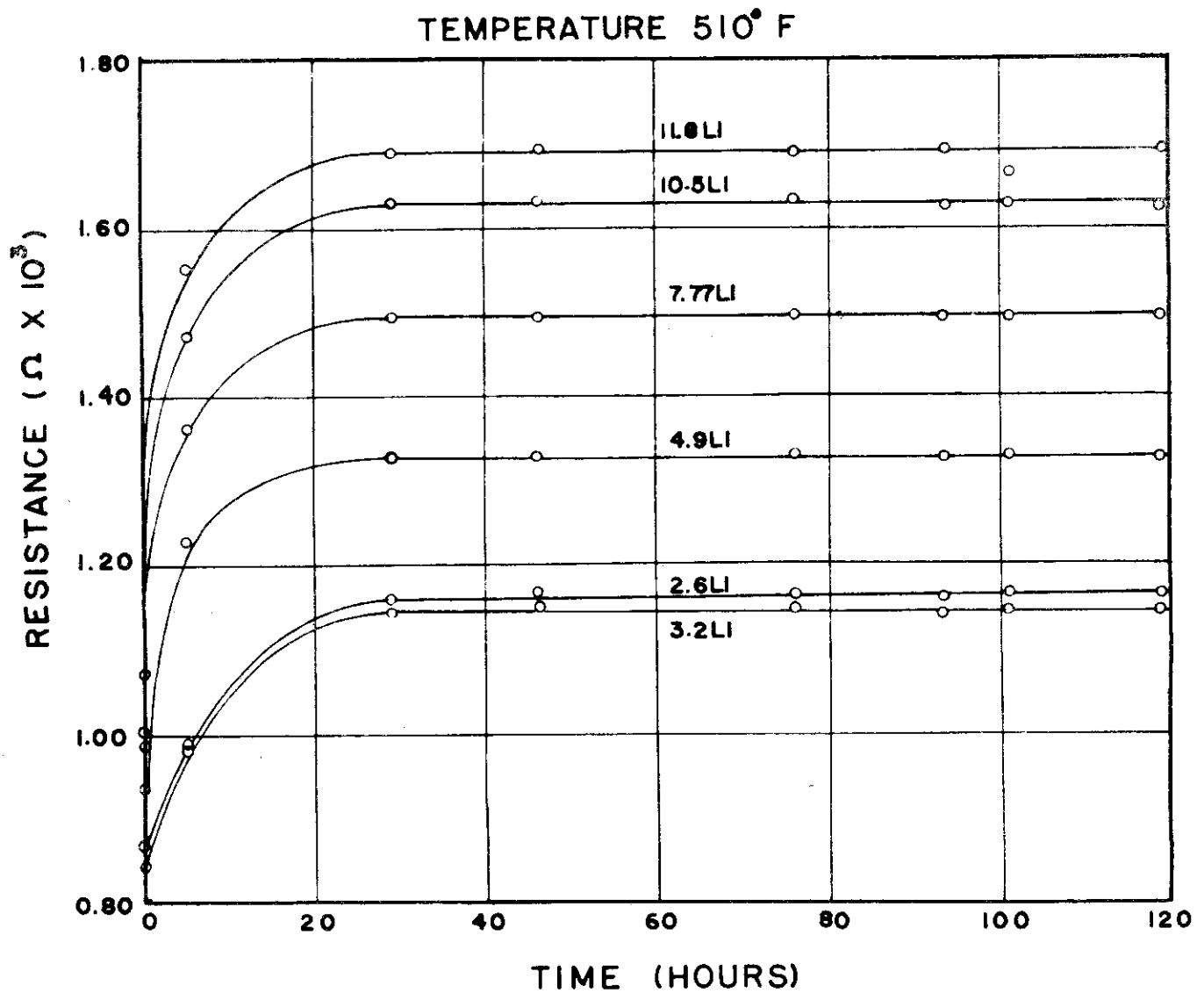
TEMPERATURE 510° F

FIGURE 4

RESISTANCE VS. TIME

MAGNESIUM—LITHIUM BINARY ALLOYS

TABLE VI

EFFECT OF TEMPERATURE ON
ELECTRICAL RESISTIVITY OF MAGNESIUM-LITHIUM ALLOYS

Temp. °F	Resistivity in ohm - cm x 10^5 for Lithium Contents of					
	2.6%	3.2%	4.9%	7.77%	10.5%	11.85%
286	1.309	1.387	1.564	1.650	1.727	1.732
406	1.440	1.519	1.724	1.840	1.960	1.950
505	1.547	1.631	1.820	2.001	2.159	2.125
603	1.680	1.740	1.981	2.170	2.447	2.323
710	1.741	1.832	2.097	2.331	2.794	2.661
715	1.747	1.834	2.098	2.335	2.797	2.662

Resistivity of Magnesium-Lithium Ternary Alloys

Electrical resistivity measurements up to 700°F were made over a period of 16 days on selected magnesium-lithium ternary alloys in which microscopic examination had shown distinct phase changes between 500° and 700°F. The composition and structure of these alloys are given in Table VII and Table VIII and in Fig. 6. Phase changes between 500° and 700°F were indicated by changes in the slope of the resistivity curves for alloys L-119, L-100, L-141 and L-148. Microscopic examination showed that the structure of L-141 changed only from 97% alpha and 3% $Mg_{17}Al_{12}$ at 500°F to 100% alpha at 700°F but the resistivity curve showed a pronounced change in slope at 520°F. However, the curves for L-112 and L-139 showed no change in slope above 500°F even though microscopic examination showed a distinct difference between their structure at 500°F and at 700°F. The amount of the phase change in these alloys was greater than in L-141 but the electrical resistivity of the old and new phases might have been the same or errors might have been caused by oxidation of these specimens.

Electrical resistance measurements up to 685°F were also made over a period of 35 days on a series of magnesium-lithium -aluminum alloys in which microscopic examination had shown distinct phase changes between 500° and 700°F. The composition and structure of these alloys are given in Table IX and the resistance measurements are shown in Table X and in Fig. 7. No change in the slope of the resistance curve between 500° and 700°F was found for L-123 but a change in slope between 500° and 700°F was found for the other alloys. Changes in slope between 350° and 500°F were also found for all of these alloys
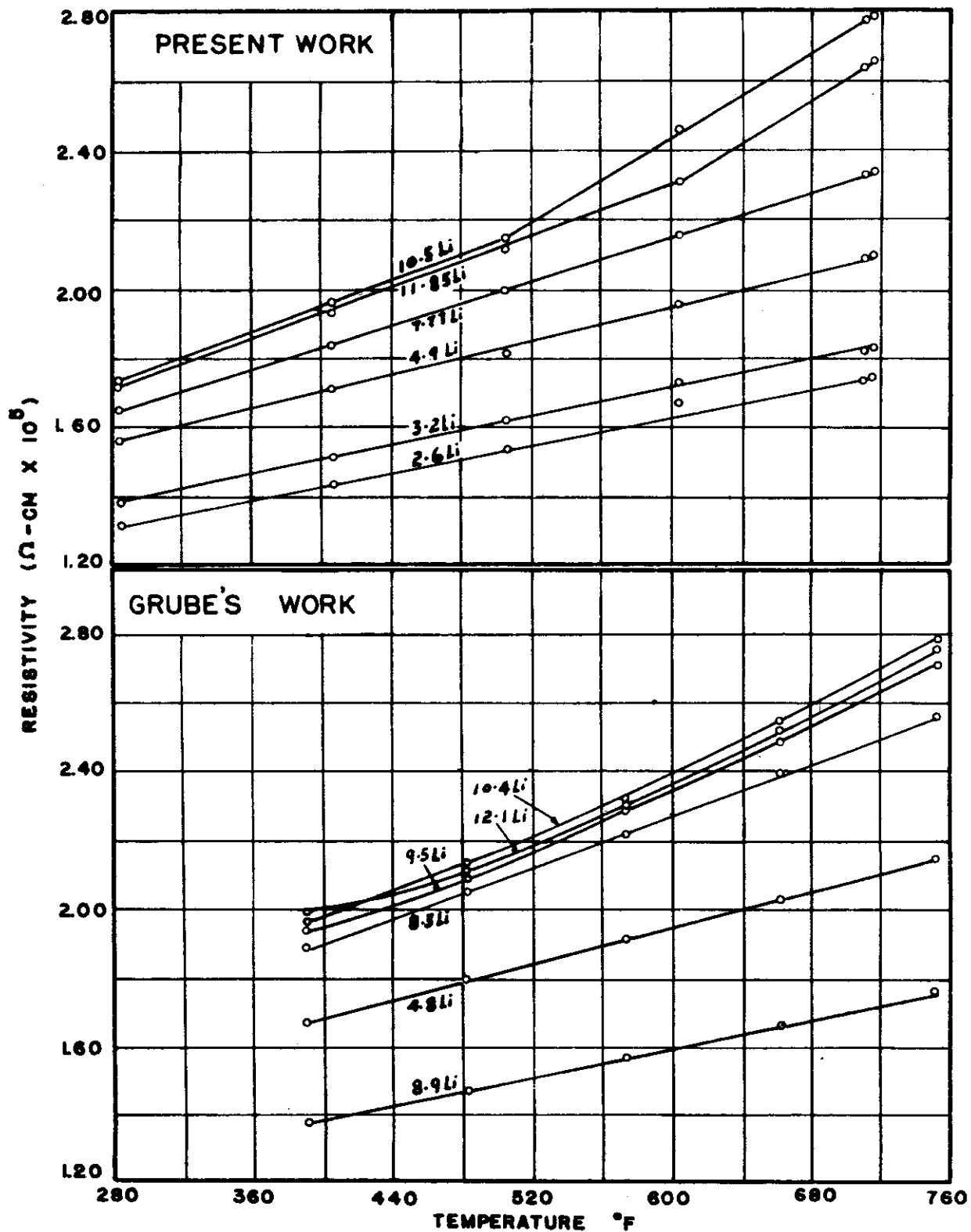
FIGURE 5

RESISTIVITY VS. TEMPERATURE

MAGNESIUM-LITHIUM BINARY ALLOYS

TABLE VII

MAGNESIUM-LITHIUM TERNARY ALLOYS
STUDIED BY
ELECTRICAL RESISTIVITY METHOD

Alloy Number	Intended Composition* and (Analysis)			Treatment		Microscopic Estimation of Phases Present		
	Li	Al	Zn	Time Hours	Temp. °F	Alpha	Beta	Other
L-119	3.0%	--	8.0%	As Extruded		70%	--	30% MgLiZn
	--	--	--	72	500	70	--	30
	(2.5)	--	(8.5)	24	700	100	--	--
L-112	5.6	--	10.0	As Extruded		80	--	20% MgLiZn
	(4.8)	--	(9.2)	72	500	65	--	35
	(4.8)	--	(9.2)	24	700	85	15%	--
L-100	11.2	--	10.0	As Extruded		--	80	20% MgLiZn
	(9.9)	--	9.8	72	500	--	70	30
	(9.8)	--	(9.0)	24	700	--	100	--
L-141	1.0	8.0%	--	As Extruded		100	--	--
	--	--	--	72	500	97	--	3% $Mg_{17}Al_{12}$
	(0.9)	(6.3)	--	24	700	100	--	--
L-139	8.5	6.0	--	As Extruded		55	35	10% AlLi
	--	--	--	72	500	58	35	7
	(8.3)	(6.4)	--	24	700	59	40	1
L-148	15.0	7.0	--	As Extruded		--	80	20% AlLi
	--	--	--	72	500	--	95	5
	(14.2)	(6.1)	--	24	700	--	100	--

* Balance was magnesium

TABLE VIII

EFFECT OF TEMPERATURE ON
ELECTRICAL RESISTIVITY OF MAGNESIUM-LITHIUM TERNARY ALLOYS

Temp. °F	Resistivity in ohm-cm x 10^5 for Alloys					
	L-119	L-112	L-100	L-141	L-139	L-148
312	---	1.873	---	---	---	---
367	1.499	1.788	2.138	1.479	2.088	2.365
402	1.528	1.815	2.230	1.511	2.142	2.470
474	1.615	1.941	2.412	1.715	2.355	2.738
503	1.652	1.969	2.495	1.788	2.465	2.844
556	1.737	2.057	2.680	1.882	2.722	3.152
600	1.803	2.110	2.761	1.913	2.919	3.370
703	1.978	2.262	2.938	1.983	3.395	3.848

TABLE IX

MAGNESIUM-LITHIUM-ALUMINUM ALLOYS
STUDIED BY
ELECTRICAL RESISTANCE METHOD

Alloy Number	Intended Composition* and (Analysis) Li	Al	Treatment Time Hours	Temp °F	Microscopic Estimation of Phases Present Alpha	Beta	Other
L-123	8.5% (7.4)	4.0% (6.7)	72 24	500 700	55% 60	37% 40	8% AlLi ---
L-128	12.5 (11.0)	6.0 (4.8)	72 24	500 700	--- ---	90 100	10 ---
L-122	12.0 (10.8)	2.5	72 24	500 700	5 ---	95 100	--- ---
L-152	20.0 (19.2)	8.0 (8.2)	72 24	500 700	--- ---	95 100	5 ---
L-141	1.0 (0.9)	8.0 (6.3)	72 24	500 700	97 100	--- ---	3% $Mg_{17}Al_{12}$ ---
L-142	11.0 (10.3)	4.0 (6.0)	72 24	500 700	35 25	60 75	5% AlLi ---

* Balance was magnesium

FIGURE 6
RESISTIVITY VS. TEMPERATURE
MAGNESIUM-LITHIUM BASE TERNARIES

TABLE X

EFFECT OF TEMPERATURE ON
ELECTRICAL RESISTANCE OF MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

Temp.	Resistance in ohms x 10^3 for Alloys					
°F	L-123	L-128	L-122	L-152	L-141	L-142
304	1.392	1.394	1.388	1.745	1.099	1.441
386	1.504	1.577	1.568	1.955	1.099	1.608
483	1.715	1.846	1.854	2.310	1.208	1.877
511	1.790	1.931	1.941	2.432	1.255	1.968
532	1.844	2.001	1.984	2.524	1.279	2.032
561	1.940	2.109	2.077	2.697	1.298	2.146
584	2.019	2.194	2.109	2.835	1.310	2.226
631	2.207	2.429	2.210	3.127	1.336	2.440
685	2.415	---	2.295	---	1.367	---

except L-122. The change in slope near 400°F for L-141 was
found in the separate experimental runs shown in Figs. 6 and 7.
These changes in slope between 350° and 500°F suggested phase changes
in this region but microscopic examination did not detect any
changes in structure when these alloys were heat treated at 500°,
450°, 350° and 300°F.

Value of the Resistivity Equipment

Resistivity measurements on magnesium-lithium ternary alloys
did not give definite and conclusive evidence of phase changes.
Changes in the slope of the curves were small so that great care
had to be used to avoid confusion between breaks due to corrosion
or other errors and to changes in structure. However, the ex-
perimental work with this equipment emphasized the easy oxidation
of high lithium alloys and the difficulty in preventing this
trouble. This equipment should be useful for determining
temperature coefficients of electrical resistance, time to approach
equilibrium and phase changes in other magnesium alloys which are
more resistant to corrosion.
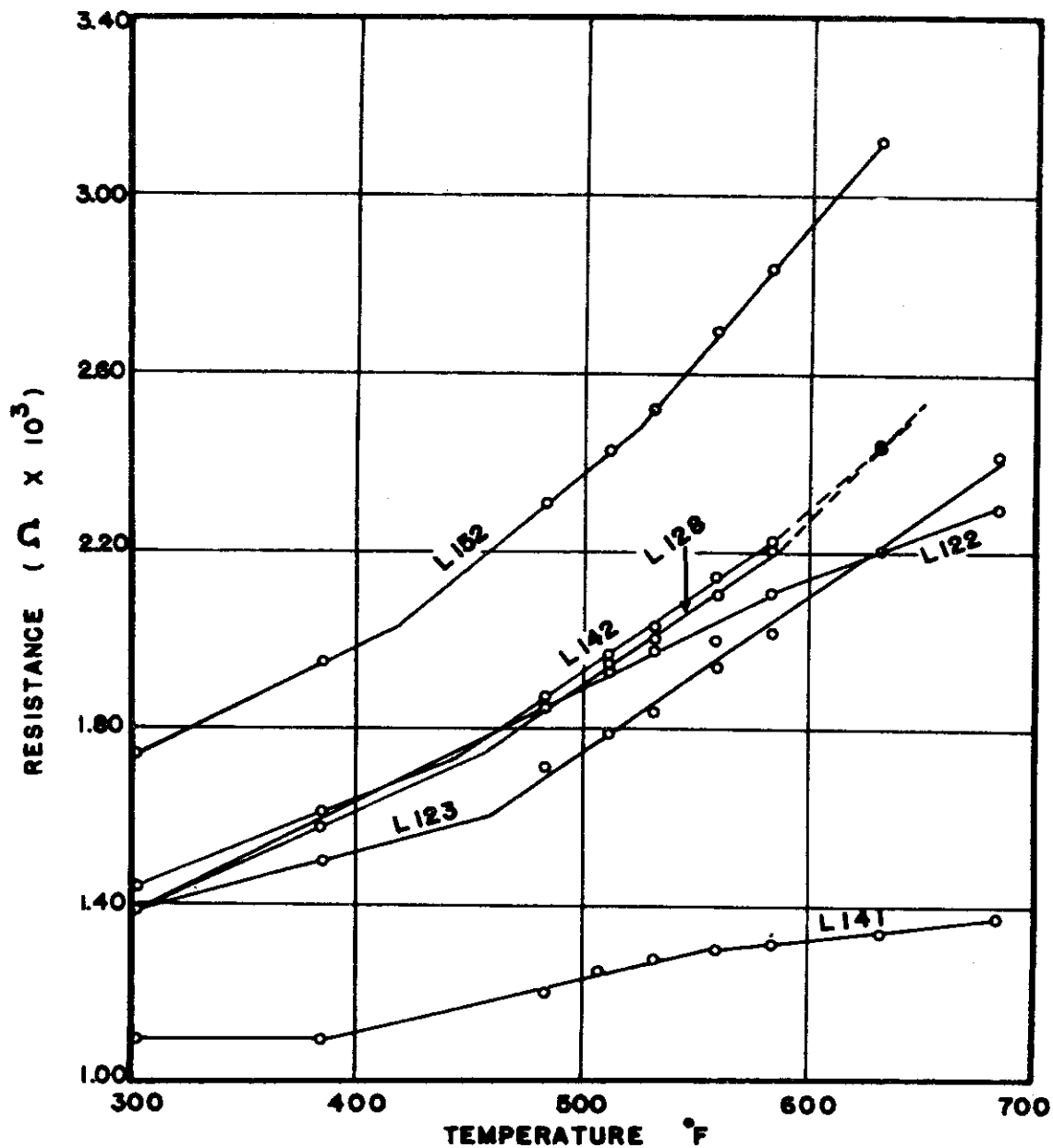
FIGURE 7

RESISTANCE VS. TEMPERATURE

MAGNESIUM - LITHIUM - ALUMINUM ALLOYS

CONSTITUTION OF MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

Phases Present

The phases found in this alloy system were the hexagonal close packed alpha solid solution, the body centered cubic beta solid solution, $Mg_{17}Al_{12}$ and AlLi. Diffraction patterns of these phases are shown in Figs. 1 and 2 and photomicrographs are shown in Figs. 8 through 15. These photomicrographs also show the effect of various etchants on these phases.

No metallographic technique was found for distinguishing with certainty between AlLi and $Mg_{17}Al_{12}$ when these occurred together. The use of kerosene rather than water as a carrier for the abrasive eliminated pitting and gave a good polished surface but no etchant was developed to give a different appearance to these phases. Some work was done to distinguish between these materials by the phase contrast method but this work was not sufficient to solve the problem. Also an attempt was made to differentiate between these phases by microhardness tests but the particle size was too fine and was not coarsened enough by treating at 700°F for one week.

The presence of $MgLi_2Al$ was not found in any alloys examined in this research. This phase was considered in connection with the changes below 500°F in the slope of the resistivity curves for some alloys as shown in Figs. 6 and 7. This possibility was studied by treating six alloys for extended periods of time at 700°, 500°, 450°, 400°, 350° and 300°F, respectively, quenching in kerosene and then investigating their structure by microscopic and x-ray techniques. The data in Table XI show no $MgLi_2Al$ so this phase was not an equilibrium phase in these alloys.

Phase Boundaries at 700°F

The phase boundaries at 700°F in the magnesium-rich corner of the magnesium-lithium-aluminum alloy system are shown in Fig. 16 together with the composition of those alloys whose structure showed them to be near phase boundaries. To avoid errors due to oxidation and loss of lithium, these compositions were determined by chemical analysis after heat treatment rather than on samples of the as extruded rod. In addition to the compositions plotted on this constitutional diagram, the structure of many other alloys was studied in searching for the location of phase boundaries. The intended composition, chemical analysis and structure of all magnesium-lithium-aluminum alloys examined are given in Appendix I, Table XXI

Phase boundaries are shown in Fig. 16 between the alpha plus AlLi and the alpha plus AlLi plus $Mg_{17}Al_{12}$ fields and also between the alpha plus AlLi plus $Mg_{17}Al_{12}$ and the alpha plus $Mg_{17}Al_{12}$ fields although these boundaries were not located in this work. These boundaries must exist but no metallographic
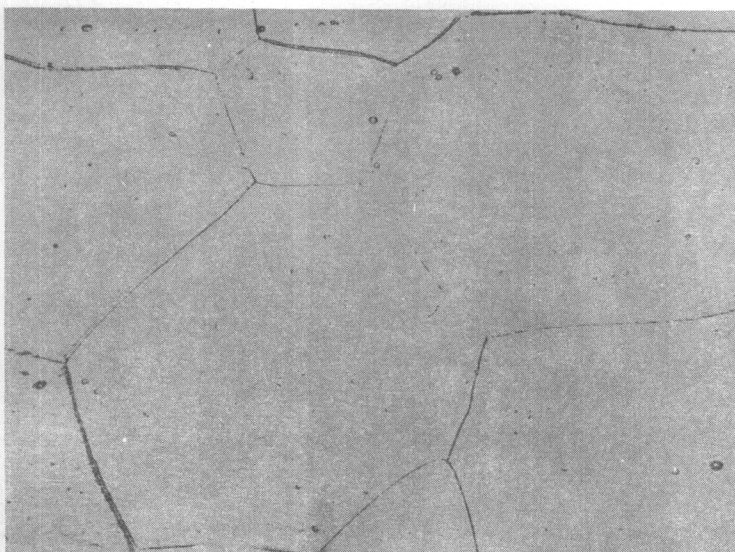
Figure 8

Neg: 274   Mag: 500X
Spec: M831   Etch: 100 Picral, 5 Glacial Acetic
                            Acid, 10 Water, 10 Sec.

Longitudinal section of alloy L-54 (Mg – 5.4Li – 1.9 Al) heat treated 24 hours at 700°F and quenched in kerosene. This structure is 100% alpha solid solution with some polishing and etching pits.
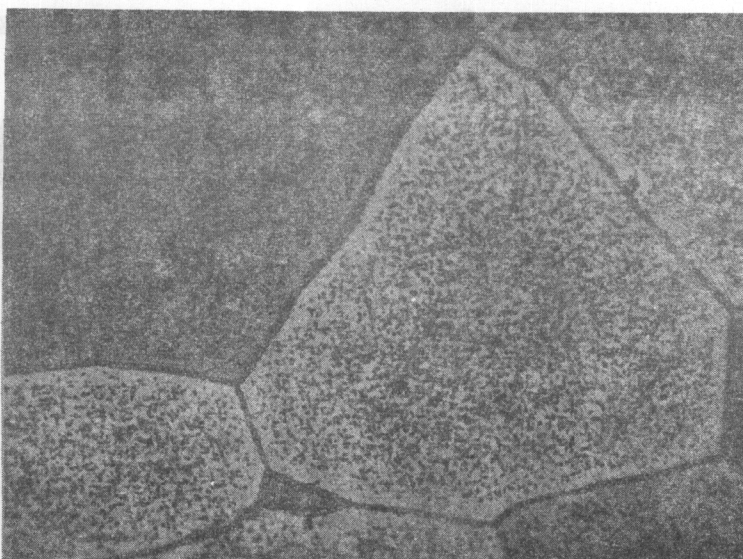
Figure 9

Neg: 275   Mag: 500X
Spec: M891   Etch: 100 Picral, 5 Glacial Acetic
                            Acid, 10 Water, 10 Sec.

Longitudinal section of alloy L-128 (Mg – 11.0Li – 4.8Al) heat treated 24 hours at 700°F and quenched in kerosene. The beta solid solution was colored blue to black by the etching reaction. The mottled appearance of the grains was due to the deposition of some products of the etching reaction on the surface. The grains in the beta phase field grow very large during thermal treatment.

Figure 10

Neg: 267   Mag: 500X
Spec: M782   Etch: 100 Picral, 5 Glacial Acetic
                          Acid, 10 Water, 5 Sec.
    Longitudinal section of alloy L-26 (Mg - 8.44Li
- 4.65Al) heat treated 24 hours at 700°F and quenched
in kerosene. The grains of the alpha solid solution
(light) and the beta solid solution (dark) have
grown quite large. The markings within the beta grains
were believed to represent rupture of the etching film
rather than a precipitate.

Figure 11
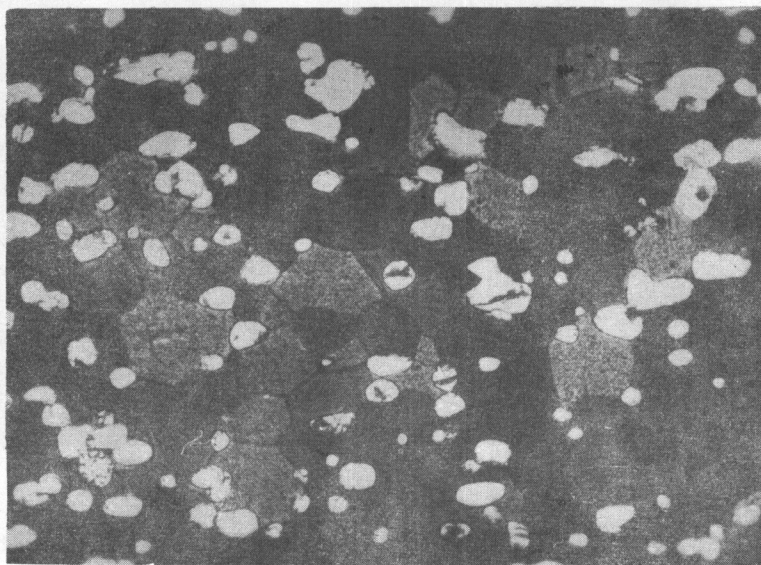
Neg: 263   Mag: 500X
Spec: M932   Etch: 100 Picral, 5 Glacial Acetic
                          Acid, 10 Water, 5 Sec.
    Longitudinal section of L-153 (magnesium - 13.9Li
- 15.8 Al) heat treated 24 hours at 700°F and quenched
in kerosene. The dark areas are the beta solid solution
and the white globular phase is AlLi.

WADC TR 52-169   28
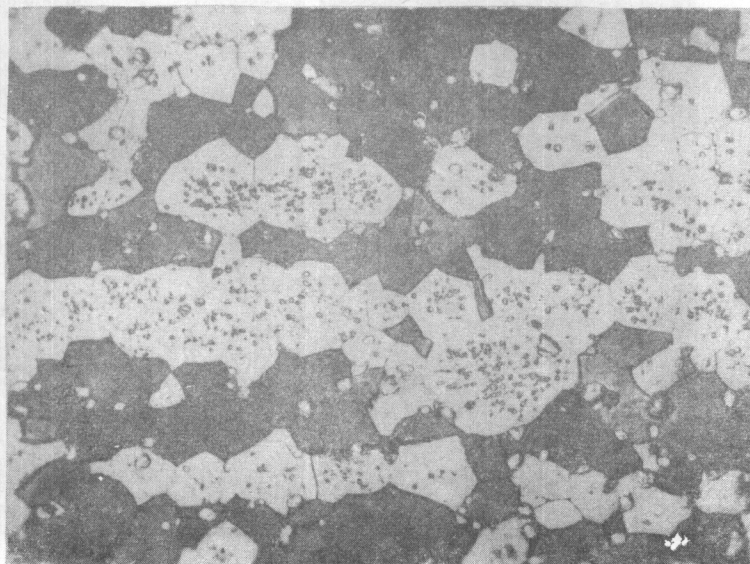
Figure 12

Neg: 249   Mag: 500X
Spec: M695   Etch: 100 Picral, 5 Glacial Acetic Acid,
                    10 Water, 8 Sec.

Longitudinal section of alloy L-26 (Mg - 8.44Li - 65Al) heat treated 72 hours at 500°F and quenched in kerosene. The beta solid solution appears dark. The alpha solid solution and the intermediate phase appear light, not clearly separated. Compare with Fig. 10 heat treated at 700°F.
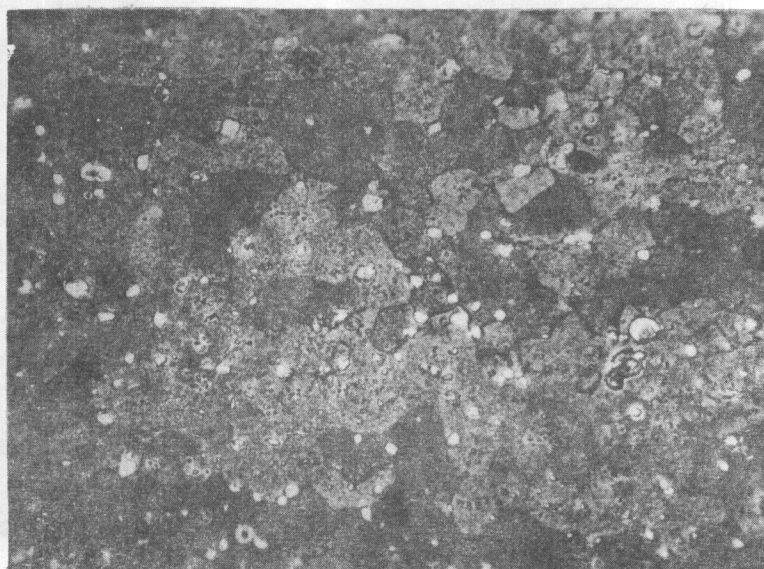
Figure 13

Neg: 248   Mag: 500X
Spec: M694   Etch: 100 Picral, 5 Glacial Acetic, 10
                    Water, 10-10% Tartaric Acid

Same structure as shown in Fig. 12. The modified acetic-picral solution produces a color distinction between the alpha solid solution and the intermediate phase AlLi.

WADC TR 52-169   29
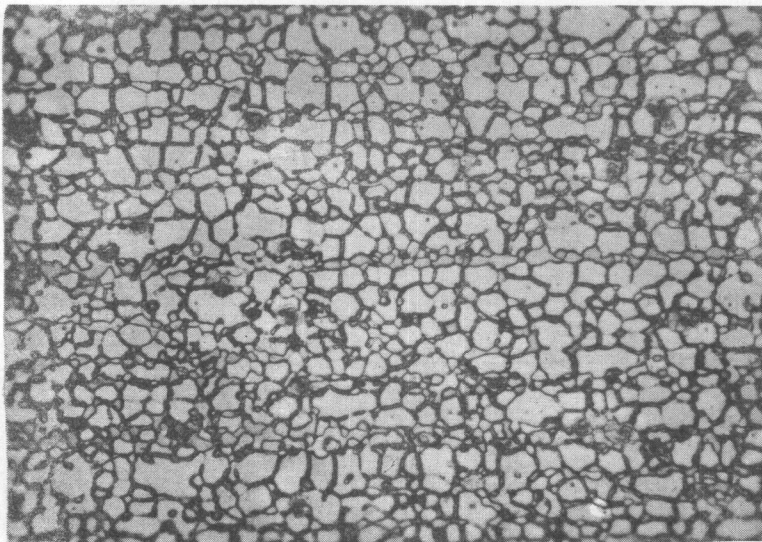
Figure 14

Neg: 270   Mag: 500X
Spec: M934   Etch: 100 Picral, 5 Glacial Acetic Acid,
                          10 Water, 6 Sec.

Longitudinal section of alloy L-145 (Mg - 4.6 Li - 23.3 Al) heat treated 24 hours at 700°F and quenched in kerosene. This etchant attacked the alpha much more severely than the $Mg_{17}Al_{12}$ grain boundaries. The equiaxed alpha grains appeared white as did the $Mg_{17}Al_{12}$ grains. Grain growth and phase agglomeration was much less than in other alloys given the same thermal treatment.
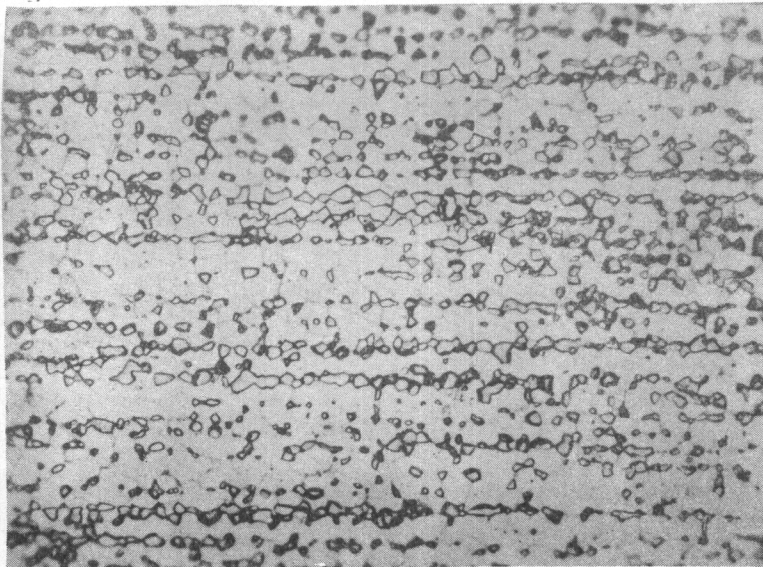
Figure 15

Neg: 272   Mag: 500X
Spec: M934   Etch: 10 - 48% HF, 90 Water, 4 Sec.

Same structure as shown in Figure 14. The $Mg_{17}Al_{12}$ grains were attacked and colored a very light brown and the grain boundaries sharply resolved. The alpha phase was white but the grain boundaries were not clearly resolved.

TABLE XI

PHASES IN MAGNESIUM-LITHIUM-ALUMINUM ALLOYS
TREATED AT 700°, 500°, 400°, 350° AND 300°F

| Alloy Number | Intended Composition* and Chemical Analysis | | Phases Present |
	Li	Al	
L-123	8.5% (7.4)	4.0% (6.7)	alpha + beta + AlLi
L-128	12.5 (11.0)	6.0 (4.8)	beta + AlLi
L-122	12.0 (10.8)	2.5	alpha + beta
L-152	20.0 (19.2)	8.0 8.2	beta + AlLi
L-141	1.0 (0.9)	8.0 (6.3)	alpha + $Mg_{17}Al_{12}$
L-142	11.0 (10.3)	4.0 (6.0)	alpha + beta + AlLi

* Balance was magnesium
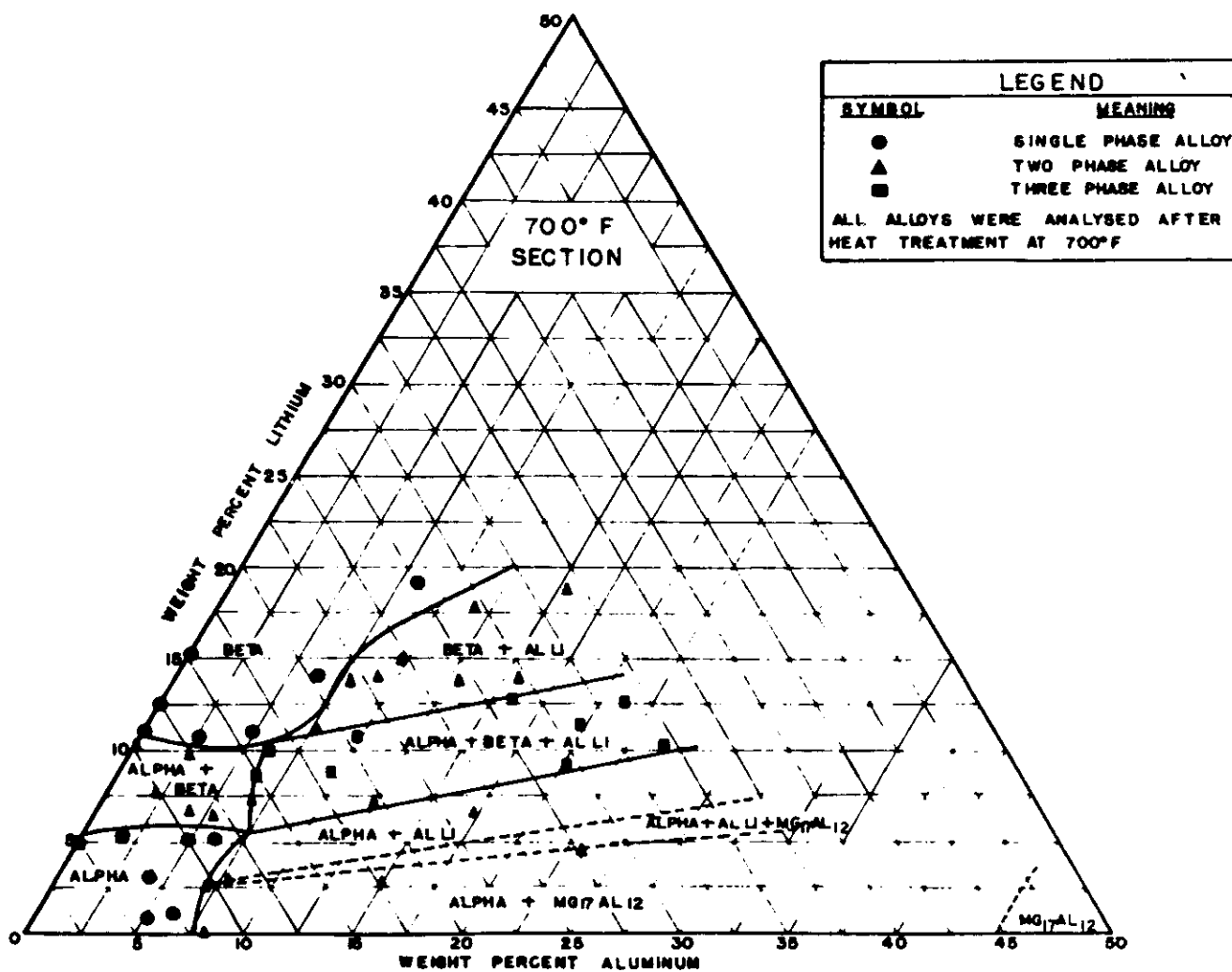
FIGURE 16

PHASE BOUNDARIES IN THE MAGNESIUM CORNER OF
THE MAGNESIUM- LITHIUM- ALUMINUM SYSTEM AT 700° F

technique was developed to distinguish between the AlLi and $Mg_{17}Al_{12}$ phases when they occurred together. The other phase boundaries are considered as located within 2-1/2 percent of lithium. The major portion of this possible error was due to the oxidation and loss of lithium from the alloys during storage and heat treatment.

A previous study of the constitution of magnesium-lithium -aluminum alloys at 400°C (752°F) was presented in Russian by Shamrai.[11] His results have been plotted in Fig. 17 in terms of weight percentages for easier comparison with the results of the present investigation but no correction could be made for the difference of 52°F between the temperature levels presented in Figs. 16 and 17. Shamrai's paper has not been translated but the phases found by him and indicated by Roman numerals can be identified from their location on the diagram. However, the exact significance of the solid and dotted boundaries is not known.

The most obvious difference between the two diagrams is the larger region shown by Shamrai for the beta solid solution. This difference seems greater than can be explained by the difference in the temperature levels. Another difference is that Shamrai found $MgLiAl_2$ in an extensive three phase field but this phase was not detected by x-ray diffraction or microscopic examination in the present investigation. The $AlLi_2$ phase was found by Shamrai in a region above 20% lithium but this region was not included in the present study.

Phase Boundaries at 500°F

The constitution of this alloy system at 500°F is shown in Fig. 18 but the phase boundaries were not located as accurately at this temperature level as at 700°F. The compositions plotted on this diagram were determined by analysis of selected specimens after heat treatment at 500° or at 700°F. but these represent only a portion of the alloys which were studied. The boundaries which were located most accurately were between alpha and alpha plus $Mg_{17}Al_{12}$, between beta and alpha plus beta and between beta and beta plus AlLi. As at 700°F, phase boundaries are shown between alpha plus AlLi and alpha plus AlLi plus $Mg_{17}Al_{12}$ and between alpha plus $Mg_{17}Al_{12}$ and alpha plus AlLi plus $Mg_{17}Al_{12}$ although these boundaries were not located in this work.

Comparison of the Constitution at 500°F and at 700°F.

The major difference between the diagrams for 500° and 700°F was the difference in the extent of the alpha, alpha plus beta and beta phase fields. All of these fields were smaller in area at 500° than at 700°F. The amount of lithium in solid solution
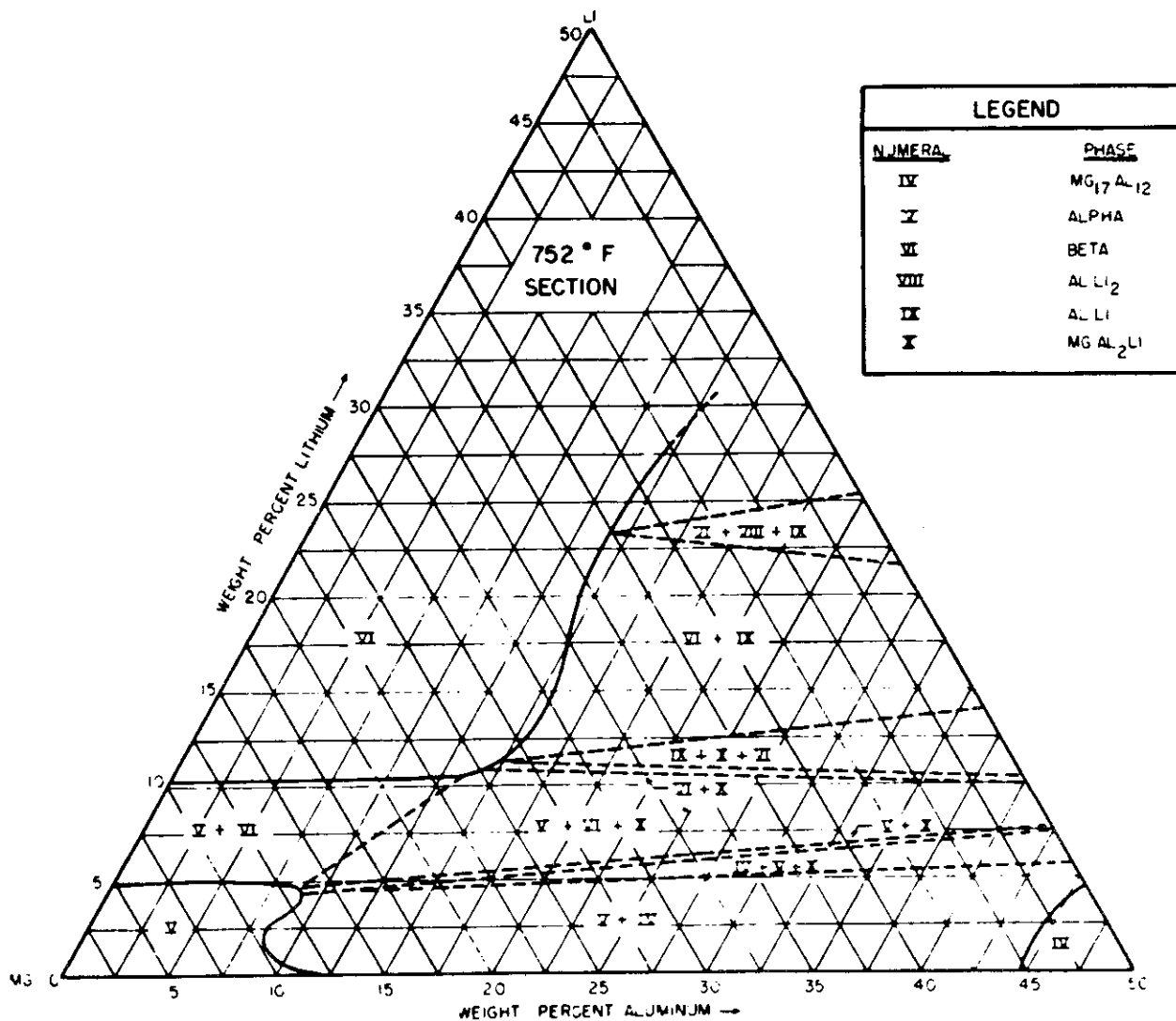
FIGURE 17

LOCATIONS OF PHASE BOUNDARIES IN THE MAGNESIUM CORNER OF THE
MAGNESIUM-LITHIUM-ALUMINUM SYSTEM AT 752°F (400°C) AS REPLOTTED
FROM SHAMRAI'S TERNARY DIAGRAM   THE LEGEND GIVES SHAMRAI'S
PHASE NOMENCLATURE
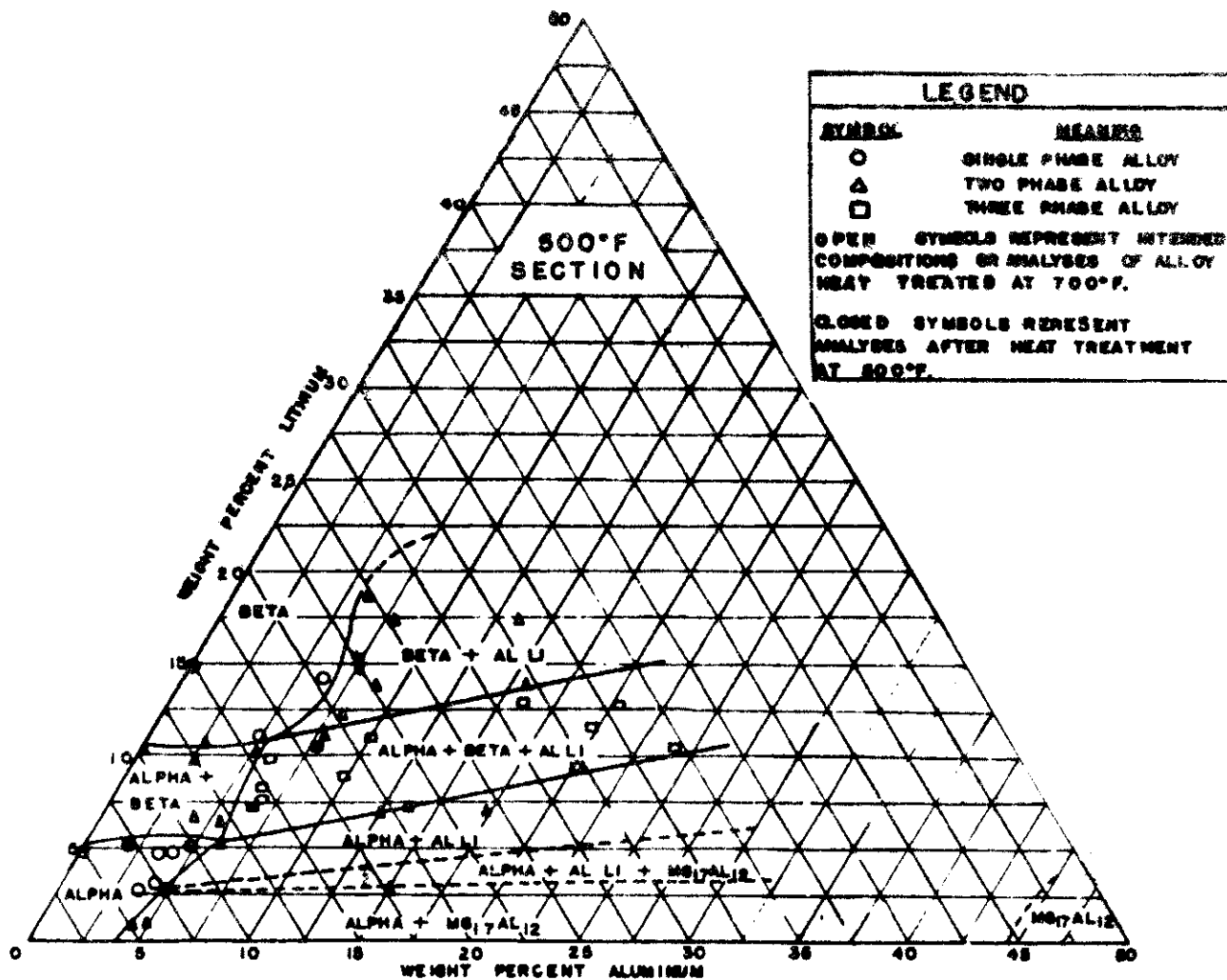
FIGURE 18

APPROXIMATE LOCATIONS OF PHASE BOUNDARIES IN THE
MAGNESIUM CORNER OF THE MAGNESIUM-LITHIUM-ALUMINUM
SYSTEM AT 500°F

was nearly the same but the solubility of aluminum was much less at 500°F. In addition to this major change in the phase boundaries, the position of other boundaries changed slightly as shown in Figs. 16 and 18.

CONSTITUTION OF MAGNESIUM-LITHIUM-ZINC ALLOYS

Phases Present

The solid phases found in this alloy system were the close packed hexagonal alpha solid solution, the body centered cubic beta solid solution, MgLiZn and an unidentified phase at 500°F in alloys containing less than 5% lithium. A feathery precipitate of $MgLi_2Zn$ was found in some alloys but this was not considered an equilibrium phase at either 700° or 500°F. In addition to these solid phases, a liquid phase existed at 700°F in some low lithium alloys. These phases are shown in the photomicrographs of Figs. 19 through 26.

The feathery precipitate which appeared along grain boundaries in some alloys was identified as $MgLi_2Zn$ by x-ray diffraction. This precipitate is shown in Figs. 25 and 26 along the boundaries of the very large grains of the beta solid solution. Such coarse grains, usually found only in single phase alloys, together with the form and location of this precipitate indicated that this phase did not exist at 700°F but formed during quenching. In order to test this theory, six alloys were heat treated at temperatures ranging from 300° to 700°F and then quenched into kerosene maintained at 28°F. The intended compositions of these alloys, their heat treatment and their constitution are given in Table XII.

No $MgLi_2Zn$ was found in alloys L-181 and L-87 which contained low zinc -- 4.6 and 2.2% respectively -- but it was found in the other alloys which contained a similar lithium content and a zinc content of 7.5% or more. Data on the beta alloys L-38, L-39, L-40, L-87, L-96, L-97, L-98, L-181 and L-184 showed that $MgLi_2Zn$ was not found in alloys containing less than 6% zinc. These data are given in Appendix I, Table XXII. In this table, data for two specimens of L-109 treated at 500°F show a different content of $MgLi_2Zn$ and beta but the same content of MgLiZn. Possibly, the difference in the amount of $MgLi_2Zn$ and beta was due to a difference in quenching conditions for these two specimens. If the precipitation of $MgLi_2Zn$ was due to a quenching rate which was too slow, the amount of this precipitate would be greater near the center than near the surface. In some specimens, the $MgLi_2Zn$ was uniformily distributed as shown in Fig. 27 but, in others, a greater amount was found near the surface. This effect, shown in Fig. 28, was believed to be due to a loss of lithium from the surface regions during the heat treatment.
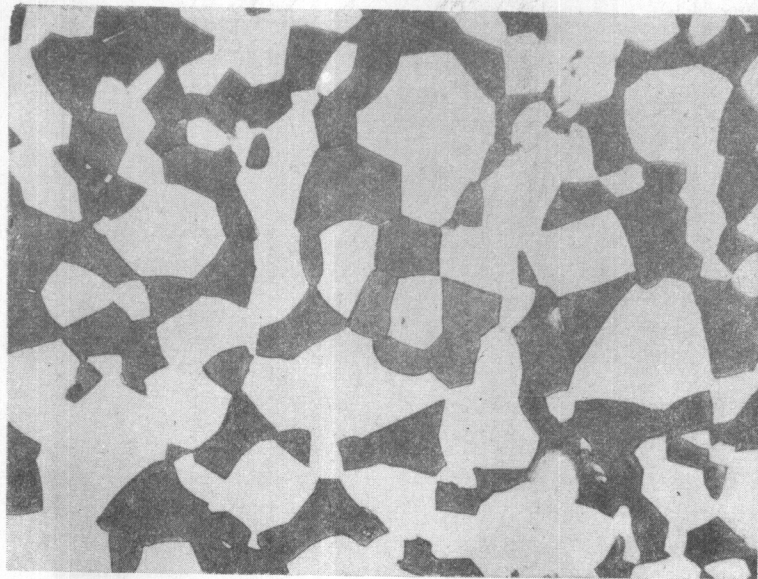
Figure 19

Neg: 298   Spec: M708   Magnification: 500X
Etch: 100 pts. picral:5 pts. glacial acetic acid:10 pts.
        water, 4 sec.
L-33, Charge 174, intended 8.9%Li, 2.0% Zn. Heat treated
24 hrs. at 700°F and quenched in kerosene. Two phases:
alpha and beta. Alpha phase is white and unattacked; beta
phase is etched dark.
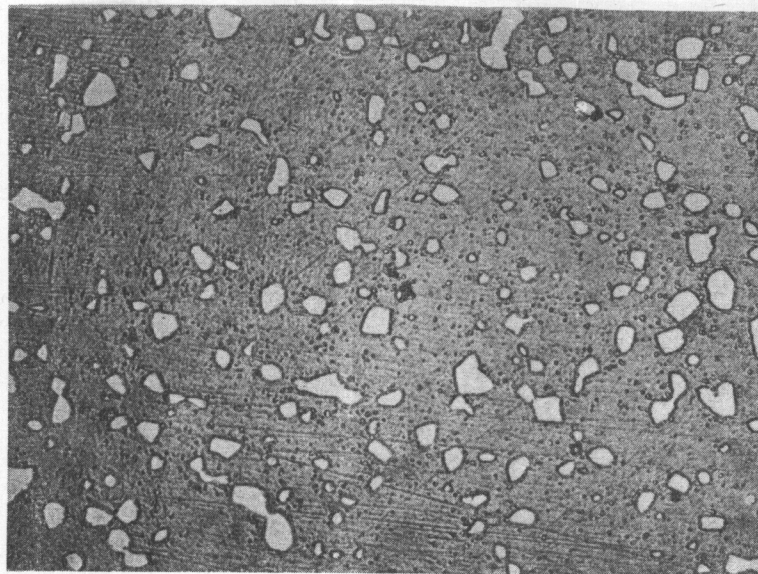
Figure 20

Neg: 280   Spec. M1034   Magnification: 750X
Etch: 10 gm. salicylic acid in 300 ml. ethyl alcohol, 55 sec.
L-170, Charge 300, intended 3.7%Li, 21.5%Zn. Heat treated
24 hrs. at 700°F and quenched in kerosene. Two phases: alpha
and MgLiZn. The grain boundaries of the alpha matrix are not
revealed; the MgLiZn grains are clearly outlined.
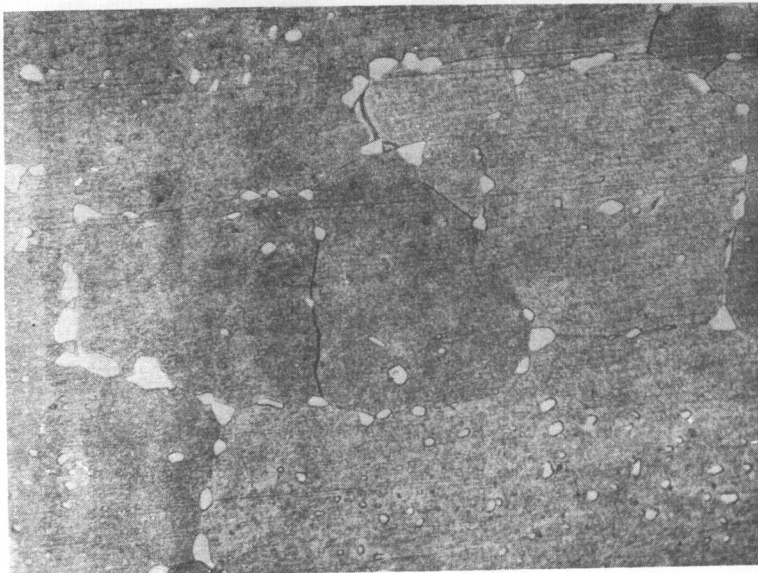
Figure 21

Neg. No. 299   Spec. M1070   Magnification: 500X
Etch: 10 gm. salicylic acid in 300 ml. ethyl alcohol, 10 sec.
L-188, Charge 316, analyzed 9.5%Li, 12.9%Zn. Heat treated
72 hrs. at 500°F and quenched in kerosene. Two phases: beta
and MgLiZn. Beta phase is etched tan with grain boundaries
clearly outlined; MgLiZn phase is white and unattacked.
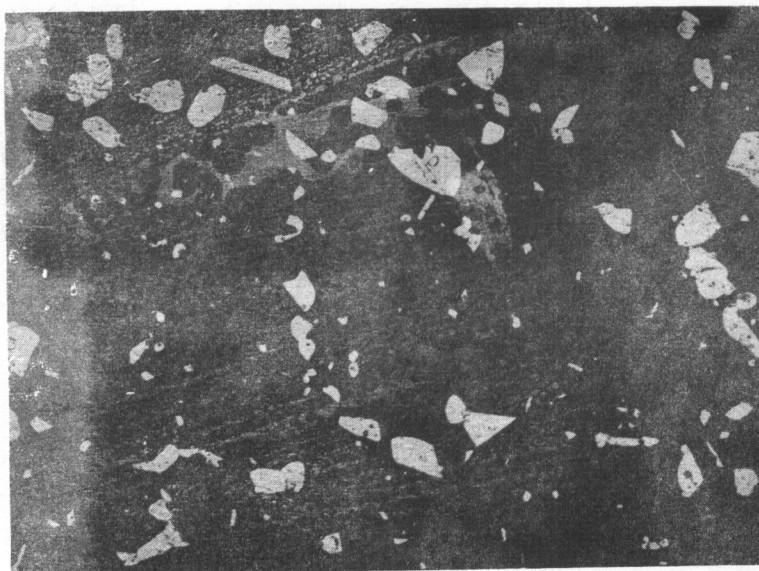
Figure 22

Neg. No. 284   Spec. M1068   Magnification: 200X
Etch: 100 pts. picral: 5 pts. glacial acetic acid: 10 pts.
      water, 6 sec.
L-186, Charge 314, analyzed 9.2%Li, 10.9%Zn. Heat treated
72 hrs. at 500°F and quenched in kerosene. Three phases:
alpha, beta, and MgLiZn. Beta matrix is etched dark, both
alpha and MgLiZn are not attacked and not plainly distinguished
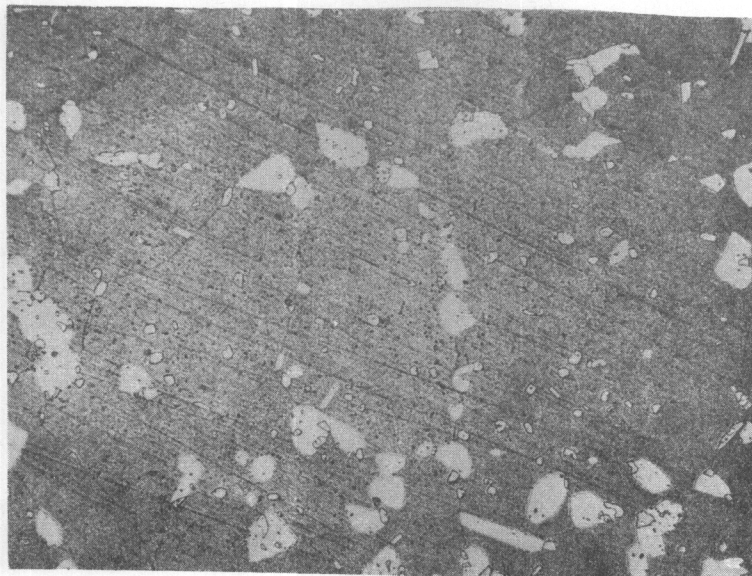
Figure 23

Neg. No. 285   Spec. M1068   Magnification: 200X
Etch: 10 gm. salicylic acid in 300 ml. ethyl alcohol, 30 sec.
The same area as shown in Figure 22. The MgLiZn grains are
clearly outlined while the alpha grains are not.
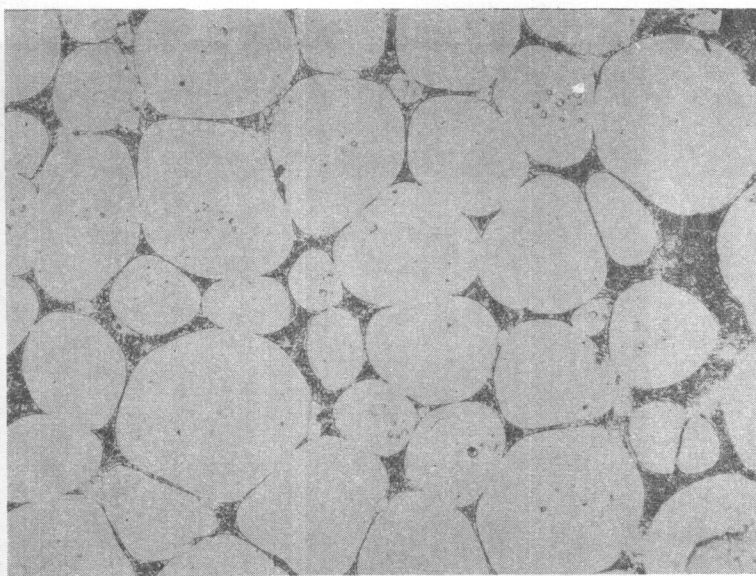
Figure 24

Neg. No. 278   Spec. M1030   Magnification: 100X
Etch: 10 gm salicylic acid in 300 ml. ethyl alcohol, 30 sec.
L-166, Charge 396, analyzed 0.45%Li, 20.1%Zn. Heat treated
24 hyrs. at 700°F and quenched in kerosene. Three phases:
alpha, MgLiZn, and grain boundary melting.
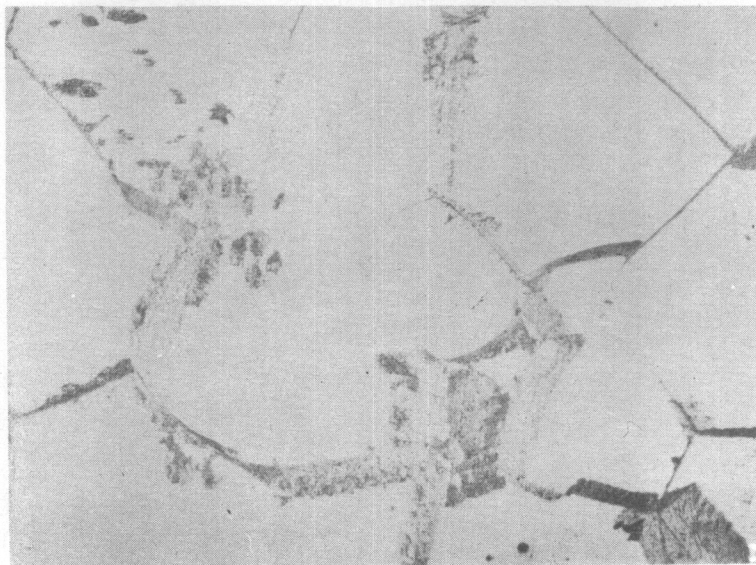
Figure 25

Neg. No. 287   Spec. M1052   Magnification: 100X
Etch: 10 gm. salicylic acid in 300 ml. ethyl alcohol, 30 sec.
L-190, Charge 318, analyzed 12.8%Li, 16.8%Zn. Heat treated
24 hrs. at 700°F and quenched in kerosene. Two phases: beta
and feathery grain boundary precipitate $MgLi_2Zn$.
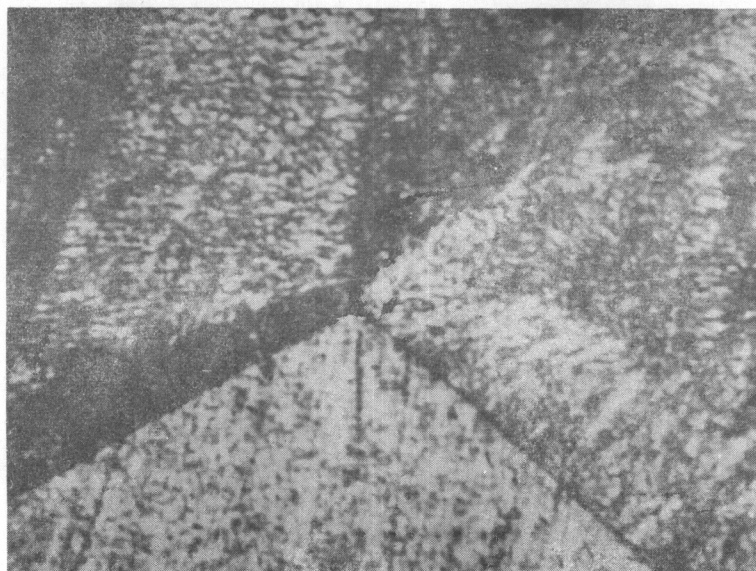
Figure 26

Neg. No. 288   Spec. M1052   Magnification: 2500X
Etch: 10 gm. salicylic acid in 300 ml. ethyl alcohol, 30 sec.
Same alloy as above. The $MgLi_2Zn$ phase is not resolved at
such high magnifications.
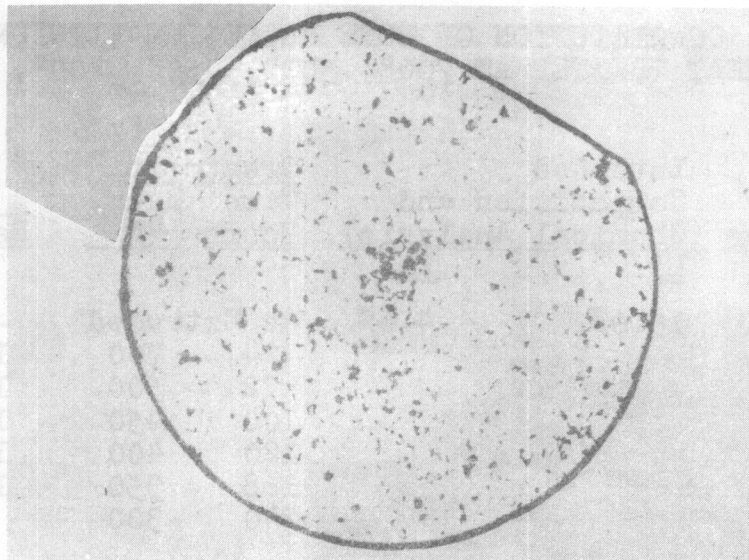
Figure 27

Neg. No. 300   Spec. M1100   Magnification: 25X
Etch: 100 pts. picral: 5 pts. glacial acetic acid: 10 pts.
       water, 2 sec.
L-230, Charge 342, intended 15.0% Li, 7.5% Zn. Heat treated
72 hrs. at 500°F and quenched in kerosene. Two phases:
beta and MgLi$_2$Zn precipitate is uniformly distributed in
the beta matrix.
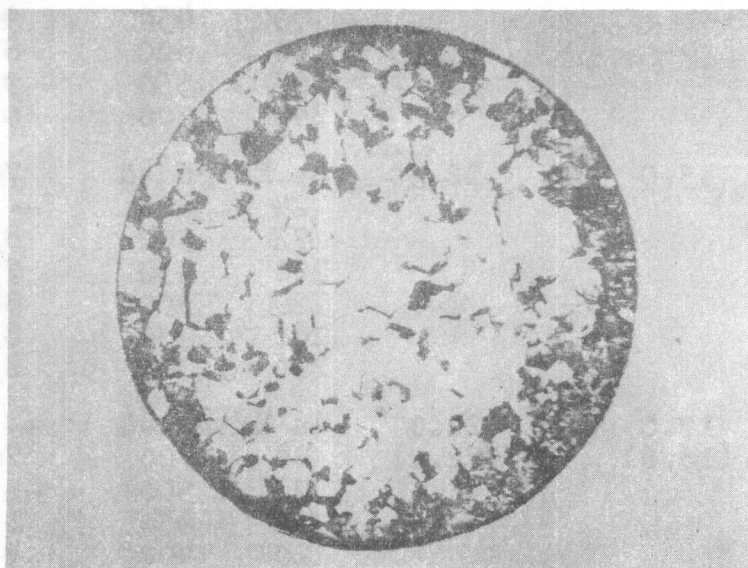
Figure 28

Neg. No. 301   Spec. M1099   Magnification: 25X
Etch: 100 pts. picral: 5 pts. glacial acetic acid: 10 pts.
       water, 2 sec.
L-232, Charge 344, intended 15.0% Li, 11.0% Zn. Heat treated
72 hrs. at 500°F and quenched in kerosene. Two phases: beta
and MgLi$_2$Zn phase is non-uniformly distributed in the beta
matrix.

TABLE XII

CONSTITUTION OF SOME MAGNESIUM-LITHIUM-ZINC ALLOYS
HEAT TREATED AT 700°, 500°, 450°, 400°, 350° AND 300°F

Alloy Number	Intended Composition and (Chemical Analysis)		Treatment		Microscopic Estimation of Phases Present		
	Li	Zn	Time Hours	Temp. °F	Beta	MgLiZn	MgLi$_2$Zn
L-181	15.0%	4.6%	As Extruded		---	--	--
			24	700	100	--	--
			72	500	100	--	--.
			100	450	100	--	--
			120	400	100	--	--
			168	350	100	--	--
			240	300	98	2	--
L-87	14.0	2.2	As extruded		100	--	--
			24	700	100	--	--
			72	500	100	--	--
			100	450	100	--	--
			120	400	100	--	--
			168	350	100	--	--
			240	300	100	--	--
L-230	15.0	7.5	As Extruded		100	--	--
			24	700	---	--	--
			72	500	90	--	10
			100	450	90	5	5
			120	400	87	10	3
			168	350	90	10	--
			240	300	90	10	--
L-233	15.0	12.5	As Extruded		70	3	27
			24	700	--	--	--
			72	500	85	--	15
			100	450	73	7	20
			120	400	88	10	2
			168	350	85	15	--
			240	300	85	15	--
L-192	17.0 (16.6)	22.0 (22.2)	As Extruded		--	--	--
			24	700	70	5	25
			72	500	--	--	--
			100	450	15	15	70
			120	400	45	15	40
			168	350	75	15	10
			240	300	85	15	--
L-109	7.8 (15.6)	15.0 (17.9)	As Extruded		15	5	85
			24	700	50	--	50
			72	500	--	10	90
			100	450	40	10	50
			120	400	25	15	60
			168	350	68	17	15
			240	300	80	20	--

A consideration of the phase diagram gave the strongest argument against accepting $MgLi_2Zn$ as an equilibrium phase. A three phase region (beta plus MgLiZn plus $MgLi_2Zn$) between the nominal composition of $MgLi_2Zn$ and the two phase region (beta plus MgLiZn) would not be consistent with the principles for ternary phase diagrams. For these reasons, it was concluded that $MgLi_2Zn$ was not present at high temperatures but that it formed from the beta solid solution during quenching.

An unidentified phase was found from the x-ray diffraction patterns for some alloys of low lithium content after they had been heat treated at 500°F. A study of the diffraction data in Table XIII and of the diffraction patterns in Fig. 29 showed that the alpha solid solution and MgLiZn would account for all lines in the pattern for alloy L-167 but would not account for nine lines in the pattern for alloy L-166. These lines could be due to $MgZn_2$ except for their relative intensities. The data for $MgZn_2$ on ASTM card No. 3185 show that the intensities of the $d_{2.20}$, $d_{2.005}$ and $d_{2.245}$ lines are nearly equal. However, Table XIII shows very strong $d_{2.20}$ and $d_{2.245}$ lines and a very weak $d_{2.005}$ line. The high intensity of the $d_{2.245}$ line could be accounted for by the overlapping of the strong $d_{2.25}$ line from MgLiZn. However, there is no overlapping line corresponding to the $d_{2.20}$ line. Therefore, this phase was not considered to be $MgZn_2$.

The estimation of this unknown phase was difficult in microscopic work because its etching characteristics were similar to those of MgLiZn. No etchants were found which gave a clear distinction between these two phases. A photomicrograph is shown in Fig. 30 for an alloy containing the alpha solid solution, MgLiZn and this unidentified phase.

Phase Boundaries at 700°F

The locations of the phase boundaries at 700°F are believed to be well established as shown in Fig. 31. In addition to the alloys whose analyses are shown on this diagram, many other alloys were studied. The composition and constitution of all alloys are given in Appendix I. The boundary of the beta solid solution field was located by many experimental points as was the boundary between alpha plus beta and alpha plus beta + MgLiZn. The intersection of this latter boundary with the boundary of the beta field fixed one end of the boundary between beta plus MgLiZn and alpha plus beta plus MgLiZn. The other end of this straight line boundary was fixed by the nominal composition of MgLiZn (25.3% Mg, 7.2% Li, 67.5% Zn). The boundary between alpha and alpha plus beta was fixed at one end by the point on the binary diagram determined by Hume-Rothery[10]. The intersection of this boundary with the boundary between alpha plus beta and alpha plus beta plus MgLiZn was established by experimental points. The boundary

TABLE XIII

DIFFRACTING PLANES AND INTERPLANAR SPACINGS IN
SOME MAGNESIUM-LITHIUM-ZINC ALLOYS[a]

Diffracting Planes in			Spacing and Intensity for			
			M-1060[b]		M-1061[c]	
Alpha	MgLiZn	MgZn$_2$(?)	d	I[d]	d	I[d]
	110		5.30	VW	5.28	M
		100	4.45	M		
	111				4.26	S
		101	4.04	VW		
	211				3.03	W
100			2.81	S	2.75	S
002			2.62	VS	2.56	VS
101			2.46	VS	2.41	VS
	311	200	2.25	S	2.24	VS
		201	2.20	S		
	222		2.15	S	2.14	VS
		004	2.11	S		
		202	2.00	VW		
102			1.90	S	1.87	S
		203	1.77	VW		
	331		1.71	VW	1.70	W
110			1.60	M	1.58	S
103			1.47	VS	1.45	VS
	(511)(333)		1.42	VW	1.42	M
		006	1.40	VW		
200			1.38	VW	1.37	VW
112			1.36	S	1.35	M
201			1.34	M	1.33	M
	440		1.31	W	1.31	M
004			1.30	W	1.28	M
		311	1.25	VW		
202			1.22	VW	1.21	W
(113)(104)			1.17	M	1.16	M
		313	1.15	VW		
	533		1.14	VW	1.13	W
	622		1.12	M	1.11	M
203			1.08	M	1.07	M
211			1.03	M	1.02	M
114			1.01	M	1.00	M
	(731)(553)		0.96	M	0.97	S
204			0.95	VW	0.94	VW
	800		0.94	VW	0.93	VW
300			0.92	VW	0.92	VW
213			0.90	M	0.89	M

a Nickel filtered Cu$K\alpha$ radiation
b M-1060, Alloy L-166 (0.52%Li, 20.0%Zn). Heat treated
   for 72 hours at 500°F, quenched in kerosene.
c M-1061, Alloy L-167 (3.4%Li, 18.1%Zn). Heat treated
   for 72 hours at 500°F, quenched in kerosene.
d Relative intensities judged by naked eye:-
   S = strong; M = medium; W = weak; VS = very strong;
   VW = very weak.
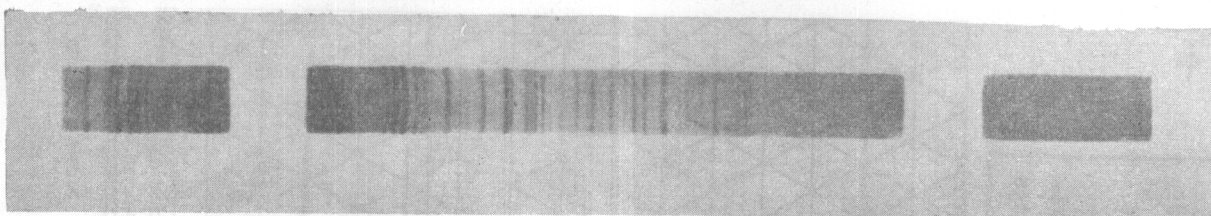
Alloy L-167, Specimen M1061
Alpha plus MgLiZn phases (500°F)
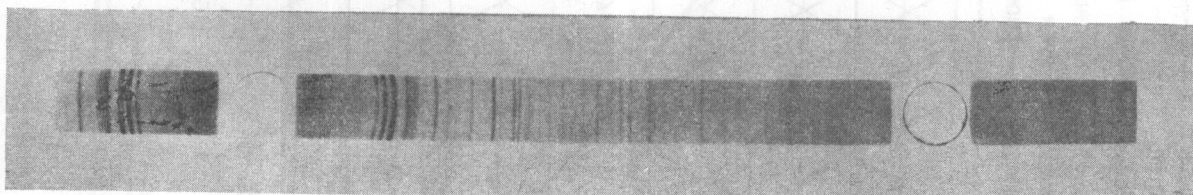
Alloy L-166, Specimen M1060
Alpha plus MgLiZn plus and unknown phase (500°F)

Fig. 29 X-ray Diffraction Patterns
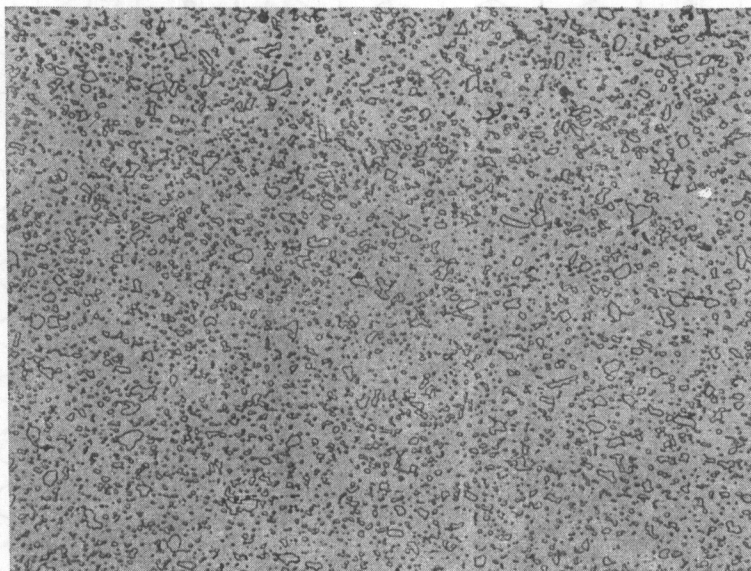
Figure 30

Neg. No. 302   Spec. M1262   Magnification: 300X
Etch: 10 gm. salicylic acid in 300 ml. ethyl alcohol, 8 sec.
L-273, Charge 414, intended 0.5%Li, 20.0%Zn. Heat treated
72 hrs. at 500°F and quenched in kerosene. Three phases:
alpha, MgLiZn, and X. The unknown phase X is detected by
x-ray diffraction but could not be identified. Its etching
characteristics appear to be similar to those of MgLiZn.

LEGEND

SYMBOL	MEANING
●	ONE PHASE ALLOY
▲	TWO PHASE ALLOY
■	THREE PHASE ALLOY

CLOSED SYMBOLS REPRESENT ANALYSES OF HEAT TREATED SAMPLES OPEN SYMBOLS RE-PRESENT INTENDED COMPOSITION

700°F SECTION

BETA + MGLIZN

ALPHA+BETA+ MG LIZN

ALPHA + MG LIZN

ALPHA + MGLIZN + LIQUID

ALPHA+ LIQUID

BETA

ALPHA+ BETA

ALPHA

WEIGHT PERCENT ZINC

WEIGHT PERCENT LITHIUM
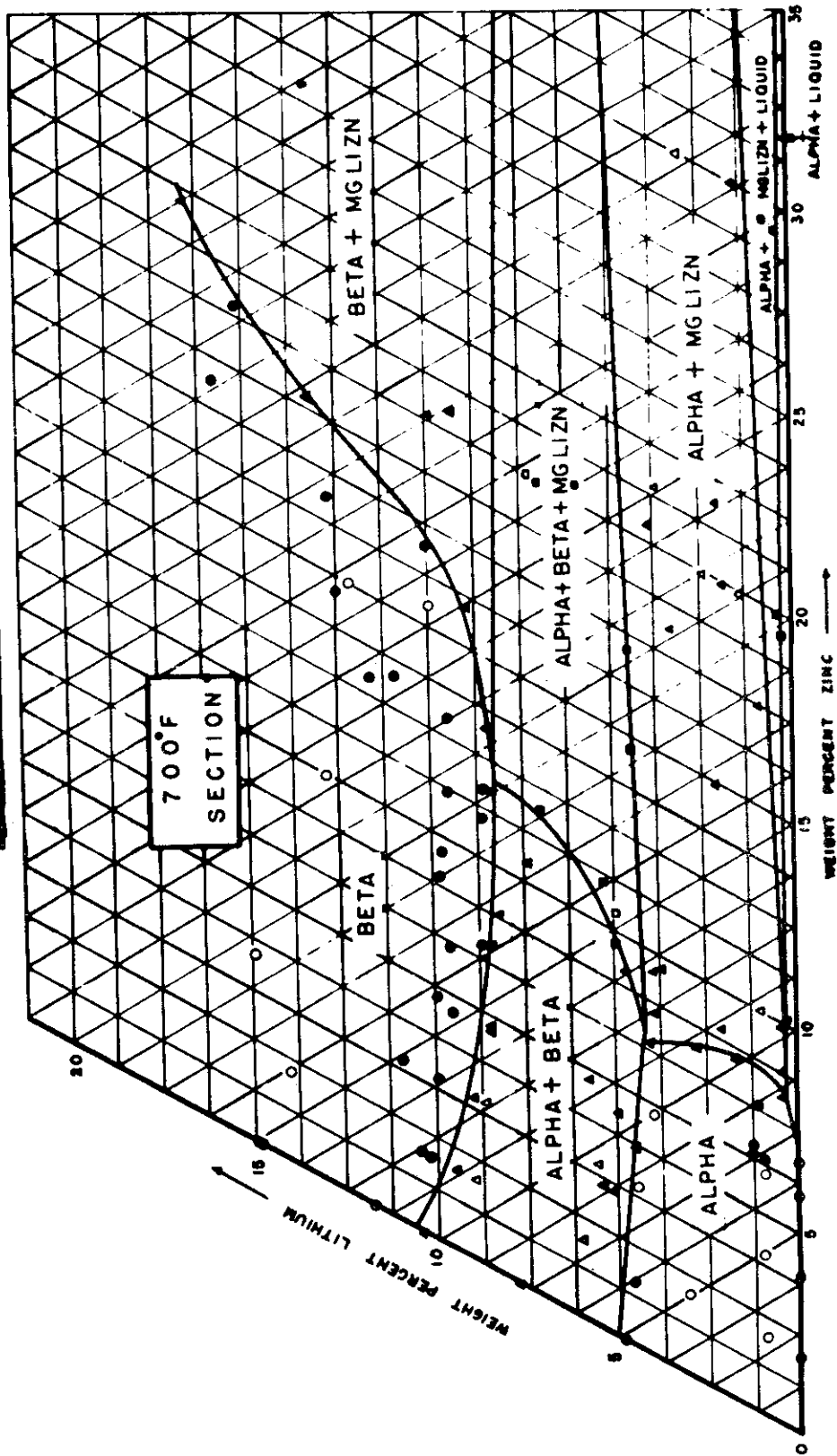
FIGURE 31

PHASE BOUNDARIES IN THE MAGNESIUM CORNER OF
THE MAGNESIUM-LITHIUM-ZINC SYSTEM AT 700°F

WADC TR 52-169

46

between alpha plus MgLiZn and alpha plus beta plus MgLiZn must
be a straight line from the intersection just mentioned to the
composition of MgLiZn. The boundary between alpha and alpha
plus MgLiZn was well fixed by several experimental points. For
the three phase region - alpha plus MgLiZn plus liquid, the
boundaries were drawn from experimental points and a considera-
tion of the composition of MgLiZn. The boundary between alpha
and alpha plus liquid was fixed by the known point on the
binary magnesium-zinc diagram at one end and by experimental
points at the other end.

Phase Boundaries at 500°F

The results of microscopic examination are plotted on
Fig. 32 for alloys heat treated at 500°F and the phase boundaries
are drawn in their most probable position. The three boundaries
of the alpha plus beta region were fixed by the points on the
binary magnesium-lithium diagram and by experimental points in
the ternary diagram. The three straight line boundaries of the
alpha plus beta plus MgLiZn field were established by experi-
mental points and confirmed by the extrapolation to the composi-
tion of MgLiZn. The boundary between beta and beta plus MgLiZn
was fixed by experimental points up to about 12% lithium and
14% zinc and tentatively located for higher alloying additions.
Tentative boundaries between alpha plus MgLiZn and alpha plus
MgLiZn plus an unidentified phase and between alpha plus MgLiZn
plus this unidentified phase and alpha plus this unidentified
phase were drawn but these boundaries were not well located for
reasons stated previously.

Comparison of the Constitution at 500° and at 700°F

The most apparent difference between the constitution at
500° and at 700°F was in the extent of the alpha, alpha plus
beta and beta phase fields. As in the magnesium-lithium
-aluminum alloy system, all of these fields were smaller at
500°F than at 700°F. The amount of lithium in solid solution
was nearly the same but the solubility of zinc was much less
at 500°F. In addition to this major change in constitution, the
position of other boundaries changed slightly as shown in Figs.
31 and 32.

EXPERIMENTAL WORK IN PROGRESS

Experimental work has been discontinued on the constitution
of magnesium-lithium ternary alloys because of their lack of
stability. The present work on the constitution of magnesium
alloys is devoted to the magnesium-thorium and magnesium-zinc
-zirconium alloys.

LEGEND

SYMBOL	MEANING
●	ONE PHASE ALLOY
▲	TWO PHASE ALLOY
■	THREE PHASE ALLOY

CLOSED SYMBOLS REPRESENT

ANALYSES OF HEAT TREATED SAMPLES OPEN SYMBOLS RE–PRESENT INTENDED COMPOSITION

500°F SECTION

BETA + MGLIZN

ALPHA+BETA + MGLIZN

ALPHA + MGLIZN

BETA

ALPHA + BETA

ALPHA

ALPHA+MGLIZN+X

ALPHA + X

WEIGHT PERCENT LITHIUM

WEIGHT PERCENT ZINC
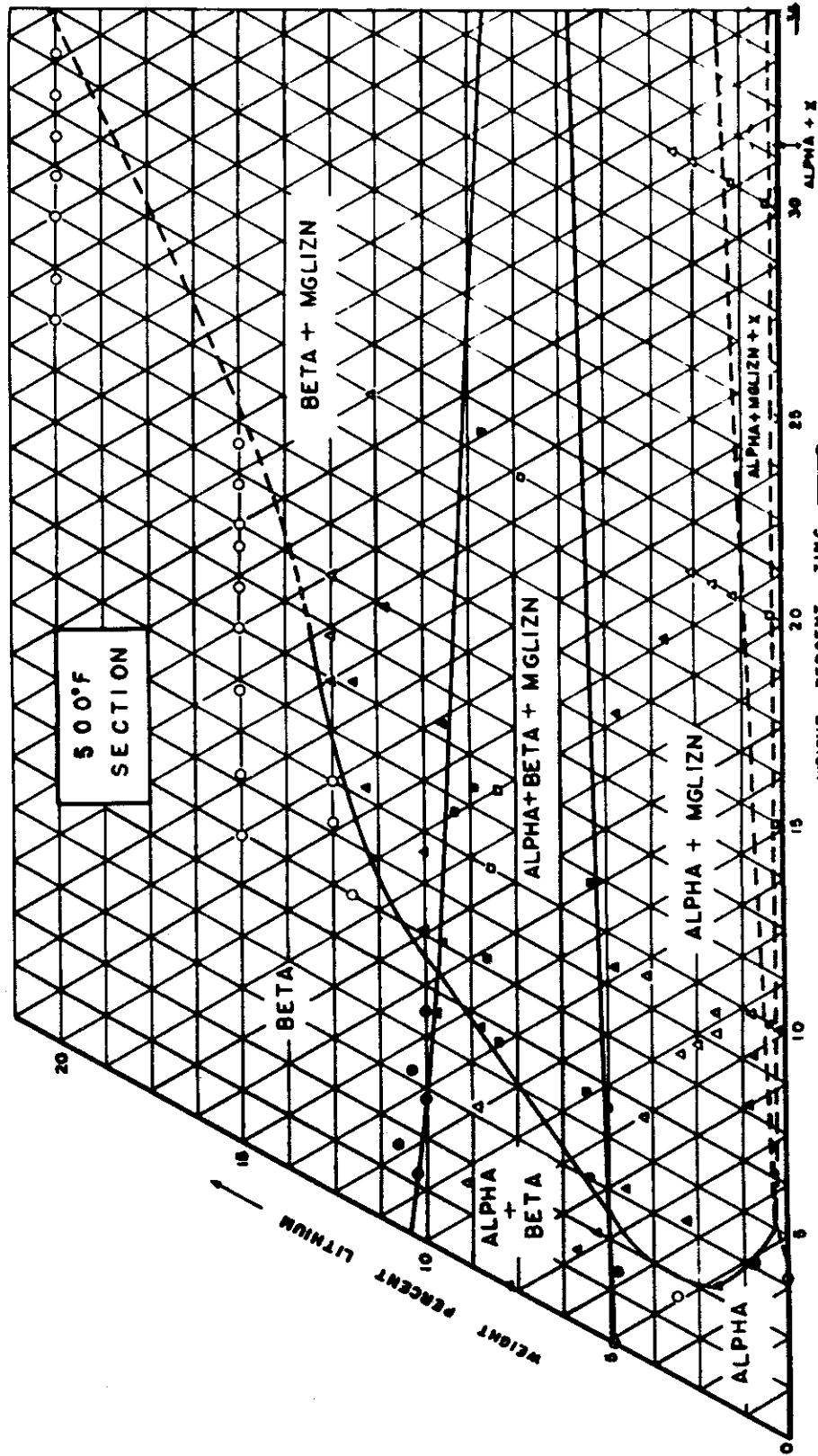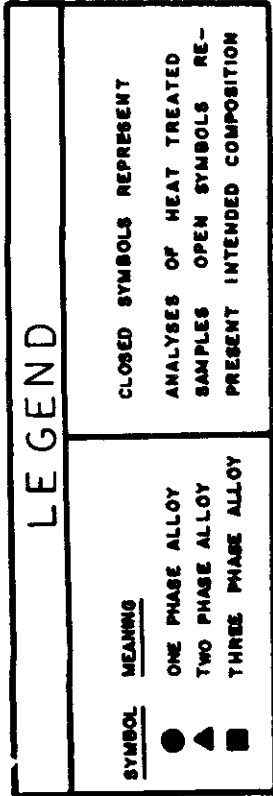
FIGURE 32

PHASE BOUNDARIES IN THE MAGNESIUM CORNER OF
THE MAGNESIUM–LITHIUM–ZINC SYSTEM AT 500°F

SECTION II

LOW ALLOY CONTENT HIGH DUCTILITY MAGNESIUM ALLOYS

INTRODUCTION

The object of this work was to produce alloys for sheet with a good combination of strength and formability by using small amounts of alloying elements and the proper combination of mechanical work and heat treatment. The idea for this study originated in a discussion with Hubert Altwicker, formerly Technical Director of the Light Metal Department, I. G. Farbenindustrie, Bitterfeld, Germany. Altwicker recommended small additions of zinc, zirconium, cerium, calcium, titanium and possibly aluminum and thallium. He believed that an excellent combination of strength and formability could be obtained with a total alloy content of less than 1% by the proper balance of hot rolling, warm rolling, straight and cross rolling followed by a stress-relieving treatment just below the temperature required for complete recrystallization.

A preliminary survey was made of the following alloy systems to determine what dilute alloys should be studied more thoroughly.

> Magnesium-Cerium
> Magnesium-Aluminum-Cerium
> Magnesium-Zinc-Cerium
> Magnesium-Zirconium
> Magnesium-Zinc-Zirconium

This survey indicated that good strength and formability were not obtained with magnesium-cerium or magnesium-aluminum-cerium alloys and that further study was justified on magnesium-zinc -cerium, magnesium-zirconium and magnesium-zinc-zirconium alloys. However, most of the further work was done on magnesium-zinc -cerium alloys and only a limited amount on the other alloys.

ALLOY PREPARATION AND EVALUATION

Melting and Alloying

All alloys were prepared in lots of about 3500 grams (7.7 pounds) using Tercod crucibles in a gas-fired furnace. Dow pure magnesium ingot, New Jersey Horse Head Special zinc and commercial aluminum pig were used for these alloys. Cerium was added as Cerium Standard containing about 50% cerium, 1% iron, balance other rare earths. Zirconium was added either as zirconium sponge or as dense zirconium tetrachloride supplied by the Bureau of Mines.

The general procedure was to melt down the magnesium under Dow No. 310 flux, raise the temperature to 1350° - 1400°F, make the alloying additions and stir with a graphite or steel rod for alloying and refining with further additions of flux. The use of the No. 310 flux caused some loss of cerium but this was not excessive. After refining, the melts were usually raised to 1500°F for better separation of inclusions, removed from the furnace and cooled to 1325° - 1350°F for casting. Further details on the melting operation were given in the Summary Report for 1950[2]. The intended composition, spectrographic analysis, treatment and properties of all alloys are given in the tables in Appendix III.

Casting and Homogenizing Ingots

Ingots for rolling were cast horizontally as slabs, 8 inches long, 3 inches wide, 5/8 inch thick. Two of these ingots with a large vertical riser over each were cast at the same time from a single sprue. The original mold was made of graphite but this was replaced by a cast iron mold in which bottom feeding was used. After removal of the riser, the ingots were homogenized for 16 - 20 hours at the temperature chosen for hot rolling.

Rolling Procedure and Heat Treatment

After scalping and homogenization, the ingots were rolled to sheet on an Oliver mill with rolls 3 inches in diameter and 5 inches in length and with a surface speed of 16-1/2 feet per minute. The roll temperature was maintained at 400°F for all hot and warm rolling by means of manually controlled gas burners. The rolling schedule was standardized as given in Fig. 33.

Rolling conditions were used as specified below.

1. Hot Rolling - rolling at a temperature believed to be above the recrystallization range for the conditions involved.

2. Warm Rolling - rolling at an elevated temperature believed to be below the recrystallization range for the conditions involved.

3. Cold Rolling - rolling at room temperature.

In general, slabs were reduced to 0.20 inch by hot rolling on a constant draft schedule. Stock for warm rolling was then air cooled and reheated later to the warm rolling temperature. From 0.20 inch to 0.064 inch, the material was reduced by hot or warm rolling by a constant percentage reduction between reheats. Hot rolling of sheet to be finished cold was stopped at the proper thickness above 0.064 inch. This sheet was reheated at the hot rolling temperature for one hour, air cooled, pickled and then cold rolled 0.001 inch per pass to the final thickness.

As-cast Ingots
5/8" x 3" x 7"

|

Homogenize

|

Hot Roll to 0.200" Slab

Hot Roll to 0.064" Sheet   Warm Roll to 0.064" Sheet

Determine
Recrystallization Curve
for Samples Heated One
Hour

Stress Relieve   Low Temperature   High Temperature
                            Anneal   Anneal

Determine
Mechanical Properties
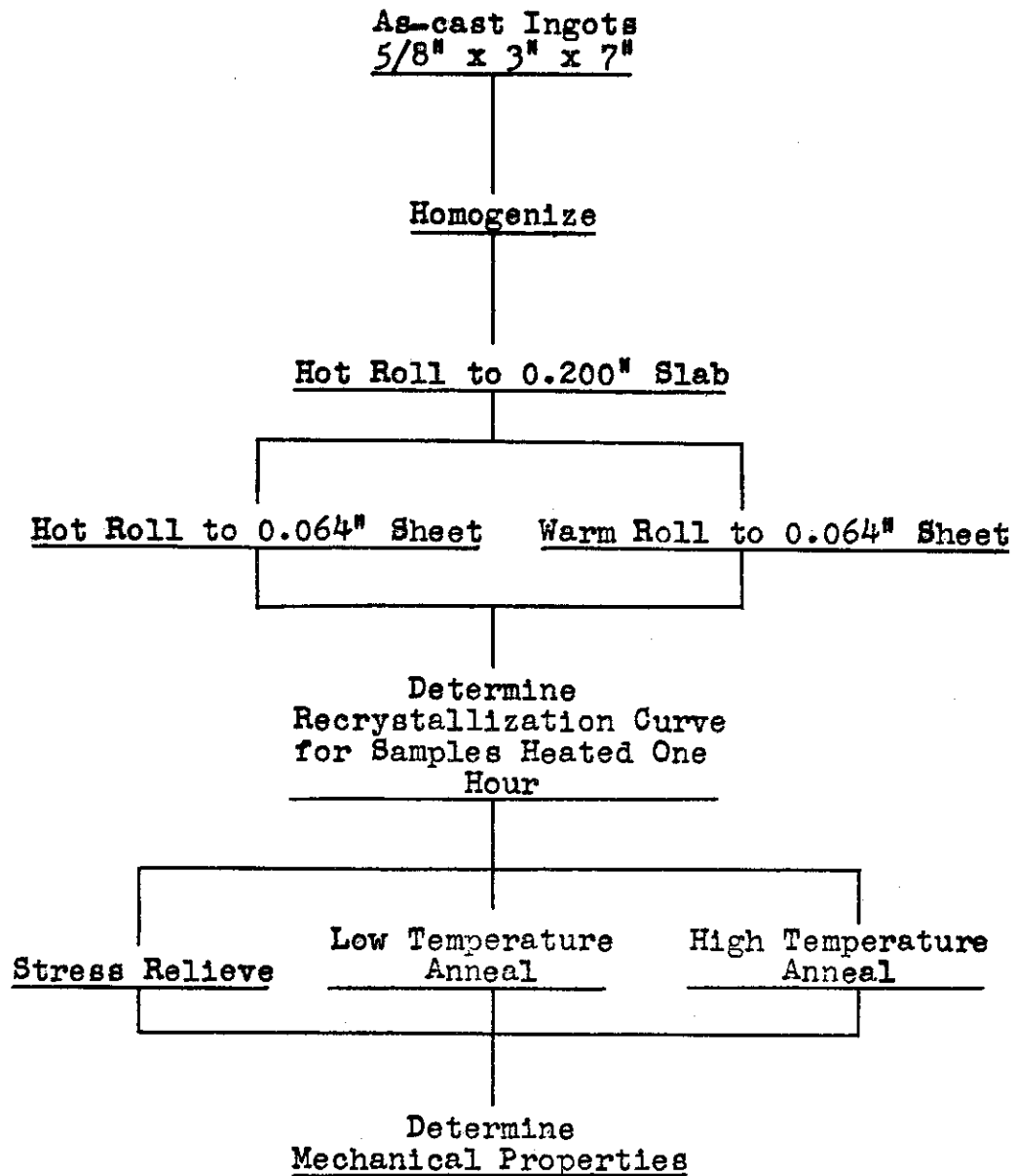
Figure 33

Standard Schedule for Survey of Mechanical Properties
of Magnesium Alloys

After rolling, recrystallization curves were determined by hardness tests and used as a basis for the thermal treatment and the specimen nomenclature are given in the following list. When necessary, specimens for mechanical tests were flattened by heating between steel plates for one hour at 250°F.

        H - hot rolled sheet
        W - warm rolled sheet
        C - cold rolled sheet
        S - stress-relieved at a temperature
             below the recrystallization range
       AL - "annealed" at the middle of the
             recrystallization range to achieve
             partial recrystallization
       AH - annealed to achieve complete
             recrystallization

Mechanical Testing

The hardness values for the recrystallization curves were determined on Vickers hardness testing equipment. A 5 kilogram load was used on specimens finished by 3/0 metallographic polishing paper.

Tensile tests were made on sheet specimens having a thickness of 0.064 inch, a width of 3/4 inch and a 2 inch gage length in a reduced section 0.500 inch wide and 3 inches long. The yield strength was taken at the offset of 0.2% strain on the stress -strain curve.

Compression tests were made on specimens of 0.064 inch sheet 5/8 inch wide and 2-5/8 inches long. These specimens were supported in a jig to prevent buckling as they were tested. The yield strength in compression was taken at the offset of 0.2% strain on the stress-strain curve.

Notch sensitivity data were determined in an Olsen Stiffness Tester using a specimen 0.062 inch thick, 1 inch wide and 3-1/8 inches long. A 45 degree notch with an 0.030 inch radius at the root was machined in each edge at 3/4 inch from one end so that the distance between the roots of the notches was 0.50 inch. Simultaneous readings of the bending moment and angular deflection were recorded as the specimen was stressed to destruction. Further information on this and the other mechanical tests was given in the Summary Report for 1950[2].

Minimum bend radius testing was done on sheared blanks 3/4 inch wide and 2-1/2 inches long. The minimum bend radius was taken as the smallest radius peg around which the specimens could be bent without fracture on a Di-Acro Bending Machine.

MAGNESIUM-CERIUM ALLOYS

The average mechanical properties for a limited number of magnesium-cerium alloys are given in Appendix III, Table XXV. These results showed low values of strength and only fair values of elongation compared to the commercial alloy AZ31. Therefore, further work on magnesium-cerium alloys was not done.

MAGNESIUM-ALUMINUM-CERIUM ALLOYS

Low values of strength and ductility were found for these alloys in the initial survey so that a further study was not made. The average mechanical properties for the magnesium-aluminum-cerium alloys tested are given in Appendix III, Table XXVI.

MAGNESIUM-ZINC-CERIUM ALLOYS

Optimum Composition and Treatment

The early work in this system showed that the best composition for a total alloy content of 1% was 0.8% zinc, 0.2% cerium, balance magnesium. This work also showed that the best treatment was warm rolling at 400°F followed by annealing just above the recrystallization range. This treatment gave a completely recrystallized fine grained structure with a small amount of an undissolved phase.

The good properties of these alloys led to an extension of this investigation to higher contents of zinc and cerium. A study of alloys containing from 0.2 to 3.0% zinc and from 0.1 to 1.5% cerium showed that the best properties were available with alloys containing from 0.7 to 1.5% zinc and from 0.2 to 0.6% cerium. Representative values for the machanical properties of alloys in this range are given in Table XIV. These data showed that the nominal composition of an alloy for an excellent combination of mechanical properties should be 1.0% zinc, 0.4% cerium, balance magnesium.

This optimum composition (1.0% zinc, 0.4% cerium, balance magnesium) was investigated further by determining the tensile strengths and elongation for hot and warm rolled specimens treated at 300°, 400°, 450°, 500°, 550°, 600°, 700° and 800°F for one hour. The resulting data are shown in Fig. 34. These curves show that the highest values of elongation for both hot and warm rolled sheet were obtained by annealing in the temperature range from 600° to 700°F.
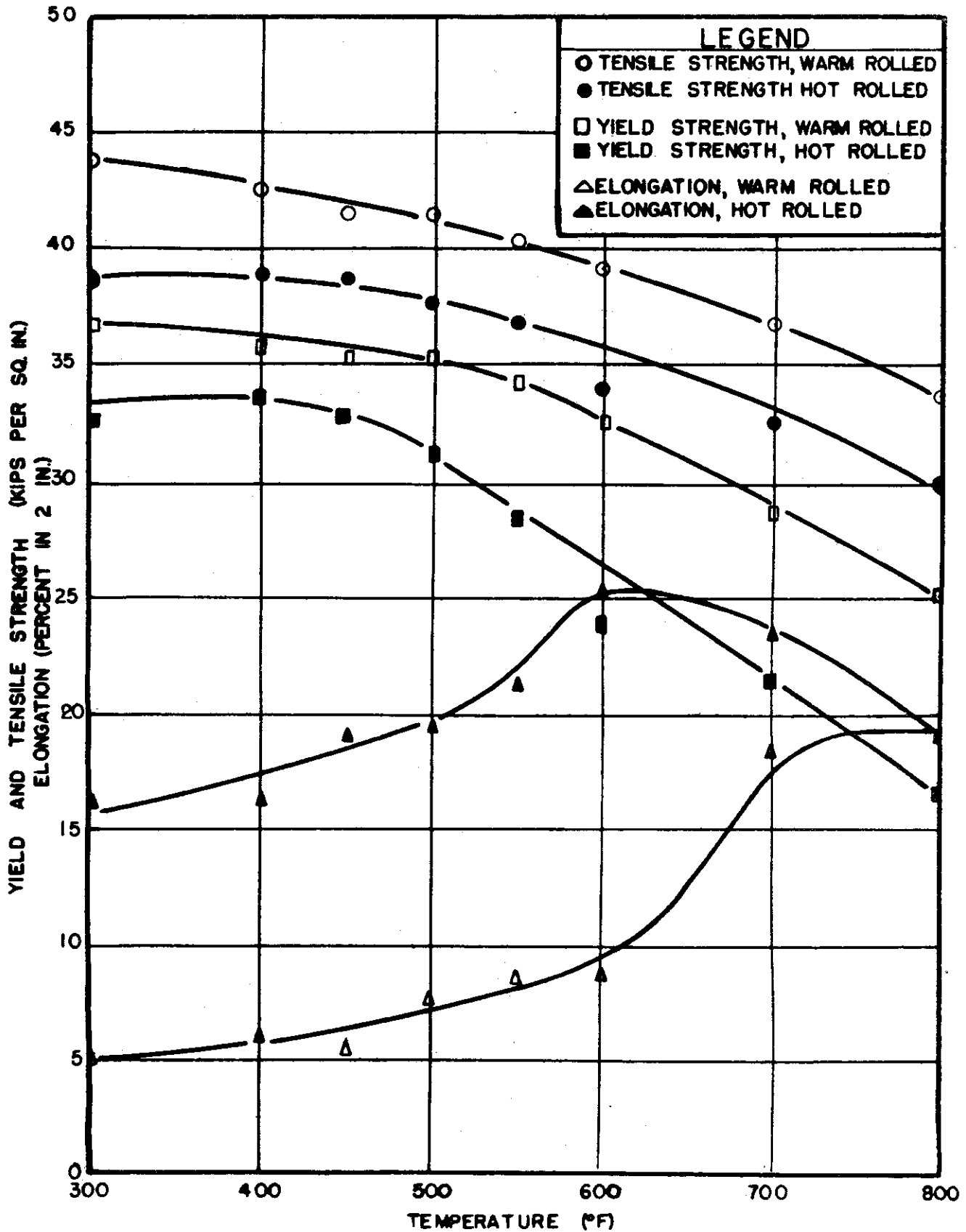
FIGURE 34

VARIATION OF MECHANICAL PROPERTIES OF THE ALLOY MAGNESIUM-1.0 ZINC-
0.4 CERIUM WITH TEMPERATURE OF HEAT TREATMENT

TABLE XIV

MECHANICAL PROPERTIES OF MAGNESIUM-ZINC-CERIUM ALLOYS
0.7-1.5% ZINC, 0.2-0.6% CERIUM

Alloy Designation	Intended Composition and (Spectro. Anal.) Zinc	Cerium	Kips per sq. in. CYS	TYS	UTS	Elong. % in 2 inches
R791HAH	0.8% (0.9)	0.3% (0.15)	12.6	22.7	33.0	22.0
R788HAL	0.8 (0.91)	0.3 (0.40)	22.7	30.2	37.3	20.0
R853WAL	1.2 (1.18)	0.5 (0.60)	13.9	22.9	33.4	20.0
R848HAL	0.8 (0.68)	0.5 (0.43)	15.7	20.6	31.7	20.7
R814WS	1.5 (1.2)	0.3 (0.38)	24.4	32.6	40.5	20.5
R855HAL	1.5 (1.45)	0.6 (0.45)	15.8	21.3	33.3	21.7

Mechanical Properties

A comparison is given in Table XV between the mechanical properties of commercial sheet alloys and of the magnesium, 1.0% zinc, 0.4% cerium alloy treated at 600°, 650° and 700°F after hot and warm rolling. The magnesium-zinc-cerium alloy showed a greater elongation than the other alloys for similar values of the compressive and tensile yield strengths. Also, the toughness was good for this alloy as shown by the high values for the static rupture energy. The minimum bend radius for the magnesium-zinc -cerium alloy indicated good formability but these values were determined under different testing conditions than used for the commercial alloys.

Most of the mechanical properties were determined parallel to the direction of rolling and only a small number of tests were made transverse to the rolling direction. This was due to the limitations of the equipment available for rolling wide sheet. However, data from a limited number of transverse specimens are given in Table XVI in comparison with data from longitudinal specimens. The sheet for these tests could not be rolled according to the standard rolling procedure but the condition approximated hot rolling.

TABLE XV

MECHANICAL PROPERTIES OF MAGNESIUM—1.0% ZINC—0.4% CERIUM AND COMMERCIAL MAGNESIUM SHEET ALLOYS

Alloy Designation	Condition	Kips per sq. in. CYS	TYS	UTS	Elong. % in 2 inches	Static Rupture Energy in.-lb.	Minimum Bend Radius
Magnesium -1.0% Zinc -0.4% Cerium	Hot rolled, plus 1 hr. at 600°F	17.3	24.0	34.2	25.0	20.4	3T
	Hot rolled, plus 1 hr. at 650°F	14.6	—	—	—	20.8	2T
	Hot rolled, plus 1 hr. at 700°F	13.5	21.4	32.6	23.5	19.4	2T
	Warm rolled, plus 1 hr. at 600°F	12.2	33.2	39.6	15.0	17.9	4T
	Warm rolled, plus 1 hr. at 650°F	15.6	30.2	38.0	18.0	18.6	4T
	Warm rolled, plus 1 hr. at 700°F	13.6	29.4	37.8	17.0	19.4	4T
FS-1h	Hard rolled	26.0	33.0	43.0	11.0	13.4	10T
FS-1a	Annealed	16.0	22.0	37.0	21.0	—	5T
J-1h	Hard rolled	27.0	34.0	47.0	9	5.07	17T
J-1a	Annealed	16.0	26.0	43.0	16	—	9T
Mh	Hard rolled	20.0	29.0	37.0	8	—	12T
Ma	Annealed	12.0	15.0	33.0	17	—	7T
Elektron AM537	Not specified	—	25.4	32.4	21.0	—	—

Note:— Notes for this table are found on next page.

Data for FS-1, J-1 and M from Dow Metal Data Booklet and
  ASM Metals Handbook, 1948 Edition
Data for Elektron AM537 from The Technology of Magnesium and Its
  Alloys by A. Beck
Minimum bend radius for 180° bend determined with specimen 3/4 inch wide
  for Mg-Zn-Ce and for 90° bend with specimen 6 inches wide for FS-1,
  J-1 and M.
  "T" refers to the thickness of the sheet

TABLE XVI

TRANSVERSE AND LONGITUDINAL MECHANICAL PROPERTIES
OF THE ALLOY MAGNESIUM-1.0% ZINC-0.4% CERIUM

Condition	CYS Kips per square inch		TYS		UTS		Elong.% in 2 in.		Static Rupture Energy (in.-lb.)		Minimum Bend Radius	
	Long.	Trans.	Long.	Trans.	Long.	Trans.	Long.	Trans.	Long.	Trans.	Long.	Trans.
Hot rolled, heated one hour at 500°F	24.3	20.1	28.8	19.6	36.3	33.2	19.5	25.0	--	--	--	--
Hot rolled, heated one hour at 600°F	17.4	14.8	22.4	14.9	34.0	31.3	22.0	27.0	20.4	21.5	2T	2T
Hot rolled, heated one hour at 650°F	14.6	12.9	20.5	13.8	33.0	30.7	20.0	24.8	20.8	21.2	2T	2T
Hot rolled, heated one hour at 700°F	14.3	12.2	19.7	13.3	32.3	30.4	17.2	23.8	19.4	22.3	2T	2T

Notes:- These values are the average of several determinations.
  "T" refers to the thickness of the sheet.

The average values of the elongation in the transverse direction exceeded those parallel to the rolling direction and one transverse value was 32%. The values for compressive yield, tensile yield and ultimate strength were lower in the transverse specimens than in the longitudinal specimens but the difference was not excessive. However, good toughness and formability was indicated for both directions.

Warm rolling of magnesium-zinc-cerium alloys produced a good combination of mechanical properties but this method is not ideal for commercial operations. Therefore, an attempt was made to achieve the same structure and properties by cold rolling and annealing. Hot rolled sheet was given cold reductions of 10, 15, 20 and 25% and then heat treated. These temperatures for heat treatment were chosen to give various amounts of stress-relief and recrystallization. An upward trend in strength and ductility was evident as the amount of cold work was increased but the best results were not as good as those obtained by warm rolling. However, a series of cold reductions and anneals might reproduce the structure and properties obtained by warm rolling.

A summary of the average mechanical properties of all magnesium-zinc-cerium alloys is given in Appendix III, Table XXVII. A summary of the properties obtained by cold rolling and annealing is given in Appendix III, Table XXVIII.

Microstructure

In studying the structure of magnesium-zinc-cerium alloys, it was found that the best combinations of strength and elongation were associated with a fine equiaxed grain structure. A completely recrystallized structure gave better properties than a stress-relieved structure. The microstructure for alloy R851 (magnesium, 1.0% zinc, 0.44% cerium) hot rolled and then heated one hour at 300°F is shown in Fig. 35. The average grain size was 0.00031 inch and the grains were slightly elongated. The alloy in this condition had an elongation of 17% in 2 inches. Heating this alloy for one hour at 600°F gave equiaxed grains with an average grain diameter of 0.00042 inch as shown in Fig. 36 and an elongation of 27%.

The addition of cerium to magnesium-zinc alloys introduced a small amount of a second constituent and caused a reduction in grain size for all conditions of treatment. The second constituent did not dissolve during the processing to produce sheet. The hot rolled and annealed structure of the alloy magnesium, 1.0% zinc is shown in Fig. 37. The structure of this alloy was coarse compared to that of magnesium, 0.8% zinc, 0.2% cerium shown in Fig. 38 and to that of magnesium, 1.0% zinc, 0.44% cerium shown in Fig. 40. A similar reduction in grain size was observed for each of the other conditions of rolling and heat treatment.

The second constituent due to cerium appeared as fine particles, globules and stringers in the finished sheet. This condition is shown in Fig. 39 for the alloy magnesium, 1.0% zinc, 0.44% cerium hot rolled and stress-relieved one hour at 300°F. Heating this alloy for one hour at 600°F caused coalesence of the particles and the stringers appeared less continuous. This structure is shown in Fig. 40.

MAGNESIUM-ZIRCONIUM ALLOYS

The most successful methods for adding zirconium were from dense zirconium chloride and from zirconium sponge obtained from the Bureau of Mines. These materials gave better results than TAM zirconium flux and a master alloy containing 60 magnesium - 40 zirconium but many of the alloys contained a large quantity of inclusions so that they were considered too dirty for testing. The alloys tested did not show a typical recrystallization curve so all rolling was considered to have been hot working.

The average mechanical properties of these magnesium -zirconium alloys are given in Table XXIX of Appendix III. However, these properties are not considered to be representative of the best obtainable from magnesium-zirconium alloys.

MAGNESIUM-ZINC-ZIRCONIUM ALLOYS

The alloys in this system were tested only in the hot rolled condition. These alloys rolled very well so homogenization was not necessary and greater reductions per pass were possible. The mechanical properties of these alloys are given in Table XXX of Appendix III.

The outstanding feature of these magnesium-zinc-zirconium alloys was the high ratio of compressive yield strength to tensile yield strength. The strength values were good and the elongation values were fair. There were considerable quantities of inclusions in these alloys so that these elongation values were not considered as representative of the best obtainable from clean alloys in this system.

EXPERIMENTAL WORK IN PROGRESS

Work has been started to determine the properties of the dilute magnesium-zinc-calcium alloys. In addition, work is planned to determine the effects of small additions of lithium to magnesium-zinc-cerium and magnesium-zinc-calcium alloys.
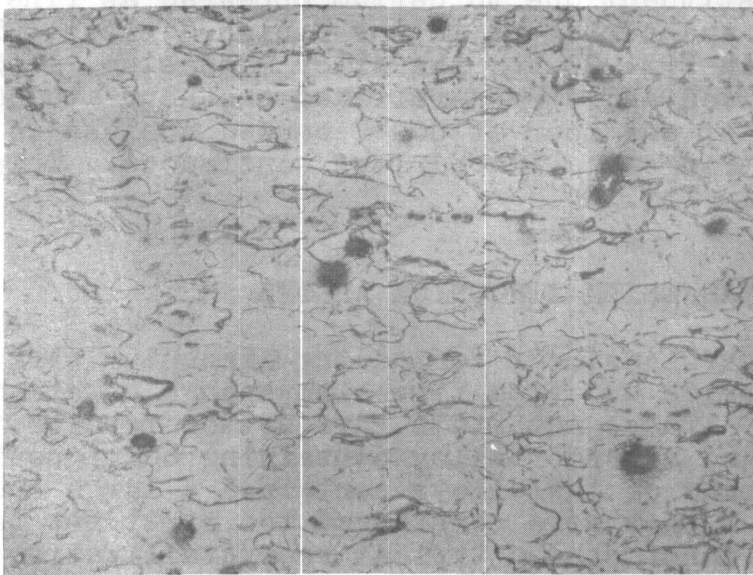
Figure 35

Neg: 137   Spec: M1309-1   Mag: 500X   Etch: Acetic Picral
      Oblique illumination, longitudinal section of
R851H magnesium-1.0 zinc-0.44 cerium hot rolled and stress-
releived one hour at 300°F. Average grain size was 0.00031
inches. Elongation in 2 inches was 17%.
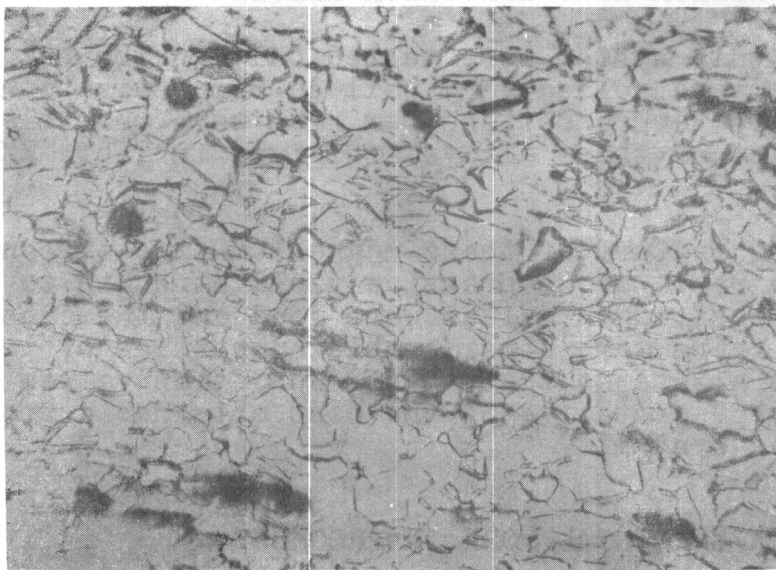
Figure 36

Neg: 139   Spec: M1309-3   Mag: 500X   Etch: Acetic Picral
      Oblique illumination, longitudinal section of R851H, hot
rolled and heated for one hour at 600°F. Average grain size was
0.00042 inches. Elongation in 2 inches was 27%.
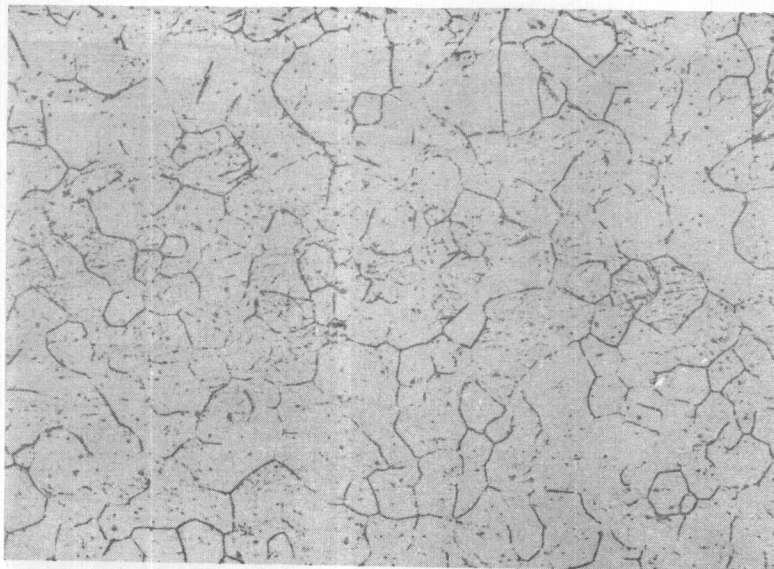
Figure 37

Neg: 201   Spec: M-630-2   Mag: 100X   Etch: Acetic Picral
     Longitudinal section of R672H, magnesium-1.0 zinc, hot
rolled and annealed. Completely recrystallized with grain
size between 0.0013 and 0.0035 inches.
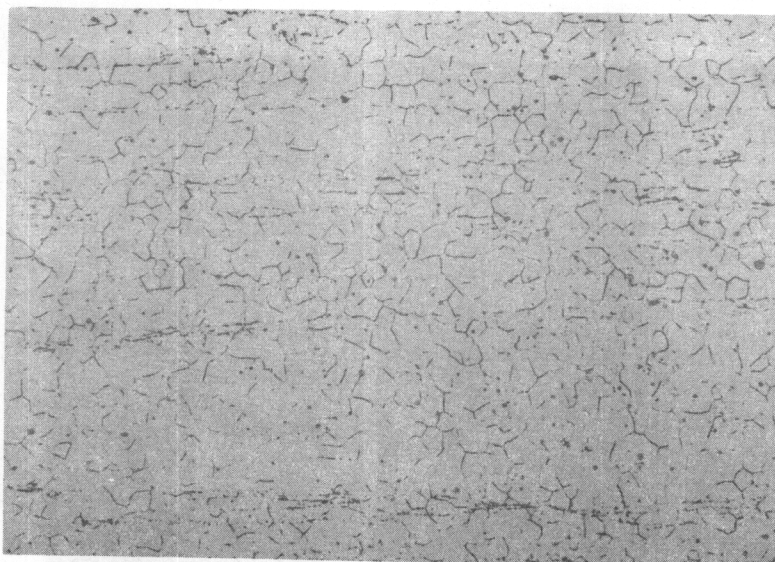
Figure 38

Neg: 206   Spec: M633-4   Mag: 100X   Etch: Acetic Picral
     Longitudinal section of R614, magnesium-0.8 zinc-0.2 cerium,
hot rolled and annealed. Completely recrystallized with grain size
averaging 0.0013 inches.
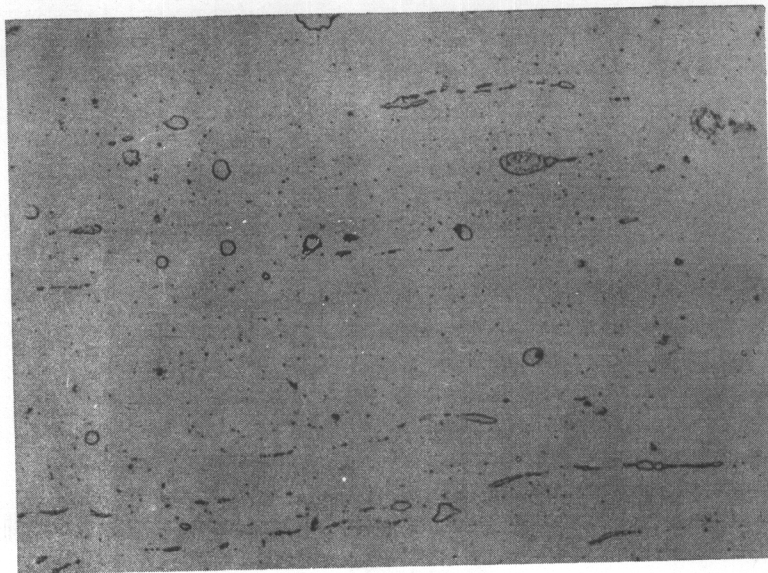
Figure 39

Neg: 134   Spec: M1309-1   Mag: 500X   Etch: Glycol
Longitudinal section of R851H, hot rolled and stress relieved. Secondary constituents are visible. Note the apparent duplex structure of some of the globules.
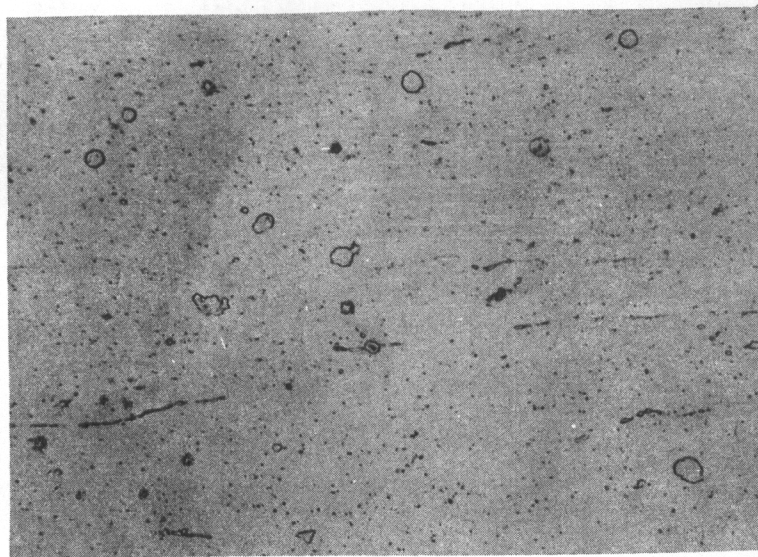
Figure 40

Neg: 136   Spec: 1309-3   Mag: 500X   Etch: Glycol
Longitudinal section of R851H, hot rolled and heated one hour at 600°F. Note growth in number and size of fine particles.

SECTION III

STUDY OF SINGLE CRYSTALS OF MAGNESIUM ALLOYS

INTRODUCTION

The purpose of this work was the growth of magnesium alloy single crystals and a study of their mechanical properties to determine the effects of the various alloying elements under conditions which are not influenced by the presence of grain boundaries. This research includes the preparation of single crystals, the determination of the properties of these crystals and evaluation of the data to determine the specific effects of individual alloying elements in strengthening magnesium. Equipment has been constructed and used successfully for growing single crystals of magnesium but this equipment was not successful in growing single crystals of magnesium-aluminum alloys during the latter part of 1951.

METHOD FOR PREPARATION OF SINGLE CRYSTALS

Selection of a Method for Growth

Three requirements were used as a basis for the choice of a method for producing single crystals. These were:

1. The method should produce single crystals approximately 1/2 inch in diameter and 8 inches or more in length.

2. The method should produce substantial quantities of single crystals with a high degree of perfection of surface and internal structure.

3. The method should be as simple and as free from manual operation as possible.

After discussions with other investigators and a literature survey which was reviewed in the Summary Report for 1949, it was decided to use a modified Bridgman method. This method grows single crystals during the solidification of a melt under a controlled temperature gradient. The equipment for this method was based on the principle of construction used by Farnsworth[12] and on the design described by Jillson.[13] The advantages of this equipment were considered to be as follows:—

1. The size of the single crystals would be limited only by the size of the furnace and of the molds for the crystals.

2. The temperature gradient could be varied over a wide range and controlled to close limits.

3. The effects of crystal mold movement would be eliminated.

4. The equipment would be equally suitable for producing single crystals by controlled growth from the liquid state and by the critical deformation-thermal treatment method in the solid state.

Principle of Operation and Construction of Equipment

The original Bridgman method uses relative motion between the furnace and the melt in order to cause solidification under controlled conditions. The modified Bridgman method produces the desired temperature gradient in the melt, keeps the furnace and melt stationary and then moves the temperature gradient to lower temperature levels at a controlled rate. A detailed discussion of the principle, construction and operation of this equipment was given in the Summary Report for 1949.[3] The essential features of construction and operation are summarized below.

The electric gradient furnace consists of a silicon carbide tube mounted vertically with adequate insulation in a steel shell. This refractory tube has an internal diameter of 3-1/2 inches, an external diameter of 4-1/2 inches and a length of 36 inches. A main winding of Nichrome V wire was placed along the entire length of this tube and auxiliary windings, insulated electrically from the main winding, were placed along the last 6 inches at each end of the tube. The electrical circuits of all three windings are individually controlled so it is possible (a) to change and control the general furnace temperature by varying the current in the main winding and (b) to adjust the temperature gradient along the length of the furnace tube by proper adjustment of the current in each end winding.

A gas tight stainless steel container was constructed to fit within the furnace tube in order to furnish a chamber for growing single crystals in an inert atmosphere. Six chromel-alumel thermocouples were placed at 3 inch intervals along the crystal molds in this container so that the temperature gradient could be determined at any time. Recently, this container was modified to provide:

1. New container flanges for use with a metallic
    gasket rather than an asbestos gasket

2. Eight thermocouples centrally located in the
    container and readily replaceable

3. A hermetically sealed terminal panel for leading
    thermocouple circuits out of the container

These revisions have given greater economy in the use of helium
and considerable improvement in the ease of operation.

The furnace temperature can be changed at a specified
rate — without changing the temperature gradient along the
length of the furnace — by means of a motor driven gear train
linked to the temperature dial on the controller which governs
the current in the main furnace winding. Rates of change of
temperature from 720° to 1.3°F per hour are possible by the
proper selection of three interchangeable parts in the gear
train. Therefore, after a temperature gradient is established
along the length of the crystal molds, this gradient may be
moved in magnitude of temperature without appreciable change
in this gradient. If the temperature is decreased, this should
result in solidification beginning at the bottom of the molds
and progressing toward the top without relative motion between
the molds and the furnace.

General Procedure for Growth of Single Crystals

The following procedure was used in all attempts to grow
single crystals of magnesium and of magnesium alloys.

1. Molds were machined from 1 inch diameter Acheson*
    graphite rods. The original molds produced a
    casting which began to solidify in a 1/8 inch
    diameter, 3/4 inch long cavity at the bottom of
    the mold and then progressed to a 1/2 inch
    diameter chamber. The external diameter of the
    mold was 7/8 inch.

2. A solid rod of magnesium or magnesium alloy was
    placed in the graphite mold. The standard
    preparation of this rod was to etch it in a 10%
    hydrochloric acid solution for about 10 minutes.
    This treatment thoroughly cleaned the rod and
    reduced its diameter to provide adequate
    clearance between it and the graphite mold.

----

* Supplied by National Carbon Company, Inc.

3. The mold — or up to a total of four molds — was suspended in the atmosphere container which was then inserted into the gradient furnace operating at a temperature near the desired maximum.

4. The container was flushed with high purity helium at approximately 5 psi for 7 minutes. During the remainder of the run, only a small positive pressure of helium was maintained. This pressure was read on an open end manometer using oil as the fluid.

5. When the mold bottom was about 50° - 100°F above the liquidus temperature, final adjustments of the temperature gradient were made to provide a linear slope of the desired magnitude.

6. The temperature of the furnace was allowed to drop at the selected constant rate until the upper part of the mold was at least 100°F below the solidus temperature.

7. All heating current was turned off and the molds cooled with the furnace to room temperature. The positive pressure of helium was maintained until the mold temperature was below 400°F.

Experimental Operation of the Gradient Furnace

The initial operation of the gradient furnace was for the growth of magnesium castings. The material used in this work was high purity magnesium in the form of 1/2 inch extruded rod. The impurities in this magnesium were as follows:-

Al	<0.003%	Ni	<0.001%
Ca	<0.01	Pb	<0.01
Cu	<0.001	Si	<0.01
Fe	0.002	Sn	<0.001
Mn	0.006	Zn	<0.01

Experimental details of mold preparation and growth conditions for five runs with high purity magnesium are summarized in Table XVII . The basis for deciding whether or not the casting was a single crystal was visual inspection after etching for about one minute in 10% hydrochloric acid solution. A single crystal exhibited clear evidence of six zones of high intensity reflection, extending longitudinally for the entire length, when rotated through one complete revolution.

A general gray surface film and a condition of top oxidation was observed on all of the castings. It was believed that the major cause of these conditions was the presence of moisture or adsorbed materials in the graphite. As shown in Table XVII, attempts to remove these materials improved the general surface of the castings but did not eliminate the top oxidation of the castings. However, these conditions did not prevent the growth of high purity magnesium single crystals.

In preparation for the growth of magnesium alloy single crystals, 15 high purity alloys were melted and cast under a protective atmosphere of helium and then extruded to 7/16 inch diameter rod. The intended compositions of these alloys are listed in Table XVIII. The magnesium used was a redistilled product with impurities as follows:

Al	<0.003%	Ni	<0.001%
Ca	<0.01	Pb	<0.01
Cu	<0.001	Si	<0.01
Fe	<0.001	Sn	<0.001
Mn	0.002	Zn	<0.01

The aluminum was a special purity grade containing more than 99.99% aluminum and the zinc was Horse Head Special grade with 99.99+% zinc. The cadmium was purchased as a high purity grade but an analysis was not available.

Before the high purity magnesium-aluminum alloys were prepared, one run with three crystal molds was made in an attempt to produce magnesium-zinc single crystals. These three alloys were prepared with Dow Pure magnesium and were found to contain 0.85, 2.65 and 4.00% zinc, respectively. A temperature gradient of 20 °F/in. and a rate of cooling of 26 °F/hr. were used as for the successful growth of single crystals of high purity magnesium but all of the castings were polycrystalline. The first attempts to grow high purity magnesium alloy single crystals were limited to the magnesium - 0.5% aluminum and magnesium - 1.0% aluminum alloys. A summary of the experimental conditions and of the results for four runs to produce 12 castings of these alloys is given in Table XIX. All of the rods were polycrystalline but favorable conditions for the growing of single crystals were approached in some cases.

Castings 7A, 7B and 7C were not single crystals but they had large columnar grains along the top half of their length. The study of these structures and the temperature conditions during their production led to the belief that a temperature gradient of 15°F per inch would be more favorable for growing single crystals. This new growth condition was used for the next run which also used a mold slightly modified at the teat cavity. As shown for mold modification No. 1 in Table XX, a taper pin reamer was used to finish this cavity because the castings were firmly held at this point although they were loose in the main chamber.

TABLE XVII

CONDITIONS AND RESULTS OF CRYSTAL GROWTH
FOR
HIGH PURITY MAGNESIUM CASTINGS

Casting Number	*Mold* Preparation	Gradient Furnace Conditions Temp. Gradient	Rate of Cooling	Max. Temp. at Mold Bottom	Condition of the Casting
1	Original mold design; bore polished with 1 pass of #1 emery paper supported by wooden dowel.	20°F/in.	60°F/hr.	1280°F	Polycrystalline
2	Same as for casting No. 1.	20°F/in.	26°F/hr.	1350	Possibly single crystal.
3	Original mold design; sealed in a vacuum system and pumped 24 hrs. at an average pressure of 0.02 mm. of mercury.	20°F/in.	26°F/hr.	1300	Single crystal
4	Original mold design; bore polished with #1 and #3/0 emery papers; mold heated to bright yellow color with oxy-acetylene flames and transferred rapidly to growth container.	20°F/in.	26°F/hr.	1280	Single crystal

TABLE XVII(cont'd)

CONDITIONS AND RESULTS OF CRYSTAL GROWTH
FOR
HIGH PURITY MAGNESIUM CASTINGS

Casting Number	*Mold Preparation	Gradient Furnace Conditions		Max. Temp. at Mold Bottom	Condition of the Casting
		Temp. Gradient	Rate of Cooling		
5A	Same as for casting No. 3 except pumped 95 hrs. at an average pressure of less than 0.0001 mm of mercury.	20°F/in.	26°F/hr.	1290°F	Single crystal
5B	Same as for casting No. 5A except mold was irradiated with heat lamp throughout pumping.	20°F/in.	26°F/hr.	1290	Single crystal

* Original design mold was made by (a) machining 1 inch diameter Acheson graphite rods to 7/8 inch outside diameter and 8 inches long and (b) drilling to form a 1/2 inch diameter bore with a 1/8 inch diameter and 3/4 inch long cavity at its bottom.

TABLE XVIII

HIGH PURITY BINARY MAGNESIUM ALLOYS

Alloy	Intended Composition		
	Al	Zn	Cd
SC-1	0.5%	--	--
SC-2	1.0	--	--
SC-3	2.0	--	--
SC-4	4.0	--	--
SC-5	100.0	--	--
SC-6	--	0.5%	--
SC-7	--	0.5	--
SC-8	--	1.0	--
SC-9	--	1.0	--
SC-10	--	2.0	--
SC-11	--	4.0	--
SC-15	--	100.0	--
SC-12	--	--	1.0%
SC-13	--	--	5.0
SC-14	--	--	30.0

Castings 8A, 8B and 8C were easily removed by inverting the molds and allowing them to slide out under their own weight. However, the modification of the temperature gradient did not produce single crystals although all of the castings were very coarse grained. Casting 8B showed some grains extending for its entire length and its 1/2 inch diameter cross section contained only five or six grains. The examination of these castings showed that the transition zone from the teat cavity to the main chamber was a region of multiple nucleation.

Mold modifications No. 2, 3 and 4 were used for the next run in an attempt to eliminate multiple nucleation above the teat cavity but they were not successful. Castings 9A and 9B were finer grained than those produced in the two previous runs and also showed considerable solidification shrinkage along their length. Casting 9C was polycrystalline but it had large columnar grains above the transition zone. From these results, it was concluded that a teat cavity should be used together with an additional device to prevent the continued growth of more than one grain.

TABLE XIX

CONDITIONS AND RESULTS OF CRYSTAL GROWTH

FOR

HIGH PURITY MAGNESIUM–ALUMINUM ALLOY CASTINGS

Casting Number	Alloy Addition	*Mold Preparation	Gradient Furnace Conditions		Condition of the Casting
			Temp. Gradient	Rate of Cooling	
7A	1.0%Al	Original	20°F/in.	10°F/hr.	Polycrystalline; Extremely coarse grained; surface relatively smooth.
7B	0.5%Al	Original	20°F/in.	10°F/hr.	Polycrystalline; grain extremely coarse in top half of casting.
7C	1.0%Al	Original	20°F/in.	10°F/hr.	Polycrystalline, grain structure generally finer than 7A and 7B.
8A	1.0%Al	Modification No.1	15°F/in.	10°F/hr.	Polycrystalline; some extremely large grains running entire length of casting; small grain at junction of 1/8 inch teat and 1/2 inch section; casting removed from mold with ease.
8B	0.5%Al	Same as for 8A	15°F/in.	10°F/hr.	Polycrystalline but a closer approach to a single crystal than 8A.
8C	1.0%Al	Same as for 8A	15°F/in.	10°F/hr.	Polycrystalline; similar to 8A in top half.

TABLE XIX (Cont'd)

CONDITIONS AND RESULTS OF CRYSTAL GROWTH
FOR
HIGH PURITY MAGNESIUM-ALUMINUM ALLOY CASTINGS

Casting Number	Alloy Addition	*Mold* Preparation	Gradient Furnace Conditions		Condition of the Casting
			Temp. Gradient	Rate of Cooling	
9A	0.5%Al	Modification No.2	15°F/in.	10°F/hr.	Polycrystalline; fine grained; considerable solidification shrinkage along length of casting.
9B	0.5%Al	Modification No.3	15°F/in.	10°F/hr.	Polycrystalline; similar to 9A.
9C	0.5%Al	Modification No.4	15°F/in.	10°F/hr.	Polycrystalline; equi-axed grains in test and transition zone but columnar grains in 1/2 inch diameter section.
10A	1.0%Al	Modification No.6-1	15°F/in.	10°F/hr.	Polycrystalline, entire casting adhered rigidly to mold; coarse solidification shrinkage along side of casting; a single grain started from orifice and grew approximately 1/2 inch before the structure became coarse polycrystalline
10B	1.0%Al	Modification No.6-2	15°F/in.	10°F/hr.	Polycrystalline; finer grained than 10A; solidification shrinkage present; casting adhered rigidly to mold.
10C	1.0%Al	Modification No.6-3	15°F/in.	10°F/hr.	Similar to 10B

*See Table XX for details on mold preparation.

TABLE XX

PREPARATION AND SHAPE OF GRAPHITE MOLDS
FOR
GROWTH OF SINGLE CRYSTALS

Modification Number	Teat Cavity	Internal Contour at Bottom of 1/2 inch Diameter Chamber	External Contour of Mold at the Bottom
Original	Produced by drilling hole 3/4 inch deep with standard 1/8 inch drill	Produced by drilling chamber with a standard 1/2 inch drill; bore polished with one pass of #1 and #3/0 emery paper on wooden dowel.	Right angle as produced by the machining of 1 inch diameter rods to 7/8 inch diameter.
1	Same as for original but finishing the 1/8 inch hole with No.2/0 reamer.	Same as for original.	Diameter reduced and tapered to provide a progressively greater mold wall thickness from the extreme bottom of the cavity to the 1/2 inch diameter zone.
2	None used	Produced by drilling chamber with a 1/2 inch drill with cutting lips ground to give smooth transition from bottom to the side of the chamber.	Same as for Modification No. 1
3	Pointed but shallow.	Teat cavity and main chamber formed by a single tool ground to give a pointed but shallow tip with a smooth transition to the 1/2 inch diameter chamber.	Same as for Modification No. 1.

TABLE XX (Cont'd)

PREPARATION AND SHAPE OF GRAPHITE MOLDS
FOR
GROWTH OF SINGLE CRYSTALS

Modification Number	Teat Cavity	Internal Contour at Bottom of 1/2 inch Diameter Chamber	External Contour of Mold at the Bottom
4	Same as for Modification No. 1.	Same as for Modification No. 1 but finished with the teat for Modification No. 3.	Same as for Modification No. 1
5	None used	A sharp, pointed cone, 1/2 inch long, with a smooth transition to the 1/2 inch diameter chamber.	Same as for Modification No. 1
6-1	Same as for Modification No. 1.	Same as for Modification No. 1 but with a graphite insert to produce a central orifice 0.067 inch diameter and 11/16 inch long. Transition to orifice and from orifice to main chamber were smooth, curved surfaces.	Same as for Modification No. 1
6-2	Same as for Modification No. 1.	Same as Modification 6-1 except orifice was 0.093 inch diameter and 5/8 inch long.	Same as for Modification No. 1
6-3	Same as for Modification No. 1.	Same as for Modification 6-2 except orifice was 1 inch long.	Same as for Modification No. 1

74

Bridgman[16] described a three chambered vessel which was used successfully in growing single crystals of low-melting metals. The essential feature of this device was a constriction between the region of initial solidification and the chamber for the growth of the large single crystal. The constriction minimized the chances for the continued growth of more than one crystal even though multiple growth occurred in the first chamber. Therefore, a constriction between the teat cavity and the main chamber was provided by the use of a graphite insert with a central orifice as shown in Table XX for mold modifications No. 6-1, 6-2 and 6-3.

Castings 10A, 10B and 10C show the results from using these three variations in the length and diameter of the constriction between the two chambers. These castings were polycrystalline but an encouraging result was obtained in casting 10A for which the smaller diameter orifice (0.067 inch) was used. Growth of a single crystal continued from the orifice for a distance of approximately 1/2 inch in this casting before the growth of a coarse columnar structure occurred. Apparently, the constriction caused the growth of a single crystal to start and to continue for a short distance before additional nuclei were formed. The formation of these new nuclei may have been due to faulty conditions of heat flow. Under optimum conditions, all of the heat should flow away axially through the solid metal. Then the center of the rod is colder than the surface and the solid-liquid interface is convex rather than horizontal or concave.

Modification of the Container Sealing System

When all of the thermocouples except one developed open circuits in run No. 9, it was decided to reconstruct the sealing system after run No. 10 in accordance with plans for which equipment had been obtained. The revised equipment provided:-

1. New container flanges for use with a metallic gasket.

2. Eight thermocouples located along the axis of the container and readily replaceable in case of failure.

3. A hermetically sealed 20 terminal panel for leading thermocouple circuits out of the container.

The first tests of this revised equipment showed considerable improvement. Less helium was used and the ease of operation and control were considerably greater.

EXPERIMENTAL WORK IN PROGRESS

Further studies with the gradient furnace are being made to determine why single crystals of magnesium alloys were not obtained although single crystals of pure magnesium were grown. The cause may have been the presence of some foreign material or impurity which caused multiple nucleation or it may have been due to a deviation from the conditions of heat flow which were favorable to the exclusive growth of one grain. The polycrystalline castings will be examined microscopically to determine whether some non-metallic inclusion or secondary microconstituent was the cause for their being polycrystalline. Also, the equipment will be studied carefully and revised, if necessary, so that heat will be removed more easily in the axial direction than in any other direction.

Attempts will be made to grow large single crystals by critical deformation followed by thermal treatment. This method was used by Schmid and his co-workers[14,15] for the growth of crystals of magnesium-aluminum, magnesium-zinc and magnesium-aluminum-zinc alloys. The present furnace equipment is well suited for the thermal treatment needed for this work.

Equipment is being designed for determining the orientation of magnesium crystals. Also, equipment is planned for determining the shearing stress to start plastic flow and to cause fracture. This equipment will provide axial loading as the stressed crystal distorts and will show the progress of elongation as the specimen is stressed.

CONCLUSIONS

SECTION I:- TERNARY MAGNESIUM-LITHIUM BASE CONSTITUTIONAL DIAGRAMS, MAGNESIUM-LITHIUM-ALUMINUM AND MAGNESIUM-LITHIUM-ZINC

Microscopic examination was found to be the most reliable method for the study of magnesium-lithium-aluminum and magnesium-lithium-zinc alloys. The XX Welding Grade of helium gave good protection but corrosion and loss of lithium prevented the successful use of x-ray diffraction and electrical resistivity measurements at high temperatures.

The solid phases found in the magnesium-lithium-aluminum system were the hexagonal close packed alpha solid solution, the body centered cubic beta solid solution, $Mg_{17}Al_{12}$ and AlLi. The presence of $MgLi_2Al$ was not found in the alloys examined in this research. The isothermal sections of Figs. 16 and 18 show smaller fields for the alpha, alpha plus beta and beta fields at 500° than at 700°F. However, the solubility for lithium appeared to be nearly the same at these two temperatures.

The diagram of Fig. 17 by Shamrai[11] at 400°C (752°F) shows a larger region for the beta solid solution than the present diagram at 700°F. This difference appeared more than that due to the difference in temperature. $MgLiAl_2$ appears on the Shamrai diagram but it was not detected in this investigation.

The solid phases found in the magnesium-lithium-zinc alloy system were the close packed hexagonal alpha solid solution, the body centered cubic beta solid solution MgLiZn and an unidentified phase at 500°F in alloys containing less than 5% lithium. A feathery precipitate of $MgLi_2Zn$ was not considered an equilibrium phase at either 700° or 500°F. A liquid phase existed at 700°F in some alloys. The isothermal sections of Figs. 31 and 32 show smaller fields for the alpha, alpha + beta and beta fields at 500° than at 700°F. As before, the solubility of lithium appeared to be nearly the same although the solubility for zinc was much less at 500°F.

Further investigations on the constitution of magnesium-lithium ternary alloys are not recommended for the immediate future. These alloys were very reactive at high temperatures and also lost lithium during storage at room temperature. Studies of the constitution of magnesium-zinc-zirconium, magnesium-thorium and magnesium-thorium-zirconium should be more useful as these alloys show interesting commercial possibilities.

SECTION II: LOW ALLOY CONTENT HIGH DUCTILITY MAGNESIUM ALLOYS

Good combinations of strength, toughness and formability were found in magnesium alloys containing from 0.7 to 1.5% zinc together with from 0.2 to 0.6% cerium. The best properties were found with an alloy whose nominal composition was magnesium -1.0% zinc-0.4% cerium. The longitudinal properties of this alloy in the warm rolled and annealed condition were as follows:-

Alloy Additions		kips per sq. in.			Elongation
Zn	Ce	CYS	TYS	UTS	in 2 inches
1.0%	0.4%	17.3	24.0	34.2	25.0%

Higher average elongations and lower but comparable strengths were obtained in the limited work done with specimens transverse to the rolling direction.

The addition of 0.4% cerium to magnesium-1.0% zinc refined the grain structure and introduced a small amount of a second phase. The maximum elongation was associated with a fine equiaxed grain structure produced by warm rolling and then heat treating just above the recrystallization range. The structure and properties corresponding to the warm rolled and annealed condition were not reproduced by a single cycle of cold rolling and annealing.

A series of cold reductions and heat treatments should be tried to duplicate the structure and properties obtained by warm rolling and annealing. Also, this magnesium-zinc-cerium alloy should be melted in larger quantities and rolled to wider sheet for a more extensive study of its properties transverse to the rolling direction.

SECTION III: STUDY OF SINGLE CRYSTALS OF MAGNESIUM ALLOYS

The temperature gradient furnace was found suitable for the growth of large single crystals of high purity magnesium by controlled solidification. The etched surfaces of these crystals were relatively smooth and free from imperfections.

The conditions of growth were found to be much more critical for the production of single crystals of magnesium alloys. Single crystals of magnesium-aluminum and magnesium-zinc alloys were not obtained by any procedure tried for their growth by controlled solidification. The etched surfaces of the castings were rougher than those of pure magnesium and more solidification shrinkage was observed.

Favorable conditions for the growth of very coarse grains were found but multiple nucleation was not prevented. Multiple nucleation may have been due to the presence of some foreign material or to a breakdown of the conditions for controlled directional solidification.

Further work is recommended to establish the conditions for the growth of magnesium alloy single crystals by controlled solidification. Careful attention should be given to the conditions of heat flow to make sure that all of the heat flows away axially through the solid metal and the mold bottom rather than laterally through the mold wall.

Experimental work should also be done on the growth of magnesium alloy single crystals in the solid state by critical deformation followed by thermal treatment. This method was used successfully by Schmid and his co-workers[14,15] to grow magnesium-aluminum, magnesium-zinc and magnesium-aluminum-zinc alloy single crystals.

BIBLIOGRAPHY

1. Jackson, J. H. and others, Magnesium-Lithium Base Alloys -- Preparation, Fabrication and General Characteristics. Transactions of the American Institute of Mining and Metallurgical Engineers. Volume 185, 1949. pp. 149-168.

2. Jones, A. and others, Magnesium Alloy Research. Summary Report to United States Air Force, Air Materiel Command. March 1951. Contract No. W33-038 ac 22542.

3. Jones, A. and others, Magnesium Alloy Research. United States Air Force Technical Report No. 6174, United States Air Force, Air Materiel Command, June 1950.

4. Jones, A., Malin, R. D., Nash, R. R., New Magnesium Alloys. Summary Report to United States Air Force, Air Materiel Command. June 1948. Contract No. W33-038 ac 16541.

5. George, P. F., Some Special Metallographic Techniques for Magnesium Alloys. Transactions of the American Society for Metals. Volume 38, 1947. pp. 686-708.

6. ASTM, Identification of Crystalline Materials by the Hanawalt X-ray Diffraction Method. Standards of American Society for Testing Materials, E43-42T. 1949, Part II, p. 1058.

7. ASTM, Alphabetical Index of X-ray Diffraction Patterns. American Society for Testing Materials. June 1945, and the actual ASTM cards.

8. Fink, W. A. and Willey, L. A., Equilibrium Relations in Aluminum-Zinc Alloys of High Purity, II. Transactions of the American Institute of Mining and Metallurgical Engineers. Volume 122, 1936. pp. 244-265.

9. Grube, G., Zeppelin, H. V., Bumm, Electrische Leitfahigkeit und Zustandsdiagram Bie Binaren Legierungen. Zeitschrift fur Electrochemie. Volume 40, 1934. p. 160.

10. Hume-Rothery, W., Raynor, G. V., Butchers, E., Equilibrium Relations and Some Properties of Magnesium-Lithium and Magnesium-Lithium-Silver Alloys. Journal of Institute of Metals. Volume 71, 1945. pp. 589-601.

11. Shamrai, F. I., Ternary Systems: Aluminum-Magnesium -Lithium III. Description of the Ternary System of Aluminum-Magnesium-Lithium; Projection of the Liquidus Surface; Isotherms at 400°C and 20°C and Process of Crystallization. Izvestiza Akademii Nauk USSR. Otdelenie Khimicheskikh Nauk, May-June 1948. pp. 290-301.

12. Farnsworth, H. E., A Vacuum Furnace for the Production of Large Refractory Metal Single Crystals. Physical Review, Volume 48, 1935 p. 972. (Abstract) Paper presented to the New England Section of the American Physical Society, 26 October 1935.

13. Jillson, D. C., Production and Examination of Zinc Single Crystals. Transactions of the American Institute of Mining and Metallurgical Engineers. Volume 188, 1951. pp. 1005-1008.

14. Schmid, E. and Seliger, H., Magnesium-Aluminum and Magnesium -Zinc Binary Single Crystals. Metallwirtschaft, Volume 11, 1932. pp. 409-411 and pp. 421-424.

15. Schmid, E. and Siebel, G., Ternary Magnesium-Aluminum-Zinc Single Crystals. Metallwirtschaft, Volume 11, 1932. pp. 577-579.

16. Bridgman, P. W., Various Low Melting Metals. Proceedings of the American Academy of Arts and Sciences, Volume 60, 1925. p. 305.

TABLE XXI

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

Alloy	Extrusion Charge	Intended Composition and Chemical Analysis Li (wt.%)	Al (wt.%)	Heat Treatment[a] Time (Hn)	Temp (°F)	Phases Present and Estimation of Relative Amounts (%) Alpha	Beta	$Mg_{17}Al_{12}$	AlLi
L-14	–	17.6	–						
L-15	–	10.0	–						
L-16	–	15.0	–						
L-17	–	11.0	–						
L-18	–	2.9 (1.05)	–						
L-19	153	5.0 (4.87) (4.9)	– – –	– 72 72	– 700 500	100 100 100	– – –	– – –	– – –
L-20	151	8.0 (7.7)	– –	96 72	700 500	50 50 50	50 50 50	– – –	– – –
L-21	157	12.0 (12.25) (11.85)	– –	– 24	– 700	– –	100 100	– –	– –
L-22	154	10.6 (10.2)	5.0 (4.65) – –	– 96 72	– 700 500	10-15 5 15	80-85 90-95 80	– – –	5 5 5
L-23	155	10.0	10.0	– 72 72	– 700 500	33 35 35	33 35 35	– – –	33 30 30

TABLE XXI (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

Alloy	Extrusion Charge	Intended Composition and Chemical Analysis		Heat Treatment[a]		Phases Present and Estimation of Relative Amounts (%)			
		Li (wt.%)	Al (wt.%)	Time (Hn)	Temp (°F)	Alpha	Beta	$Mg_{17}Al_{12}$	AlLi
L-24	156	9.4	15.0						
				–	–	40	25	–	35
				72	700	40	25	–	35
				72	500	40	25	–	35
L-25	161	8.9 (8.54)	20.0 (18.9)						
				–	–	80	–	–	20
				72	700	80	–	–	20
				72	500	80	–	–	20
L-26	158	8.5 (8.44)	5.0 (4.65)						
				–	–	40	40	–	20
				96	700	50	50	–	0–2
				72	500	40	40	–	20
L-27	159	8.2	10.0						
				–	–	40–45	20	–	30–40
				72	700	40–45	20	–	30–40
				72	500	50	10	–	40
L-28[b]	–	8	–						
L-29[b]	–	12	–						
L-30[c]	–	12	–						
L-31	235	7.8 – (7.1) (7.1)	15.0 – (12.5) (13.8)	– 24 72	– 700 500	90 90 90	– – –	– – –	10 10 10
L-32	233	7.3 – (6.8) (6.8)	20 – (17.2) (17.5)	– 24 72	– 700 500	90 80	– –	– –	10 20
L-41	165	6.25 (2.61)	– –						

TABLE XXI (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

Alloy	Extrusion Charge	Intended Composition and Chemical Analysis		Heat Treatment[a]		Phases Present and Estimation of Relative Amounts (%)			
		Li (wt.%)	Al (wt.%)	Time (Hn)	Temp (°F)	Alpha	Beta	$Mg_{17}Al_{12}$	AlLi
L-43	175	15 (15.15)	–	–	–	–	100	–	–
				96	700	–	100	–	–
				72	500	–	100	–	–
L-44	176	20 (19.25)	– –						
L-47	178	5.9	–						
				24	700	100	–	–	–
				72	500	100	–	–	–
L-51	185	6.5 (7.6)	2.2 (2.02)	–	–	60	40	–	–
				96	500	60	40	–	–
L-52	189	5.6 (4.9)	4.0 –						
				–	–	100	–	–	–
				96	700	100	–	–	–
				72	500	100	–	–	–
L-53	192	5.5	6.0						
				96	700	100	–	–	–
				72	500	97	–	–	3
L-54	188	5.8 – (5.4) (5.1)	2.0 – (1.9) (1.9)	–	–	100	–	–	–
				24	700	100	–	–	–
				72	500	100	–	–	–
L-55	190	6.1 (5.10)	2.0 (1.87)						
L-56	191	6.0 (4.70)	4.0 (3.87)	–	–	100	–	–	–
				96	700	100	–	–	–
				72	500	100	–	–	–

TABLE XXI   (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS AND CONSTITUTION OF MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

Alloy	Extrusion Charge	Intended Composition and Chemical Analysis Li (wt.%)	Al (wt.%)	Heat Treatment[a] Time (Hr.)	Temp (°F)	Phases Present and Estimation of Relative Amounts (%) Alpha	Beta	$Mg_{17}Al_{12}$	AlLi
L-57	196	5.9	6.0						
		(3.56)	(6.14)	–	–	100	–	–	–
		(5.2)	(6.0)	24	700	100	–	–	–
		(5.1)	(6.0)	72	500	97	–	–	3
L-58	193	13.6	5.0						
		(12.6)	(5.06)	–	–	–	100	–	–
				96	700	–	100	–	–
				72	500	–	100	–	–
L-59	194	12.9	10.0						
				–	–	–	60	–	40
				144	700	–	80	–	20
				72	700	–	65	–	35
				72	500	–	65	–	35
L-60	195	12.2	15.0						
				–	–	30	50	–	20
				72	700	40	30	–	30
				72	500	25	50	–	25
L-61	234	11.4	20.0						
		–	–	–	–	33	33	–	34
		(9.2)	(20.3)	24	700	40	40	–	20
		(11.5)	(19.7)	24	700	40	40	–	20
				72	500	35	35	–	30
L-62[d]	–	–	45.4						
		–	(44.0)						
L-63[e]	–	20.47	79.53						
		(24.1)	(73.4)						
L-68	201	3.2	–						
L-69	202	3.2	2.0						
		(1.93)	(1.65)						

TABLE XXI   (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

Alloy	Extrusion Charge	Intended Composition and Chemical Analysis Li (wt.%)	Al (wt.%)	Heat Treatment[a] Time (Hr.)	Temp (°F)	Phases Present and Estimation of Relative Amounts (%) Alpha	Beta	$Mg_{17}Al_{12}$	AlLi
L-70	203	3.1 (2.75)	4.0 (3.65)	-	-	-	-	-	-
				24	700	100	-	-	-
				72	500	100	-	-	-
L-71	204	3.0 - (3.0) (2.7)	6.0 - (4.2) (5.1)	-	-	100	-	-	-
				24	700	100	-	-	-
				72	500	100	-	-	-
L-72	205	1.0	2.0						
L-73	206	1.0 (0.9)	4.0 (3.6)	72	500	95+	-	5	-
L-74	207	0.9 - (0.8) (1.0)	6.0 - (5.0) (4.9)	-	-	100	-	-	-
				24	700	100	-	-	-
				72	500	97	-	3	-
L-75	208	-	2.0						
L-76	209	-	4.0						
L-77	210	-	6.0						
L-91	260	11.0 - (10.5)	- - -	-	-	20	80	-	-
				24	700	10	90	-	-
				72	500	10	90	-	-
L-92	261	10.0 - (14.9)	- - -	-	-	-	100	-	-
				24	700	-	100	-	-
				72	500	-	100	-	-
L-120	284	9.0	2.5	-	-	50	50	-	-
				24	700	50	50	-	-

TABLE XXI (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

Alloy	Extrusion Charge	Intended Composition and Chemical Analysis Li (wt.%)	Al (wt.%)	Heat Treatment[a] Time (Hr)	Temp (°F)	Phases Present and Estimation of Relative Amounts (%) Alpha	Beta	$Mg_{17}Al_{12}$	AlLi
L-121	258	10.5	2.5						
		(99-9.8)	-	-	-	20	80	-	-
		(9.7)	-	24	700	15	85	-	-
		(10.6)	(2.6)	72	500	35	65	-	-
L-122	259	12.0	2.5						
		(11.6-11.9)	-	-	-	-	100	-	-
		(10.8)	-	24	700	-	100	-	-
		(12.2)	(2.4)	72	500	5	95	-	-
L-123	253	8.5	4.0						
		(8.0-7.9)	(5.9)	-	-	40	40	-	20
		(7.4)	(6.7)	29	700	60	40	-	-
				72	500	55	37	-	8
L-124	254	11.5	5.0						
		(10.3)	(5.3)	-	-	20	20	-	10
		(10.0)	(5.6)	24	700	30	70	-	-
				72	500	35	55	-	10
L-126	256	11.5	10.0						
		-	-	-	-	15	70	-	15
		(10.8)	(10.0)	24	700	20	65	-	15
				72	500	30	55	-	15
L-127	257	11.0	15.0						
				-	-	30	35	-	35
				24	700	38	38	-	24
				72	500	45	30	-	25
L-128	255	12.5	6.0						
		-	-	-	-	-	85	-	15
		(11.0)	(4.8)	24	700	-	100	-	-
				72	500	-	85	-	10
L-129	252	12.5	8.0						
		-	-	-	-	-	80	-	20
		-	-	24	700	1	90	-	9
		(12.3)	(8.0)	72	500	-	90	-	10

TABLE XXI (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

Alloy	Extrusion Charge	Intended Composition and Chemical Analysis Li (wt.%)	Al (wt.%)	Heat Treatment[a] Time (Hr.)	Temp (°F)	Phases Present and Estimation of Relative Amounts (%) Alpha	Beta	$Mg_{17}Al_{12}$	AlLi
L-130	268	4.5	2.0						
				—	—	100	—	—	—
				24	700	100	—	—	—
				72	500	100	—	—	—
L-131	269	3.0 —	3.0						
				—	—	100	—	—	—
				24	700	100	—	—	—
				72	500	100	—	—	—
L-132	270	5.0 — (4.7)	10 — (10.2)						
				—	—	93	—	2	5
				24	700	93	—	2	5
				24	700	93	—	2	5
				72	500	93	—	2	5
L-133	271	6.0 (5.5) (5.3)	10.0 (7.6) (10.1)	24	700	90	—	10	—
				72	500	90	—	3	7
L-134	272	7.0 (6.7)	10.0 (8.2)	24	700	90	—	—	10
L-135	273	—	10						
				—	—	70	—	30	—
				24	700	70	—	30	—
				72	500	70	—	30	—
L-136	274	3.0 — (8.8-9.0)	10.0 — (9.8)						
				—	—	50	35	—	15
				24	700	50	35	—	15
				72	500	50	35	—	15
L-137[f]	-	34	66						
L-138	275	19.3	49.1						

TABLE XXI (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS AND CONSTITUTION OF MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

Alloy	Extrusion Charge	Li (wt.%)	Al (wt.%)	Time (Hr.)	Temp (°F)	Alpha	Beta	$Mg_{17}Al_{12}$	AlLi
L-139	276	8.5	6.0			55	35	-	10
		(8.3)	(6.4)	24	100	59	40	-	1
				72	500	58	35	-	7
L-140	277	-	7.5			85	-	15	-
		-	-	24	700	85	-	15	-
		-	(8.1)	72	500	80	-	20	-
L-141	278	1.0	8.0			100	-	-	-
		(0.9)	(6.3)	24	700	100	-	-	-
				72	500	97	-	3	-
L-142	279	11.0	4.0			40	50	-	10
		(10.3)	(6.0)	24	700	35	60	-	5
		(10.2)	(5.7)	72	500	25	75	-	-
L-143	280	5.0	15.0						
		(4.9)	(15.4)	24	700	80	-	15	5
		(4.8)	(15.4)	72	500	80	-	5	5
L-144	281	3.5	15.0			80	-	20	-
		(2.8)	(15.1)	24	700	70	-	30	-
				72	500	60	-	40	-
L-145	282	5.0	20.0			60	-	40	-
		(4.6)	(23.3)	24	700	70	-	30	-
		(4.5)	(21.7)	72	500	70	-	30	-
L-146	283	3.5	20.0			50	-	50	-
				24	700	50	-	50	-

TABLE XXI (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

Alloy	Extrusion Charge	Intended Composition and Chemical Analysis		Heat Treatment[a]		Phases Present and Estimation of Relative Amounts (%)			
		Li (wt.%)	Al (wt.%)	Time (Hr.)	Temp (°F)	Alpha	Beta	$Mg_{17}Al_{12}$	AlLi
L-147[c]	-	15.0	5.0						
L-148	265	15.0	7.0						
		-	-	-	-	-	80	-	20
		(14.2)	(6.1)	24	700	-	100	-	-
				72	500	-	95	-	5
L-149	266	15.0	9.0						
		-	-	-	-	-	75	-	25
		(13.7)	(9.3)	24	700	-	85	-	15
				72	500	-	85	-	15
L-150	262	20.0	4.0						
				-	-	-	100	-	-
				24	700	-	100	-	-
				72	500	-	100	-	-
L-151	263	20.0	6.0						
		-	-	-	-	-	90	-	10
		-	-	24	700	-	100	-	-
		(18.8)	(5.9)	72	500	-	95	-	5
L-152	264	20.0	8.0	-					
		-	-	-	-	-	90	-	10
		(19.2)	(9.2)	24	700	-	100	-	-
		(17.5)	(7.9)	72	500	-	95	-	5
L-153	287	15.0	15.0						
		-	-	-	-	-	70	-	30
		(13.9)	(15.8)	24	700	-	70	-	30
		(12.9)	(16.1)	24	700	2	70	-	28
				84	500	-	75	-	25
L-154	286	15.0	20.0						
		-	-	-	-	-	60	-	40
		(12.9)	(21.3)	24	700	5	60	-	35
				24	700	1	60	-	39

TABLE XXI (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

Alloy	Extrusion Charge	Intended Composition and Chemical Analysis Li (wt.%)	Al (wt.%)	Heat Treatment[a] Time (Hr.)	Temp (°F)	Relative Amounts Alpha	Beta	$Mg_{17}Al_{12}$	AlLi
L-155	285	20.0	15.0						
		-	-	-	-	-	90	-	10
		(18.9)	(16.0)	24	700	-	90	-	10
				84	500	-	75	-	25
L-177[g]	-	21.3	41.4						
		(20.2)	(43.1)	-	-	-	-	-	-
L-199	326	10.9	6.95						
		-	-	-	-	25	60	-	15
		(10.5)	(7.6)	72	500	30	60	-	10
L-200	327	6.0	20.0						
				-	-	85	-	15	-
				24	700	75	-	25	-
				72	500	75	-	25	-
L-201	328	7.0	20.0	-	-	80	-	-	20
				24	700	90	-	-	10
				72	500	80	-	-	20
L-202	329	6.0	15.0						
				-	-	60	-	-	40
				24	700	80	-	-	20
				72	500	80	-	-	20
L-203[h]	330	5.0	30.0						
				-	-				
				24	700				
				72	500				
L-204[h]	331	6.5	30.0						
				-	-				
				72	500				
L-205[h]	332	8.0	30.0						
				-	-				
				24	700				
				72	500				

TABLE XXI (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS AND CONSTITUTION OF MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

Alloy	Extrusion Charge	Intended Composition and Chemical Analysis Li (wt.%)	Al (wt.%)	Heat Treatment[a] Time (Hr.)	Temp (°F)	Relative Amounts Alpha	Beta	$Mg_{17}Al_{12}$	AlLi
L-206	333	9.5	30.0						
				-	-	50	-	-	50
				24	700	70	-	-	30
				72	500	60	-	-	40
L-207	334	11.0	30.0						
				-	-	50	-	-	50
				24	700	60	-	-	40
				72	500	60	-	-	40
L-208	335	20.0	9.5						
		(17.5)	(9.6)	-	-	-	95	-	5
				24	700	-	99	-	1
				72	500	-	85	-	15
L-209	336	20.0	11.5						
		(17.9)	(11.5)	-	-	-	70	-	30
		(17.5)	(13.4)	24	700	-	95	-	5
				84	500	-	50	-	50
L-210	337	20.0	13.5						
				-	-	-	60	-	40
				24	700	-	80	-	20
				84	500	-	90	-	10
L-211	338	15.0	8.0						
		(13.8)	(8.3)	-	-	-	90	-	10
		(14.1)	(8.1)	24	700	-	90	-	10
				72	500	-	95	-	5
L-212	339	7.0	2.0						
				-	-	80	15	-	5
				72	500	40	40	-	20
L-213	340	7.5	5.5						
				-	-	75	25	-	-
				72	500	80	20	-	-

TABLE XXI (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

Alloy	Extrusion Charge	Intended Composition and Chemical Analysis Li (wt.%)	Al (wt.%)	Heat Treatment[a] Time (Hr.)	Temp (°F)	Relative Amounts Alpha	Beta	$Mg_{17}Al_{12}$	AlLi
L-214	346	7.3	6.5						
		-	-	-	-	40	50	-	10
		(6.8)	(6.9)	84	500	45	45	-	10
L-215	347	6.0	7.1	-	-	-	-	-	-
L-216	348	3.0	6.5						
		-	-	-	-	85	-	15	-
		(2.7)	(7.1)	24	700	95	-	5	-
				72	500	60	-	40	-
L-217	349	3.0	7.5						
		-	-	-	-	60	-	40	-
		(2.8)	(7.9)	24	700	90	-	10	-
				72	500	75	-	25	-
L-218	350	3.0	8.0						
				-	-	65	-	35	-
				24	700	80	-	20	-
				84	500	60	-	40	-
L-247	385	5.0	5.0						
		-	-	-	-	80	20	-	-
		(5.1)	(4.9)	39	700	100	-	-	-
L-248	386	6.0	4.0						
		-	-	-	-	80	20	-	-
		(6.4)	(4.2)	39	700	75	25	-	-
				92	500	80	20	-	-
L-249	387	7.0	3.0						
				-	-	60	40	-	-
				39	700	60	40	-	-
L-250	388	5.0	6.0						
		-	-	-	-	100	-	-	-
		(5.2)	(6.2)	39	700	100	-	-	-

TABLE XXI   (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS AND CONSTITUTION OF MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

Alloy	Extrusion Charge	Intended Composition and Chemical Analysis Li (wt.%)	Al (wt.%)	Heat Treatment[a] Time (Hr.)	Temp (°F)	Relative Amounts Alpha	Beta	$Mg_{17}Al_{12}$	AlLi
L-251	389	6.0	5.0	–	–	80	20	–	–
		(6.2)	(5.6)	39	700	90	10	–	–
L-252	390	7.0	4.0	–	–	70	30	–	–
				39	700	60	40	–	–
L-253	391	4.0	2.5	–	–	75	–	–	25
				92	500	85	–	–	15
L-254	392	5.0	2.5	–	–	100	–	–	–
				92	500	95	–	–	5
L-255	396	4.0	2.5	–	–	50	50	–	–
				92	500	50	50	–	–
L-256	397	4.0	3.5	–	–	85	–	–	15
				92	500	90	–	–	10
L-257	398	6.0	1.5	–	–	50	50	–	–
				92	500	60	40	–	–
L-284	425	7.0	5.0	–	–	50	30	–	10
				148	700	50	25	–	15
				148	500	80	20	–	–
L-289	429	8.0	2.5	–	–	10	90	–	–
				148	700	30	70	–	–

TABLE XXI (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

Alloy	Extrusion Charge	Intended Composition and Chemical Analysis		Heat Treatment[a]		Relative Amounts			
		Li (wt.%)	Al (wt.%)	Time (Hr.)	Temp (°F)	Alpha	Beta	$Mg_{17}Al_{12}$	AlLi
L-290	430	3.0	2.5						
				–	–	100	–	–	–
				148	700	100	–	–	–
				148	500	100	–	–	–
L-291	431	9.0	2.5						
				148	700				
L-292	432	10.0	2.5						
				–	–	25	70	–	5
				148	700	20	80	–	–
L-296	436	11.0	2.5						
				–	–	10	90	–	–
				148	700	15	85	–	–
L-297	437	12.5	6.0						
				–	–	–	95	–	5
				148	500	–	100	–	–
L-298	438	12.5	8.0						
				–	–	–	80	–	20
				148	700	–	60	–	40
				148	500	–	85	–	15
L-299	439	12.5	7.0						
				–	–	–	80	–	20
				148	500	–	90	–	10
L-300	440	12.5	9.0						
				–	–	–	80	–	20
				148	500	–	85	–	15
L-301[c]	441	17.5	4.0						

TABLE XXI   (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

Alloy	Extrusion Charge	Intended Composition and Chemical Analysis Li (wt.%)	Al (wt.%)	Heat Treatment[a] Time (Hr.)	Temp (°F)	Relative Amounts Alpha	Beta	$Mg_{17}Al_{12}$	AlLi
L-302	422	17.5	5.0						
				–	–	–	95	–	5
				148	700	–	90	–	10
				148	500	–	100	–	–
L-303	443	17.5	6.0						
				–	–	–	90	–	10
				148	700	–	80	–	20
				148	500	–	100	–	–
L-304	444	17.5	7.0						
				–	–	–	90	–	10
				148	700	–	75	–	25
				148	500	–	100	–	–
L-305	445	17.5	8.0						
				–	–	–	75	–	25
				148	700	–	65	–	35
				148	500	–	100	–	–
L-306	446	8.5	15.0						
				–	–	–	50	–	50
				148	700	–	50	–	50
				148	500	–	60	–	40

a. Specimens for which no heat treatment was specified were examined in the as extruded condition

b. Prepared for segregation study

c. Ingot scraped

d. Intended to be $Mg_{17}Al_{12}$

e. Intended to be AlLi

f. Intended to be $AlLi_2$

g. Intended to be $MgLi_2Al$

h. Believed to contain $Mg_{17}Al_{12}$ and AlLi but the relative amount of each phase could not be observed

TABLE XXII

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ZINC ALLOYS

Alloy	Extrusion Charge	Intended Composition and (Chemical Analysis) Li (wt.%)	Zn (wt.%)	Heat Treatment[a] Time (Hr.)	Temp (°F)	Phases Present and Estimation of Relative Amounts (%) Alpha	Beta	MgLiZn	Other
L-19	153	5.0 (4.87)	—	—	—	100	—	—	—
				72	500	100	—	—	—
				72	700	100	—	—	—
L-20	151	8.0 (7.77)	—	—	—				
				—	—	50	50	—	—
				72	500	50	50	—	—
				72	700	50	50	—	—
L-21	157	12.0 (11.85)	—	—	—	—	100	—	—
				24	700	—	100	—	—
L-33	174	8.9	2.0	—	—	40	60	—	—
				72	500	40	60	—	—
				24	700	40	60	—	—
L-34	173	8.7	4.0	—	—	30	70	—	—
				72	500	30	70	—	—
				24	700	30	70	—	—
L-35	172	8.5 (8.0)	6.0 (5.8)	—	—	45	55	—	—
	237			72	500	35	60	5	—
	237			29	700	40	60	—	—
L-36	171	8.4 (8.2)	8.0 (7.96)	—	—	30	65	5	—
	171	(8.3)	(7.8)						
	166			72	500	35	50	15	—
	166			29	700	30	70	—	—
L-37	170	10.9 (10.75)	2.0 (2.03)	—	—	—	100	—	—
		(10.2)	(1.6)	72	500	—	100	—	—
				72	500	—	100	—	—
		(10.2)		24	700	—	100	—	—

TABLE XXII (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS AND CONSTITUTION OF MAGNESIUM-LITHIUM-ZINC ALLOYS

Alloy	Extrusion Charge	Intended Composition and (Chemical Analysis) Li (wt.%)	Zn (wt.%)	Heat Treatment Time (Hr.)	Temp (°F)	Alpha	Beta	MgLiZn	Other
L-38	169	10.7 (10.65)	4.0	—	—	—	100	—	—
		(10.1)	(3.5)	72	500	—	100	—	—
				72	500	—	100	—	—
		(9.9)		24	700	—	100	—	—
L-39	168	10.4 (10.75)	6.0	—	—	—	100	—	—
		(10.0)	(5.7)	72	500	—	100	—	—
		(9.9)		72	500	—	100	—	—
				24	700	—	100	—	—
L-40	167	10.2	8.0	—	—	—	90	10	—
		(9.5)	(7.6)	72	500	—	95	5	—
				72	500	—	90	10	—
		(8.7)		24	700	—	100	—	—
L-42	179	6.1	2.0	—	—	80	20	—	—
		(5.32)	(2.04)	72	500	85	15	—	—
		(5.9)	(1.8)	72	500	70	30	—	—
				24	700	80	20	—	—
				72	700	80	20	—	—
L-43	175	15.0 (15.15)	-	—	—	—	100	—	—
				96	700	—	100	—	—
L-45	180	6.0	4.0	—	—	85	15	—	—
		(5.5)	(3.8)	72	500	75	20	5	—
		(5.5)	(3.6)	24	700	85	15	—	—
L-46	181	5.9	6.0	—	—	75	25	—	—
		(5.7)	(5.8)	72	500	80	15	5	—
				24	700	75	25	—	—
L-48	182	5.8	2.0	—	—	100	—	—	—
		(4.8)	(1.8)	72	500	100	—	—	—
		(4.7)	(1.6)	29	700	100	—	—	—

TABLE XXII (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ZINC ALLOYS

| Alloy | Extrusion Charge | Intended Composition and (Chemical Analysis) | | Heat Treatment[a] | | Phases Present and Estimation of Relative Amounts (%) | | | |
		Li (wt.%)	Zn (wt.%)	Time (Hr)	Temp (°F)	Alpha	Beta	MgLiZn	Other
L-49	183	5.6 (5.6)	4.0 (3.7)	—	—	80	20	—	—
				72	500	75	20	5	—
				72	500	75	20	5	—
				24	700	80	20	—	—
				72	700	80	20	—	—
L-50	184	5.5 (5.0)	6.0 (5.7)	—	—	85	15	—	—
				72	500	70	10	20	—
		(5.0)	(5.6)	72	500	60	10	30	—
				24	700	85	15	—	—
				72	700	85	15	—	—
L-78	211	—	2.0	—	—	100	—	—	—
				29	700	100	—	—	—
L-79	212	— (0.0)	4.0 (3.9)	—	—	100	—	—	—
				72	500	100	—	—	—
				29	700	100	—	—	—
L-80	213	—	6.0	—	—	90	—	—	10[b]
				72	500	85	—	—	15[b]
				29	700	100	—	—	—
L-81	214	1.0	2.0	—	—	100	—	—	—
				29	700	100	—	—	—
L-82	215	1.0 (1.0)	4.0 (3.8)	—	—	100	—	—	—
				72	500	100	—	—	—
				29	700	100	—	—	—
L-83	216	0.9	6.0	—	—	100	—	—	—
				72	500	100	—	—	—
				29	700	100	—	—	—
L-84	218	3.2	2.0	—	—	100	—	—	—
				72	500	100	—	—	—
				24	700	100	—	—	—
				72	700	100	—	—	—
L-85	219	3.1 (2.8)	4.0 (4.0)	—	—	100	—	—	—
				72	500	100	—	—	—
				72	500	90	—	10	—
				24	700	100	—	—	—
				72	700	100	—	—	—

TABLE XXII (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ZINC ALLOYS

Alloy	Extrusion Charge	Intended Composition and (Chemical Analysis) Li (wt.%)	Zn (wt.%)	Heat Treatment[a] Time (Hr)	Temp (°F)	Phases Present and Estimation of Relative Amounts (%) Alpha	Beta	MgLiZn	Other
L-87	220	14.0	2.2	–	–	–	100	–	–
				29	700	–	100	–	–
L-88	221	12.9 (11.7)	10.0 (10.3)	–	–	–	100	–	–
				72	500	–	85	15	–
				24	700	–	100	–	–
L-89	222	12.2 (11.0)	15.0 (15.0)	–	–	–	100	–	–
				72	500	–	80	20	–
				24	700	–	100	–	–
L-90	223	11.4	20.0	–	–	–	95	5	–
				72	500	–	65	35	–
				24	700	–	90	10	–c
		(9.9)	(20.2)	24	700	–	90	10	–
L-91	260	11.0 (10.5)	–	–	–	20	80	–	–
				24	700	10	90	–	–
L-92	261	10.0 (14.9)	–	–	–	–	100	–	–
				24	700	–	100	–	–
L-96	238	12.3	2.0 (1.8)	–	–				
		(10.8)	(2.0)	–	–	–	100	–	–
		(10.5)		72	500	–	100	–	–
				24	700	–	100	–	–
L-97	239	12.0 (10.4)	4.0 (4.0)	–	–	–	100	–	–
		(10.9)		72	500	–	100	–	–
				24	700	–	100	–	–
L-98	240	11.7	6.0 (12.9)	–	–	–	90	10	–
		(11.9)	(12.7)	72	500	–	70	30	–
				24	700	–	100	–	–
L-99	241	11.5 (10.0)	8.0 (7.7)	–	–	–	90	10	–
		(9.6)	(7.4)	72	500	–	85	15	–
				24	700	–	100	–	–

TABLE XXII (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ZINC ALLOYS

Alloy	Extrusion Charge	Intended Composition and (Chemical Analysis) Li (wt.%)	Zn (wt.%)	Heat Treatment[a] Time (Hr)	Temp (°F)	Phases Present and Estimation of Relative Amounts (%) Alpha	Beta	MgLiZn	Other
L-100	242	11.2	10.0						
		(9.8)	(10.2)	–	–	–	80	20	–
		(9.9)	(9.8)	72	500	–	70	30	–
		(9.8)	(9.0)	24	700	–	100	–	–
L-102	243	10.0	20.0	–	–	50	20	30	–
				72	500	35	30	35	–
		(6.0)	(20.4)	24	700	45	45	10	–
L-109	244	7.8	15.0						
		(16.1)		–	–	–	15	5	80[c]
		(15.6)	(17.9)	72	500	–	–	10	90[c]
				72	500	–	35	10	55[c]
		(15.8)	(18.2)	24	700	–	35	–	65[c]
				24	700	–	60	–	40[c]
L-111	245	5.8	8.0						
		(5.8)	(4.1)	–	–	85	10	5	–
		(5.4)	(2.5)	72	500	80	–	20	–
		(5.2)	(3.6)	24	700	90	10	–	–
L-112	250	5.6	10.0	–	–	80	–	20	–
		(4.8)	(9.2)	72	500	65	–	35	–
		(4.8)	(9.2)	24	700	85	15	–	–
L-113	267	5.3	15.0						
		(4.8)	(15.2)	72	500	55	–	45	–
		(4.6)	(14.7)	24	700	55	30	15	–
L-114	251	5.0	20.0	–	–	50	–	50	–
				72	500	55	–	45	–
		(3.9)	(20.5)	24	700	70	–	30	–
L-116	246	2.9	10.0	–	–	50	–	50	–
				72	500	70	–	30	–
		(2.3)	(10.0)	24	700	85	–	–	15[d]
L-117	247	2.7	15.0	–	–	60	–	40	–
				72	500	65	–	35	–
		(2.2)	(15.0)	24	700	80	–	20	–

TABLE XXII (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ZINC ALLOYS

Alloy	Extrusion Charge	Intended Composition and (Chemical Analysis) Li (wt.%)	Zn (wt.%)	Heat Treatment[a] Time (Hr)	Temp (°F)	Phases Present and Estimation of Relative Amounts (%) Alpha	Beta	MgLiZn	Other
L-118	248	2.6	20.0	-	-	50	-	50	-
				72	500	60	-	40	-
		(2.1)	(21.9)	24	700	60	-	40	-
L-119	249	3.0	8.0	-	-	70	-	30	-
				72	500	70	-	30	-
		(2.5)	(8.5)	24	700	100	-	-	-
L-158	293	9.8	12.0	-					
			(11.7)	-	-	10	85	5	-
		(8.7)	(11.8)	72	500	15	65	20	-
		(8.4)		24	700	10	90	-	-
L-159	294	9.5	15.0	-	-	-	90	10	-
				72	500	-	80	20	-
		(9.6)	(11.2)	24	700	-	100	-	-
L-160	288	8.9	20.0	-	-	-	80	20	-c
		(8.4)	(20.6)	72	500	100	75	15	-
		(7.0)	(20.0)	24	700	5	85	10	-
L-161	289	8.2	10.0	-	-	40	60	-	-
				72	500	40	40	20	-
		(7.4)	(10.5)	24	700	40	60	-	-
L-162	290	8.0	12.0	-	-	45	45	10	-
				6	500	40	40	20	-
				12	500	40	40	20	-
				40	500	40	40	20	-
				48	500	40	40	20	-
				72	500	40	40	20	-
				72	500	40	40	20	-
		(7.0)	(12.1)	24	700	35	60	5	-
L-163	291	7.3	20.0	-	-	35	35	30	-
				72	500	35	35	30	-
				24	700	35	45	20	-
L-164	292	3.0	8.0	-	-	90	-	10	-
				72	500	80	-	20	-
				24	700	90	-	10	-

TABLE XXII (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ZINC ALLOYS

Alloy	Extrusion Charge	Intended Composition and (Chemical Analysis) Li (wt.%)	Zn (wt.%)	Heat Treatment[a] Time (Hr)	Temp (°F)	Phases Present and Estimation of Relative Amounts (%) Alpha	Beta	MgLiZn	Other
L-166	296	1.3 (0.52) (0.45)	20.0 (20.0) (20.1)	72 24	500 700	60 65	– –	? 5	40[e] 30[d]
L-167	297	2.4 (3.4) (3.4)	20.0 (18.1) (18.2)	72 24	500 700	65 75	– –	35 25	– –
L-168	298	6.8 (5.1)	20.0 (9.6)	24	700	60	20	20	–
L-169	299	9.1 (3.7)	20.0 (9.7)	72 24	500 700	75 85	– –	25 15	– –
L-170	300	3.7	21.5	24	700	60	–	40	–
L-171	301	17.0 (15.2)	20.0 (20.3)	24	700	–	100	–	–[c]
L-172	302	10.2 (9.3)	20.0 (20.6)	24	700	–	90	10	–
L-174	304	9.7 (8.6) (8.6)	6.0 (6.0) (5.9)	72 24	500 700	40 30	60 70	– –	– –
L-175	305	9.7 (8.2)	9.0 (8.9)	24	700	20	80	–	–
L-176	306	9.7 (9.8) (9.8)	11.0 (9.6) (9.6)	72 24	500 700	– –	90 100	10 –	– –
L-179	307	1.3 (1.05)	15.0 (14.6)	24	700	75	–	20	5[d]
L-180	308	0.8 (0.95)	15.0 (6.4)	24	700	100	–	–	–
L-181	309	15.0	4.6	24	700	–	100	–	–
L-182	310	10.2 (10.3)	15.0 (13.7)	24	700	–	100	–	–

TABLE XXII (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ZINC ALLOYS

		Intended Composition and (Chemical Analysis)		Heat Treatment[a]		Phases Present and Estimation of Relative Amounts (%)			
Alloy	Extrusion Charge	Li (wt.%)	Zn (wt.%)	Time (Hr)	Temp (°F)	Alpha	Beta	MgLiZn	Other
L-183	311	11.4 (12.5)	15.0 (14.7)	24	700	-	100	-	-c
L-184	312	10.0 (9.7)	5.8 (5.8)	72	500	5	95	-	-
		(9.6)	(5.8)	24	700	-	100	-	-
L-185	313	5.8 (5.4)	11.0 (11.1)	72	500	45	30	25	-
		(5.3)	(11.1)	24	700	70	25	5	-
L-186	314	9.1 (9.2)	11.0 (10.9)	72	500	20	65	15	-
		(8.7)	(11.1)	24	700	-	100	-	-
L-187	315	9.1 (8.5)	12.0 (11.8)	72	500	20	60	20	-
		(8.5)	(11.8)	24	700	-	100	-	-
L-188	316	10.2 (9.5)	13.0 (12.9)	72	500	-	75	25	-
		(9.6)	(12.9)	24	700	-	100	-	-
L-189	317	11.4 (11.0)	13.0 (13.3)	24	700	-	100	-	-c
L-190	318	13.6 (12.8)	17.0 (16.8)	24	700	-	100	-	-c
L-191	319	13.6 (13.3)	19.0 (19.0)	24	700	-	95	5	-c
L-192	320	17.0 (16.6)	22.0 22.2	24	700	-	95	5	-c
L-194	321	1.3 (1.30)	7.0 (6.4)	24	700	100	-	-	-
L-195	322	1.3 (1.26)	7.0 (6.6)	24	700	100	-	-	-

TABLE XXII (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ZINC ALLOYS

Alloy	Extrusion Charge	Intended Composition and (Chemical Analysis) Li (wt.%)	Zn (wt.%)	Heat Treatment[a] Time (Hr)	Temp (°F)	Phases Present and Estimation of Relative Amounts (%) Alpha	Beta	MgLiZn	Other
L-196	323	1.3 (1.16) (1.16)	8.0 (7.7) (7.7)	72 24	500 700	85 100	- -	15 -	- -
L-197	324	2.5 (2.1) (2.1)	8.0 (9.1) (9.1)	72 24	500 700	80 80	- -	20 20	- -
L-198	325	2.5 (2.8)	9.0 (8.4)	24	700	80	-	20	-
L-219	351	9.5	2.0	- 72 24	- 500 700	35 40 25	65 60 75	- - -	- - -
L-220	352	9.0	4.0	- 72 24	- 500 700	30 30 20	70 70 80	- - -	- - -
L-221	353	4.5	4.0	- 72 24	- 500 700	95 85 100	- - -	5 15 -	- - -
L-222	354	4.0	6.0	- 72 24	- 500 700	- 80 100	- - -	- 20 -	- - -
L-223	355	8.5 (8.5)	13.5 (13.2)	- 72 24	- 500 700	- - -	- - 80	- - 20	- - -
L-224	356	9.5 (9.1)	16 (15.9)	- 72 24	- 500 700	- - -	- - 95	- - 5-	- - -
L-225	357	4.0	8.5	- 72 24	- 500 700	- - 90	- - -	- - 10	- - -

TABLE XXII (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ZINC ALLOYS

Alloy	Extrusion Charge	Intended Composition and (Chemical Analysis)		Heat Treatment[a]		Phases Present and Estimation of Relative Amounts (%)			
		Li (wt.%)	Zn (wt.%)	Time (Hr)	Temp (F)	Alpha	Beta	MgLiZn	Other
L-226	358	4.0	9.5	-	-	-	-	-	-
				72	500	-	-	-	-
				24	700	80	20	-	-
L-227	359	5.0	10.5	-	-	-	-	-	-
				24	700	70	20	10	-
L-228	360	1.0	9.0	-	-	-	-	-	-
				72	500	75	-	25[f]	-
		(0.5)	(8.8)	24	700	90	-	10	-
L-229	341	12.0	7.5	-	-	-	100	-	-
				72	500	-	100	-	-
L-230	342	15.0	7.5	-	-	-	100	-	-
				72	500	-	100	-	-[c]
L-231	343	15.0	9.0	-	-	-	100	-	-
				72	500	-	100	-	-
L-232	344	15.0	11.0	-	-	-	100	-	-[c]
				72	500	-	100	-	-[c]
L-233	345	15.0	12.5	-	-	-	95	5	-[c]
				72	500	-	100	-	-[c]
L-234	361	2.5 (2.0)	3.0 (2.8)	-	-	-	-	-	-
				72	500	95	-	5	-
L-236	363	0.25	15.0	-	-	-	-	-	-
				72	500	65	-	35[f]	-
L-237	378	4.0	15.5	24	700	80	10	10	-
L-238	380	4.2 (4.6)	16.5 (17.2)	24	700	83	5	12	-
L-239	381	4.7 (4.1)	8.0 (7.7)	24	700	95	-	5	-

TABLE XXII (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ZINC ALLOYS

Alloy	Extrusion Charge	Intended Composition and (Chemical Analysis)		Heat Treatment[a]		Phases Present and Estimation of Relative Amounts (%)			
		Li (wt.%)	Zn (wt.%)	Time (Hr)	Temp (°F)	Alpha	Beta	MgLiZn	Other
L-240	382	10.0	15.5	24	700	–	100	–	–
L-241	383	10.0	16.5	24	700	–	100	–	–
L-242	379	2.0 (1.8)	8.5 (8.4)	24	700	95	–	5	–
L-243	393	4.5 (4.5)	5.0 (4.9)	24	700	95	5	–	–
L-244	384	0.5 (0.6)	8.0 (8.1)	24	700	97	–	3	–
L-246	395	1.0	17.5	24	700	90	–	10	–
L-258	399	20.0	17.5	72	500	–	100	–	–
L-259	400	20.0	18.5	72	500	–	100	–	–
L-260	401	20.0	20.0	72	500	–	100	–	–
L-261	402	15.0	12.5	72	500	–	100	–	–[c]
L-262	403	15.0	13.5	72	500	–	100	–	–[c]
L-263	404	15.0	14.5	72	500	–	100	–	–
L-264	405	12.5	9.0	72	500	–	100	–	–
L-265	406	12.5	10.0	72	500	–	100	–	–[c]

TABLE XXII (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS
AND CONSTITUTION OF
MAGNESIUM-LITHIUM-ZINC ALLOYS

Alloy	Estrusion Charge	Intended Composition and (Chemical Analysis) Li (wt.%)	Zn (wt.%)	Heat Treatment[a] Time (Hr)	Temp (°F)	Phases Present and Estimation of Relative Amounts (%) Alpha	Beta	MgLiZn	Other
L-266	407	12.5	11.5	72	500	–	100	–	–[c]
L-267	408	1.0	10.0	72	500	80	–	?	20[e]
				24	700	95	–	5	–
L-268	409	0.5	10.0	72	500	85	–	?	15[e]
		(0.6)	(9.8)	24	700	97	–	3	–
L-269	410	0.2	10.0	72	500	60	–	?	40[e]
		(0.3)	(10.2)	24	700	93	–	2	5[d]
L-270	411	2.5	20.0	72	500	55	–	?	45[e]
				24	700	75	–	25	–
L-271	412	2.0	20.0	72	500	50	–	?	50[e]
				24	700	82	–	18	–
L-272	413	1.5	20.0	72	500	60	–	?	40[e]
				24	700	85	–	15	–
L-273	414	0.5	20.0	72	500	55	–	?	45[e]
				24	700	85	–	15	–
L-274	415	0.2	20.0	72	500	55	–	?	45[e]
		(0.3)	(19.6)	24	700	86	–	7	7[d]
L-275	416	3.0	30.0	72	500	50	–	?	50[e]
				24	700	65	–	35	–
L-276	417	2.5	30.0	72	500	60	–	?	40[e]
				24	700	70	–	30	–

TABLE XXII (Cont'd)

INTENDED COMPOSITION, CHEMICAL ANALYSIS AND CONSTITUTION OF MAGNESIUM-LITHIUM-ZINC ALLOYS

Alloy	Extrusion Charge	Intended Composition and (Chemical Analysis)		Heat Treatment[a]		Phases Present and Estimation of Relative Amounts (%)			
		Li (wt.%)	Zn (wt.%)	Time (Hr)	Temp (°F)	Alpha	Beta	MgLiZn	Other
L-277	418	1.5	30.0						
				72	500	40	–	?	60[e]
				24	700	70	–	30	–
L-278	419	0.5	30.0						
		(0.7)	(29.6)	72	500	55	–	?	45[e]
				24	700	80	–	15	5[d]
L-279	420	0.2	30.0						
		(0.36)	(29.4)	72	500	60	–	?	40[e]
				24	700	70	–	5	25[d]
L-280	421	20.0	21.0						
				72	500	–	100	–	–
L-281	422	20.0	22.0						
				72	500	–	100	–	–
L-282	423	20.0	23.0						
				72	500	–	100	–	–
L-283	424	20.0	24.0						
				72	500	–	100	–	–
L-285	426	15.0	15.0						
				72	500	–	100	–	–[c]
L-286	427	15.0	16.0						
				72	500	–	100	–	–[c]
L-287	428	15.0	17.0						
				72	500	–	100	–	–[c]
L-293	433	12.5	12.5						
				72	500	–	95	5	–[c]
L-294	434	12.5	13.5						
				72	500	–	95	5	–[c]
L-295	435	12.5	15.0						
				72	500	–	95	5	–[e]

See next page for footnotes.

a.   Specimens for which no heat treatment is specified were examined in the as extruded condition.

b.   Secondary phase not identified.

c.   Precipitated $MgLi_2Zn$ present in specimen

d.   Specimen contained grain boundary and eutectic melting.

e.   Specimen contained $MgLiZn$ with or without a third unidentified secondary phase.

f.   Identified by X-ray diffraction method.

TABLE XXIII

INTERPLANAR SPACING (d) AND RELATIVE LINE INTENSITY (I/Is) FOR PHASES IN MAGNESIUM-LITHIUM-ALUMINUM ALLOYS

$Mg_{17}Al_{12}$ Hanawalt Card No. 2887		$AlLi$ Data from Dow Chemical Co.		$MgLi_2Al$ Data from Dow Chemical Co.	
d	I/Is	d	I/Is	d	I/Is
2.64	0.07	3.67	75	3.85	21
2.48	1.00	2.25	100	2.36	100
2.24	0.33	1.915	25	2.03	3
2.15	0.12	1.590	10	1.675	10
2.06	0.20	1.455	8	1.535	2
1.92	0.01	1.298	25	1.362	17
1.81	0.01	1.218	15	1.285	2
1.75	0.01			1.182	3
1.71	0.01			1.133	2
1.60	0.02			1.058	2
1.52	0.05				
1.490	0.10				
1.434	0.33				
1.412	0.04				
1.386	0.05				
1.342	0.06				
1.245	0.10				
1.196	0.01				
1.165	0.03				
1.140	0.03				
1.115	0.04				

TABLE XXIV

INTERPLANAR SPACING (d) AND RELATIVE LINE INTENSITY (I/Is) FOR PHASES IN MAGNESIUM-LITHIUM-ZINC ALLOYS

MgZn Hanawalt Card[7] No. 3156		MgZn$_2$ Hanawalt Card[7] No. 3185		MgLiZn Data from Dow Chemical Co.		MgLi$_2$Zn Data from Dow Chemical Co.	
d	I/Is	d	I/Is	d	I/Is	d	I/Is
13.0	0.15	5.2	0.05	4.30	8	3.85	75
10.1	0.15	4.56	0.62	2.63	5	3.35	4
7.0	0.20	4.31	0.35	2.23	100	2.36	100
6.0	0.20	4.02	0.50	2.14	50	2.02	20
4.30	0.30	3.40	0.05	1.86	10	1.67	10
3.99	0.15	3.12	0.07	1.70	8	1.535	6
3.77	0.30	2.85	0.07	1.515	6	1.355	1
3.09	0.10	2.63	0.10	1.430	25	1.285	5
2.79	0.10	2.43	0.62	1.313	15	1.183	6
2.65	0.10	2.35	0.05	1.254	4	1.132	2
2.58	0.15	2.245	0.75	1.175	2	1.057	4
2.50	0.20	2.20	1.00	1.132	4		
2.42	0.20	2.14	0.30	1.119	8		
2.355	0.50	2.065	0.05	1.070	2		
2.29	0.40	2.005	0.05	1.038	1		
2.225	1.00	1.945	0.87	0.992	1		
2.15	0.10	1.881	0.05	0.966	8		
2.105	0.10	1.830	0.07	0.928	1		
2.06	0.15	1.780	0.35	0.874	1		
1.931	0.10	1.715	0.15	0.857	3		
1.882	0.10	1.671	0.10	0.852	3		
1.836	0.10	1.605	0.05	0.828	1		
1.778	0.15	1.557	0.05	0.813	1		
1.715	0.10	1.507	0.05				
1.649	0.10	1.470	0.15				
1.588	0.10	1.430	0.25				
1.544	0.10	1.399	0.05				
1.487	0.15	1.372	0.40				
1.460	0.10	1.340	0.20				
1.432	0.30	1.310	0.40				
		1.282	0.05				

APPENDIX III

TABLE XXV

AVERAGE MECHANICAL PROPERTIES OF MAGNESIUM-CERIUM ALLOYS

Alloy	Intended Comp. (Spectro. Analysis) %Ce	Nominal Rolling Temp. °F Hot	Warm	Heated One Hour at	Kips per sq.in. CYS	TYS	UTS	Elong. % in 2 in.	Static Rupture Energy in-lbs.
R625	1.0	700	--	600°F	17.4	24.3	32.4	8.8	-
R626	1.0	900	-	600	9.5	15.6	24.1	11.2	-
R659	0.8	800	-	550	17.2	22.5	28.4	10.0	13.4
				750	10.0	15.0	27.9	17.7	15.6
R673	1.0	800	--	600	12.7	18.9	28.2	11.4	-
				700	10.3	16.1	30.0	16.3	13.5
R677	0.2	800	-	600	15.6	20.5	26.4	12.8	-
				750	9.2	13.7	26.0	17.0	-
		15% Cold Rolling			15.5	22.6	28.2	4.3	6.8
R680	0.5	800		600	16.5	21.5	27.1	13.3	-
R690	0.5	800		750	8.8	12.7	23.8	17.8	--

TABLE XXVI

AVERAGE MECHANICAL PROPERTIES OF

MAGNESIUM-ALUMINUM-CERIUM ALLOYS

Alloy	Intended Comp. (Spectro. Analysis) %Al	%Ce	Nominal Rolling Temp. °F Hot	Warm	Heated One Hour at	Kips per sq. in. CYS	TYS	UTS	Elong. % in 2 in.	Static Rupture Energy in.-lbs.
R630	0.8 (0.7)	0.2	700	–	540°F	12.2	22.4	32.5	7.0	–
					900	9.4	20.0	31.5	4.2	–
		15% Cold Rolling			700	17.1	–	23.7	0.0	–
R631	0.8 (0.71)	0.2	700	400	400	12.8	21.4	32.4	5.2	8.0
					700	8.5	18.4	31.1	8.2	8.1
		15% Cold Rolling			400	18.4	–	26.6	0.0	–
R636	0.2 (0.17)	0.8	700	–	720	17.3	22.0	31.8	6.2	–
					900	9.1	18.0	31.6	10.0	–
		15% Cold Rolling			700	21.9	25.2	30.4	1.5	–
R637	0.2	0.8	700	400	400	24.2	22.6	27.4	0.8	10.2
		15% Cold Rolling								
R645	0.5	0.5	700	–	540	12.7	19.8	30.6	6.5	–
					900	6.9	19.0	31.4	4.5	–
		15% Cold Rolling			700	20.3	–	19.1	0.0	–

TABLE XXVII

AVERAGE MECHANICAL PROPERTIES OF

MAGNESIUM-ZINC-CERIUM ALLOYS

Alloy	Intended Comp. (Spectro. Analysis) %Zn	%Ce	Nominal Rolling Temp. °F Hot	Warm	Heated One Hour at	Kips per sq. in. CYS	TYS	UTS	Elong. % in 2 in.	Static Rupture Energy in.-lbs.
R613	0.8 (0.73)	0.2 (0.1)	700	400	600°F	16.4	25.4	35.0	22.8	19.2
					750	11.4	21.4	33.2	18.8	18.9
		15% Cold Rolling			400	34.3	38.4	43.7	1.5	-
R614	0.8	0.2	700	-	600	16.2	24.7	33.1	12.5	22.6
					750	12.1	16.2	29.9	14.5	22.0
R623	0.2	0.8	700	-	600	21.8	30.0	35.5	12.2	-
R669	0.8 (0.76)	0.2 (0.24)	700	400	600	14.6	24.3	34.3	20.6	18.9
					750	13.2	22.9	33.9	19.7	18.0
R670	0.2 (0.27)	0.8 (0.99)	700 15% Cold Rolling	-	600	20.3	29.9	35.0	9.5	-
					250	22.1	30.2	35.2	1.5	6.2
R671	0.2 (0.32)	0.8 (0.86)	700 15% Cold Rolling	-	600	23.4	29.6	34.7	8.0	-
					250	21.1	30.2	34.3	1.0	-
R730	0.6 (0.62)	0.1 (0.09)	700		500	7.9	20.1	32.3	7.0	-
					750	8.9	14.8	29.1	9.0	-
			700	400	400	9.4	22.1	32.3	11.0	-
R738	0.8 (0.84)	0.2 (0.16)	750		400	17.7	24.7	31.9	8.5	-
					750	9.4	15.1	29.1	8.0	-
		15% Cold Rolling			750	8.5	13.4	26.2	5.7	-
			750	400	400	25.8	32.9	39.7	7.7	-
					750	10.3	16.7	29.1	5.7	-
R739	0.8 (0.90)	0.2 (0.24)	700		400	26.5	31.3	37.0	12.0	-
					750	12.5	18.5	29.7	9.7	-
		15% Cold Rolling			750	10.9	14.8	27.7	7.7	-
			700	400	400	18.0	26.5	35.7	21.0	-
					750	13.1	19.5	31.3	9.3	-

TABLE XXVII Cont'd

AVERAGE MECHANICAL PROPERTIES OF

MAGNESIUM-ZINC-CERIUM ALLOYS

Alloy	Intended Comp. (Spectro. Analysis) %Zn %Ce		Nominal Rolling Temp. °F Hot	Warm	Heated One Hour at	Kips per sq. in. CYS	TYS	UTS	Elong. % in 2 in.	Static Rupture Energy in.-lbs.
R742	0.8 0.3 (0.76)0.31)		700		600	18.3	28.3	37.1	21.0	-
					650	15.6	21.0	33.5	15.0	-
					750	13.3	17.4	30.7	15.0	-
			700	400	550	18.0	27.9	36.1	10.0	-
					600	14.9	25.2	34.7	15.0	-
					750	11.5	20.6	32.6	14.0	-
R743	0.6 0.5 (0.62)(0.35)		700		600	21.9	30.6	36.8	4.0	-
					700	15.1	23.1	34.2	13.0	-
					800	12.2	19.0	31.9	12.0	-
			700	400	550	24.2	28.4	34.0	2.0	-
					650	17.1	24.8	33.8	12.0	-
					800	11.8	17.2	29.9	18.0	-
R744	0.7 0.5 (0.68)0.50)		700		600	20.8	32.3	38.0	6.0	-
					700	16.0	23.5	34.1	10.0	-
					800	12.3	20.5	31.8	15.0	-
			700	400	600	20.4	28.9	34.8	6.0	-
					700	15.2	22.6	33.7	11.0	-
					800	12.9	18.3	29.7	15.0	-
R745	0.8 0.5 (0.74)(0.47)		700		550	23.6	32.1	38.4	7.0	-
					600	19.1	30.5	38.4	9.0	-
					800	12.9	19.6	31.3	10.0	-
			700	400	550	21.9	28.5	35.6	4.0	-
					600	18.9	26.9	35.2	9.0	-
					800	12.5	16.2	30.0	12.0	-
R747	0.7 0.2 (0.54)(0.23)		700		600	13.8	21.4	30.4	10.0	-
					750	9.1	13.6	28.5	10.0	-
					800	8.5	14.4	28.8	10.0	-
			700	400	500	23.4	30.1	38.1	7.0	-
					600	16.9	26.1	35.2	20.0	-
					800	10.1	15.9	29.4	14.0	-

TABLE XXVII Cont'd

AVERAGE MECHANICAL PROPERTIES OF

MAGNESIUM-ZINC-CERIUM ALLOYS

Alloy	Intended Comp. (Spectro. Analysis) %Zn	%Ce	Nominal Rolling Temp. °F Hot	Warm	Heated One Hour at	Kips per sq. in. CYS	TYS	UTS	Elong. % in 2 in.	Static Rupture Energy in.-lbs.
R754	0.6 (0.51)	0.3 (0.37)	700		600	19.6	30.3	36.0	5.0	–
					650	15.6	23.6	33.8	10.0	–
					750	13.0	19.6	31.6	15.0	–
			700	400	550	25.2	29.0	35.6	6.0	–
					600	19.4	27.9	33.1	13.0	–
					750	13.3	20.1	31.5	13.0	–
R755	0.7 (0.57)	0.3 (0.28)	700		600	21.8	30.8	37.6	10.0	–
					650	16.3	23.9	34.7	13.0	–
					750	13.1	22.6	33.2	13.0	–
			700	400	550	21.3	28.5	36.7	11.0	–
					600	16.9	26.0	35.4	14.0	–
					750	13.0	19.3	31.8	13.0	–
R756	0.8 (0.68)	0.2 (0.22)	700		700	8.3	14.9	28.6	10.0	–
					750	7.7	13.1	27.4	12.0	–
					800	7.7	13.2	28.6	13.0	–
			700	400	450	24.1	31.3	39.1	16.0	–
					600	13.3	25.8	34.8	16.0	–
					800	7.9	20.0	31.6	14.0	–
R757	0.8 (0.78)	0.1 (0.21)	700		400	10.9	23.0	32.6	11.0	–
					650	7.6	21.1	32.3	8.0	–
			700	400	400	14.0	24.8	34.9	14.0	–
					600	9.6	21.3	32.5	13.0	–
R759	0.8 (0.78)	0.2 (0.24)	650		550	16.4	24.7	34.5	20.0	–
					600	12.0	24.6	35.1	14.0	–
					800	9.2	16.7	30.2	15.0	–
			650	400	500	19.7	26.9	37.0	17.0	–
					600	13.5	25.1	34.6	18.0	–
					800	9.6	17.7	31.3	12.0	–
R760	0.7 (0.53)	0.1 (0.18)	700		400	9.6	20.3	31.8	8.0	–
					650	6.8	19.1	31.3	9.0	–
			700	400	400	9.7	23.2	33.6	15.0	–

Alloy	Intended Comp. (Spectro. Analysis) %Zn	%Ce	Nominal Rolling Temp. °F Hot	Warm	Heated one Hour at	Kips per sq. in. CYS	TYS	UTS	Elong. % in. 2 in.	Static Rupture Energy in-lbs.
R761	0.6 (0.46)	0.2 (0.23)	700		600	11.6	21.4	30.2	12.0	-
					750	9.2	13.4	27.5	8.0	-
					800	8.0	13.9	28.1	9.0	-
			700	400	500	23.8	29.5	36.3	4.0	-
					650	13.5	24.1	35.5	12.5	-
					800	9.7	14.9	29.2	11.0	-
R778	1.5 (1.6)	0.3 (0.13)	700	400	450	24.7	30.1	38.6	10.2	-
					575	14.9	25.6	34.6	20.0	-
R781	1.0 (1.0)	0.3 (0.29)	700		500	23.8	30.5	37.5	12.5	-
					600	18.0	27.1	35.4	17.0	-
			700	400	500	17.5	28.0	36.2	21.0	-
					600	14.7	25.6	34.4	18.3	-
R788	0.8 (0.91)	0.3 (0.4)	700		450	22.7	29.7	36.8	19.2	-
					475	22.7	30.2	37.3	20.0	-
			700	400	400	19.7	27.4	36.6	21.5	-
					450	15.5	25.3	35.4	20.0	-
R789	0.8 (1.0)	0.3 (0.27)	700		325	17.0	27.5	34.8	18.5	-
					450	16.8	25.2	35.5	16.3	-
			700	400	400	28.0	32.2	39.9	8.7	-
					550	19.4	27.3	35.5	23.0	-
R791	0.8 (0.9)	0.3 (0.15)	700		600	17.7	28.3	35.7	13.0	-
					675	24.8	30.0	36.2	17.3	-
					700	12.6	18.6	30.8	19.0	-
			700	400	450	28.0	31.5	38.2	11.0	-
					550	19.4	29.9	36.7	18.0	-
					700	12.6	22.7	33.0	22.0	-
R793	0.8 (0.8)	0.3 (0.15)	700		450	19.3	25.0	32.3	11.7	-
					575	15.0	20.6	32.5	20.5	-
			700	400	300	26.0	35.9	39.4	10.5	-
					575	14.5	25.0	34.4	20.0	-

TABLE XXVII Cont'd

AVERAGE MECHANICAL PROPERTIES OF

MAGNESIUM-ZINC-CERIUM ALLOYS

Alloy	Intended Comp. (Spectro. Analysis) %Zn	%Ce	Nominal Rolling Temp. °F Hot	Warm	Heated One Hour at	Kips per sq. in. CYS	TYS	UTS	Elong. % in 2 in.	Static Rupture Energy in-lbs.
R794	1.5 (1.4)	0.6 (0.23)	700		575	18.2	24.3	35.7	15.8	-
					700	13.2	18.0	32.0	17.0	-
			700	400	350	30.1	34.9	42.8	11.3	-
					500	22.0	30.5	38.9	17.0	-
R796	2.0 (2.3)	0.8 (0.37)	700		475	19.6	26.5	36.2	10.5	-
					550	14.6	21.7	34.1	14.5	-
			700	400	300	26.8	34.3	41.4	8.0	-
					425	22.3	29.3	39.3	10.8	-
R798	3.0 (3.3)	0.3 (0.18)	700		500	10.7	22.3	34.9	12.5	-
					550	8.8	24.3	33.9	13.0	-
			700	400	350	17.1	27.2	37.9	18.2	-
					475	13.6	25.1	36.3	18.5	-
R807	1.5 (1.4)	0.6 (0.43)	700		325	18.9	30.7	38.3	12.0	-
			700	400	400	24.6	33.0	40.7	11.0	-
					525	14.3	25.0	35.1	12.0	-
R808	2.0 (2.15)	0.8 (0.64)	700		375	18.9	29.7	36.3	13.0	-
					475	17.8	24.6	34.2	13.5	-
			700	400	375	23.3	32.6	40.0	10.0	-
					500	14.8	25.0	36.6	17.0	-
R809	2.5 (2.5)	1.0 (0.55)	700		400	22.2	30.7	37.0	12.0	-
					550	17.0	24.9	36.3	12.0	-
			700	400	375	26.9	33.8	41.3	6.0	-
					500	17.4	25.6	36.7	13.0	-
R810	1.5 (1.2)	0.6 (0.3)	700		550	16.9	26.8	34.9	12.3	-
					625	16.1	23.6	34.3	7.5	-
			700	400	350	29.3	34.9	42.2	13.0	-
					550	18.9	27.6	37.7	15.0	-
R811	2.0 (1.65)	0.8 (0.4)	700		425	20.5	32.3	37.3	9.5	-
					525	19.8	29.1	36.9	9.0	-
			700	400	450	27.4	34.1	39.2	11.0	-
					600	18.0	25.9	36.8	11.0	-

TABLE XXVII Cont'd

AVERAGE MECHANICAL PROPERTIES OF

MAGNESIUM-ZINC-CERIUM ALLOYS

Alloy	Intended Comp. (Spectro. Analysis) %Zn	%Ce	Nominal Rolling Temp. °F Hot	Warm	Heated One Hour at	Kips per sq. in. CYS	TYS	UTS	Elong. % in 2 in.	Static Rupture Energy in-lbs.
R812	2.5 (2.3)	1.0 (1.1)	700		500	21.5	20.3	35.7	11.0	-
					575	19.4	26.6	36.3	7.0	-
			700	400	475	27.4	34.0	41.3	11.0	-
					600	18.2	27.6	37.8	9.0	-
R813	3.0 (2.5)	1.2 (0.37)	700		425	17.5	26.4	36.1	13.0	-
					525	16.5	22.1	33.3	10.5	-
			700	400	325	23.6	35.1	42.6	13.0	-
					450	15.4	26.5	31.2	12.0	-
R814	1.5 (1.2)	0.3 (0.38)	700		500	20.3	27.6	35.7	11.0	-
					650	12.2	18.4	31.6	10.0	-
			700	400	450	24.5	32.6	40.5	20.5	-
					575	16.8	25.9	36.7	14.0	-
R815	2.0 (2.0)	0.3 (0.3)	700		375	17.9	27.2	36.4	17.0	-
					525	12.9	20.9	34.4	15.2	-
					700	11.2	17.9	34.7	18.2	-
			700	400	350	24.7	33.9	40.9	14.6	-
					525	13.1	25.0	35.8	14.5	-
					700	10.6	23.0	33.5	18.8	-
R817	3.0 (3.2)	0.3 (0.3)	700		400	12.6	25.1	34.3	12.0	-
					525	8.5	18.0	32.4	9.0	-
			700	400	325	17.8	28.5	37.7	15.0	-
					475	10.6	20.9	34.4	8.0	-
R822	2.5 (2.8)	0.3 (0.4)	700		350	19.5	28.3	36.6	16.0	-
					450	14.1	24.1	35.6	11.0	-
			700	400	375	16.5	28.2	38.5	14.5	-
					500	11.9	24.8	34.8	15.0	-
R823	3.0 (3.2)	0.3 (0.34)	700		350	17.6	29.4	37.8	14.5	-
					475	10.5	23.0	34.9	17.0	-
			700	400	375	17.0	27.2	37.9	14.0	-
					500	10.7	23.8	35.8	14.0	-

TABLE XXVII Cont'd

AVERAGE MECHANICAL PROPERTIES OF

MAGNESIUM-ZINC-CERIUM ALLOYS

Alloy	Intended Comp. (Spectro. Analysis) %Zn	%Ce	Nominal Rolling Temp. °F Hot	Warm	Heated One Hour at	Kips per sq. in. CYS	TYS	UTS	Elong. % in 2 in.	Static Rupture Energy in.-lbs.
R824	3.5 (3.4)	0.3 (0.39)	700		350	17.3	28.1	37.4	14.0	—
					500	11.0	23.0	34.9	10.5	—
			700	400	325	18.5	31.1	39.5	14.0	—
					400	16.2	27.3	38.6	14.5	—
R846	1.3 (1.5)	0.5 (0.5)	700		450	21.3	30.6	34.6	16.2	—
					600	17.0	21.0	32.4	18.0	—
					700	12.4	17.5	30.7	19.5	—
			700	400	450	26.8	32.9	39.1	12.7	—
					550	19.3	29.8	36.6	14.5	—
					800	10.7	18.7	30.9	16.2	—
R847	1.3 (1.34)	0.5 (0.36)	700		450	22.5	31.0	36.6	15.3	—
					600	18.2	23.6	34.4	17.7	—
					700	13.9	19.7	32.6	17.5	—
			700	400	350	29.6	36.9	43.2	18.0	—
					550	20.6	29.0	37.6	20.5	—
					800	13.1	22.3	34.2	20.7	—
R848	0.8 (0.68)	0.5 (0.43)	700		450	22.7	32.3	36.5	12.5	—
					650	15.7	20.6	31.7	20.7	—
			700	400	450	31.0	34.3	40.1	2.5	—
					550	23.7	31.9	37.9	15.0	—
					800	12.6	18.0	30.3	17.0	—
R849	0.8 (0.71)	0.6 (0.4)	700		500	25.8	33.0	37.6	11.3	—
					600	22.4	29.7	36.1	20.5	—
					700	19.9	21.1	32.2	20.5	—
			700	400	450	30.4	32.4	41.5	2.2	—
					550	24.6	32.6	38.0	6.0	—
					800	13.9	18.3	30.8	15.2	—
R853	1.2 (1.2)	0.5 (0.6)	700		400	22.7	32.2	37.7	16.7	—
					550	23.3	31.4	37.4	18.0	—
					700	14.5	20.0	32.1	18.0	—
			700	400	400	30.6	34.5	41.7	8.5	—
					500	27.0	32.3	39.5	18.5	—
					750	13.9	22.9	33.4	20.0	—

TABLE XXVII Cont'd

AVERAGE MECHANICAL PROPERTIES OF

MAGNESIUM-ZINC-CERIUM ALLOYS

Alloy	Intended Comp. (Spectro. Analysis) %Zn	%Ce	Nominal Rolling Temp. °F Hot	Warm	Heated One Hour at	Kips per sq. in. CYS	TYS	UTS	Elong. % in 2 in.	Static Rupture Energy in.-lbs.
R855	1.5 (1.45)	0.6 (0.45)	700		400	22.1	32.9	36.4	16.7	-
					600	15.8	21.3	33.3	21.7	-
					700	14.0	15.5	32.0	19.0	-
R856	2.0 (1.72)	0.8 (0.70)	700		450	23.1	29.8	36.6	14.8	-
					600	16.2	21.2	33.6	20.2	-
					700	15.3	19.8	32.8	19.0	-
			700	400	300	31.8	36.5	43.2	5.8	-
					500	18.8	29.8	37.6	16.8	-
					800	10.5	20.1	31.0	16.0	-
R857	1.3 (1.00)	0.5 (0.65)	700		540	22.2	29.8	36.2	15.3	-
					650	14.4	19.5	32.3	19.0	-
					800	12.3	17.2	30.3	19.5	-
			700	400	300	33.4	38.5	44.3	15.5	-
					500	25.2	32.5	38.9	19.0	-
					800	10.8	21.5	32.4	16.5	-
R869	1.4 (1.4)	0.55 (0.7)	700		300	25.0	34.9	42.9	5.5	-
					450	24.0	31.0	36.6	13.7	-
					600	16.9	22.3	33.5	14.7	-
			700	400	300	32.2	31.0	39.4	11.1	-
					450	26.7	31.5	37.0	14.2	-
R870	2.2 (2.2)	0.9 (0.7)	700		250	31.7	35.7	43.1	9.5	-
					400	24.5	31.0	38.8	14.3	-
					550	17.9	22.9	33.8	12.7	-
			700	400	300	25.4	30.2	38.8	13.3	-
					425	24.5	31.9	39.4	14.3	-
					550	17.3	27.0	36.4	14.3	-

TABLE XXVIII

AVERAGE MECHANICAL PROPERTIES OF MAGNESIUM-0.9% ZINC

0.4% CERIUM AFTER COLD ROLLING AND HEAT TREATING

% Cold* Reduction	Heated One Hour at	Kips per sq. in.			Elong. % in 2 in.
		CYS	TYS	UTS	
10	550°F	18.8	28.6	35.7	15.8
	675	14.1	21.5	33.4	16.5
	800	11.0	15.6	30.5	21.5
15	450	20.2	27.3	33.8	9.7
	600	16.6	23.5	32.9	12.8
	675	10.8	15.3	29.6	23.7
20	350	21.9	27.8	35.2	10.2
	500	20.3	25.9	34.0	12.7
	650	13.0	17.6	31.2	23.8
25	300	21.6	27.6	34.9	6.5
	475	20.1	25.4	35.8	8.8
	600	13.6	17.1	31.2	20.0

*Specimens were hot rolled at 700°F and
heated one hour at 700°F before cold rolling.

TABLE XXIX

AVERAGE MECHANICAL PROPERTIES OF MAGNESIUM-ZIRCONIUM ALLOYS

Alloy	Intended Comp. (Spectro. Analysis) %Zr	Nominal Rolling Temp. °F Hot	Warm	Heated One Hour at	Kips per sq. in. CYS	TYS	UTS	Elong. % in 2 in.	Static Rupture Energy in.-lbs.
R681	0.2	700	400	400°F	9.7	19.5	27.3	5.8	-
				700	6.3	19.1	29.8	4.8	-
R682	0.2 (0.01)	700		350	11.1	18.7	27.6	5.0	-
				650	5.4	17.4	29.2	6.0	-
R684	0.5	700	400	500	20.1	21.7	28.2	1.7	-
				750	8.0	17.3	28.9	8.5	-
		15% Cold Rolling		400	22.1	22.6	25.0	0.7	3.0
R686	0.5 (0.17)	700		500	14.4	20.1	28.3	5.3	-
				800	7.5	18.2	29.5	11.7	-
		15% Cold Rolling		700	13.8	20.9	26.6	1.5	2.9
R687	0.8	700	400	400	-	18.2	23.2	1.5	9.8
		15% Cold Rolling		400	21.2	19.8	26.5	2.5	4.9
R688	0.8 (0.17)	700		700	7.7	18.2	29.9	11.2	-
				800	7.4	17.4	29.0	12.7	-
		15% Cold Rolling		700	15.1	22.9	28.6	2.5	3.9
R690	1.0	700		700	9.5	16.2	28.8	9.5	10.5
		15% Cold Rolling		700	12.4	19.2	21.1	1.2	1.3
R691	1.0 (0.23)	700	400	500	17.2	17.4	23.4	2.2	-
R693	1.0 (0.18)	700		700	11.0	18.3	29.4	12.0	-
		15% Cold Rolling		700	14.1	22.2	26.8	2.0	-
R694	1.0 (0.20)	700	400	500	17.5	20.3	24.3	1.8	-
R751	0.1 (0.1)	700		-	12.2	13.2	24.9	7.5	-
				700	6.0	13.7	25.0	6.0	-
		700	500	-	12.2	13.1	24.5	6.0	-

TABLE XXIX Cont'd

AVERAGE MECHANICAL PROPERTIES OF MAGNESIUM-ZIRCONIUM ALLOYS

Alloy	Intended Comp. (Spectro. Analysis) %Zr	Nominal Rolling Temp. °F Hot	Warm	Heated One Hour at	Kips per sq. in. CYS	TYS	UTS	Elong. % in 2 in.	Static Rupture Energy in.-lbs.
R752	0.1 (0.09)	700 700	500	600°F – 700	10.7 15.0 7.6	15.0 13.6 13.5	25.7 23.7 25.4	5.5 4.7 5.0	– – –
R753	0.1 (0.20)	700 700	500	500 –	11.2 11.6	22.8 13.6	32.4 23.7	7.8 5.8	– –
R766	0.5 (0.44)	700 700	500	475 575 600 700	22.3 14.8 8.5 7.3	22.8 22.1 17.4 16.8	32.4 32.3 30.8 30.6	7.5 7.7 8.0 11.0	– – – –
R767	1.0 (0.73)	700 700	500	600 750 500 700	10.2 6.9 13.4 7.1	13.7 13.4 13.8 12.9	26.3 27.3 25.8 26.2	6.8 7.7 8.3 7.8	– – – –
R769	1.0 (0.76)	700 700	500	500 600 700	12.7 9.4 7.9	14.5 14.0 13.5	25.6 26.7 26.0	9.0 7.5 7.7	– – –
R771	1.0 (0.59)	700 700	500	450 600 550	14.9 9.8 12.7	13.3 12.0 14.6	24.4 26.6 26.8	8.0 7.3 8.2	– – –
R772	1.0 (0.55)	700 700	500	600 700 550 750	10.1 7.5 12.1 6.8	13.1 13.7 15.4 13.3	27.0 26.3 26.3 25.4	7.3 7.0 7.3 6.0	– – – –

TABLE XXX

AVERAGE MECHANICAL PROPERTIES OF MAGNESIUM-ZINC ZIRCONIUM ALLOYS

Alloy	Intended Comp. (Spectro. Analysis) %Zn	%Zr	Nominal Rolling Temp. °F Hot	Warm	Heated One Hour at	Kips per sq. in. CYS	TYS	UTS	Elong. % in 2 in.	Static Rupture Energy in-lbs.
R695	0.2 (0.17)	0.8 (0.17)	700	–	500°F	14.4	23.2	31.2	12.7	13.2
					750	9.8	19.4	31.6	13.3	–
		15% Cold Rolling			700	13.9	28.4	32.1	1.3	4.1
R696	0.5 (0.43)	0.5 (0.15)	700	–	350	19.4	23.9	31.9	11.3	10.8
					700	10.8	19.3	30.6	16.3	–
		15% Cold Rolling			700	15.8	–	20.6	0.0	1.0
R698	0.5	0.5	700	400	325	17.7	24.8	34.5	6.8	8.9
					700	8.8	19.5	31.4	11.7	–
		15% Cold Rolling			400	19.6	28.6	30.8	0.5	2.8
R699	0.8	0.2	700	–	700	14.3	–	27.3	0.0	1.6
		15% Cold Rolling								
R702	0.8	0.2	700	400	325	13.9	24.8	34.1	7.0	8.7
					700	6.8	19.9	31.3	12.5	–
		15% Cold Rolling			400	15.4	–	14.6	0.0	0.7
R873	0.2 (0.29)	0.8 (0.99)	500	–	400	28.7	29.5	38.6	8.7	–
					500	29.1	28.9	38.1	8.8	–
					600	14.5	24.6	36.2	12.5	–
R874	0.5 (0.64)	0.5 (0.39)	500	–	250	34.5	32.6	43.2	8.2	–
					400	34.1	33.5	42.8	8.3	–
					550	20.3	28.2	37.4	11.3	–
R875	0.8 (0.75)	0.2 (0.15)	500	–	250	25.9	29.4	38.1	5.2	–
					375	20.1	25.4	35.4	9.8	–
					500	13.7	21.3	31.5	22.0	–