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# R&D AND EVALUATION OF A LIGHTWEIGHT, HIGH STRENGTH MAGNESIUM ALLOY

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by

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## ABSTRACT

Continued evaluation of Mg-30Sc indicates that this alloy offers the best combination of room temperature strength and ductility in the as-extruded condition. Heat treatment at 950°F provides higher strength at 600°F (20 vs 12 ksi TYS) at the expense of slightly lower room temperature strength (46 vs 53 ksi TYS). The alloy has a modulus of 8.0 x $10^6$ psi and excellent cold bendability (1.5 t) and notch toughness.

Preliminary data indicate that the alloy has susceptibility to stress corrosion.

Mg-10Sc-5Li was selected for evaluation on a larger scale on the basis of mini-scale research. A five pound melt of this alloy reacted with the alumina crucible, but a 3" diameter billet large enough for extrusion into 1/16" x 7/8" strip was recovered. Evaluation of this strip is in progress.

Further work at the mini-scale level indicates that Mg-15Sc-9Ag offers the highest CYS (58 ksi) in the T6 temper of any of the Mg-Sc-Ag ternaries evaluated. Mg-Sc-Y alloys also offer high strength. Mg-15Sc-15Y, for example, is as strong (58 ksi CYS) as Mg-30Sc in the as-extruded condition but not as ductile.

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## INTRODUCTION

Prior research has shown that Mg-30Sc offers an excellent combination of properties. Evaluation of this alloy, in the form of extruded 1/16" x 1 1/4" strip, was continued during the current quarter. Work on a mini-scale has also shown that the addition of other elements provides high strength at much lower Sc levels. The optimum composition of Mg-Sc-Li, one of the most promising ternaries, was determined, and this alloy was processed on a normal laboratory scale. Two other promising ternaries, Mg-Sc-Ag and Mg-Sc-Y, were extensively studied on the mini-scale in order to select another alloy for more intensive evaluation.

## SUMMARY OF EXPERIMENTAL WORK

1) Heat treatment of the Mg-30Sc extrusion at 950°F increased TYS at 600°F from 12 to 20 ksi and decreased room temperature TYS from 53 to 46 ksi. Heat treatment of Mg-30Sc at 1250°F and cooling at $\sim$ 37°F/min. decreased room temperature strength (53 to 43 ksi TYS) and ductility (14 to 3.5% elongation).

2) More extensive testing of the Mg-30Sc extrusion indicated a tensile modulus of $8.0 \times 10^6$ psi in the as-extruded condition and $7.0\text{-}7.5 \times 10^6$ psi after heat treatment at 1250°F. The minimum bend radius (1.5 t) and notch bend toughness (13-17 in. lbs.) of Mg-30Sc were better than similar values for conventional Mg alloys (e.g., AZ31B). A notched tensile bar failed through the pin hole at 43 ksi. Stress corrosion bars failed in a rural atmosphere within 10 days at a stress of 30 ksi and within 17 days at 20 ksi.

3) A Li content of 5.5-6% produced maximum CYS (52 ksi) at a Sc level of 10%. Still higher CYS (65 ksi) in the T6 temper was obtained with Mg-15Sc-4Li.

4) A 5-pound melt of Mg-10Sc-5.5 Li reacted with the alumina crucible, and only about one-third of the metal was cast into a 3" diameter billet. The billet was extruded into 1/16" x 7/8" strip at 1 fpm. Severe die loading occurred at 10 fpm.

5) Mg-20Sc-6Ag had high strength in the as-extruded (65 ksi CYS) and T6 (56 ksi CYS) tempers. Slightly higher CYS (58 ksi) was obtained in the T6 temper with Mg-15Sc-9Ag. The low solidus (<950$^{\circ}$F) of this alloy seriously limited extrudability.

6) Yttrium was substituted for a large amount of Sc without sacrificing the high strength obtainable with Mg-Sc (e.g., Mg-30 Sc). However, at the higher alloy levels, Y impaired ductility and was not as effective in forming $\beta$ as Sc.

## CONCLUSIONS

Mg-30 Sc has an excellent combination of properties in the as-extruded condition, although stress corrosion resistance may impair its utility.

Three ternaries - Mg-Sc containing Li, Ag, or Y - offer high strength at relatively low Sc levels (e.g., 15%).

## RECOMMENDATIONS

Evaluation of Mg-30Sc and Mg-Sc ternaries should be continued in order to develop the most promising alloys.

## EXPERIMENTAL WORK

The extensive survey of Mg-Sc alloys was performed on a miniscale. Melts of about 100 grams were prepared in alumina crucibles and cast by pouring directly into the 3/4" diameter cavity of a graphite mold. Cylindrical sections of the casting were scalped and extruded from a 3/4" container into 1/8" diameter wire. Samples of the wire were tested in tension and compression. The effect of heat treatment was determined by compression testing and metallography.

During this quarter we processed Mg-10Sc-5Li on a normal laboratory scale for the first time. The procedure was very similar to that used for Mg-30Sc. Sublimed Mg (1895 grams) was melted in an alumina crucible supported in a steel can. A low density flux (85% KCl, 14% $MgCl_2$, 1% $CaF_2$) was used for protection. When the Mg was melted and heated to $\sim$ 1450°F, this flux was skimmed off and replaced by one free of $MgCl_2$ (57% KCl, 28% $CaCl_2$, 12.5% $BaCl_2$, 2.5% $CaF_2$). The Sc (250 grams) was added, and the melt was held at 1450°F for 2.5 hours to assure dissolution (which was apparently completed after 2 hours). The temperature was reduced to 1400°F, the flux was replaced with one (45% KCl, 33.8% $LiCl_2$, 11.2% LiF, 10% $MgCl_2$) especially designed for Mg-Li melts, and the Li (125 grams) was added. The melt was stirred and then poured - a small sample into a mold for analytical purposes and the balance into a 3" diameter billet mold. After about one-third of the metal was poured, flow from the crucible ceased. The remainder of the melt had thickened, apparently due to reaction with the crucible.

Several tests were later run to try to learn more about the reaction between melt and crucible. Mg-5Li was melted and held in an alumina crucible with no apparent reaction. A piece of the alumina crucible, in which the Mg-10Sc-5Li melt was made, was immersed and held in the Mg-5Li melt with no obvious attack. Finally a small melt of Mg-10Sc was prepared in an alumina crucible and sampled. Then 5% Li was added and samples taken immediately and 15 minutes later. The melt was then decanted into a steel pot, held for another 15 minutes and cast into a 3/4" diameter mold.

## DISCUSSION

### Evaluation of Mg-30Sc

Mg-30Sc has an excellent combination of strength (53 ksi yield), hardness ($\sim 62R_B$), and ductility (14% elongation) in the as-extruded condition. It also has good properties at elevated temperatures. As shown on the next page, yield strength at 600°F in this temper is 12 ksi, which is comparable to that of HM31A, the best commercial Mg extrusion alloy for service at high temperatures. The high elongation and tensile strength at 600°F suggest that Mg-30Sc may be behaving "superplastically" because of its fine grain size. A sample of the extrusion was heat treated at 950°F for 24 hours to coarsen its microstructure in the hope of reducing grain boundary sliding and, hence, increasing strength at 600°F. As shown below, strength at 600°F was markedly increased by this treatment although room temperature strength was decreased somewhat. This combination of properties at room and elevated temperatures offered by Mg-30Sc far surpasses that of any Mg alloy yet developed.

|  | 75°F* |  |  |  |  | 600°F* |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
| Heat Treatment | %E | TYS | CYS | TS | E | %E | TYS | TS | E |
| None | 14 | 53 | 53 | 59 | 7.5 | 74 | 12 | 24 | 6.1 |
| 950°F** | 13 | 46 | 48 | 53 | 7.2 | 4 | 20 | 30 | 6.3 |
| 1250°F Q 450°F | -- | 72 | 61 | -- | 8.0 | -- | -- | -- | -- |

*Strength as $10^3$ psi, modulus (E) as $10^6$ psi
**1 hour for 75°F, 16 hours for 600°F

As shown above, even higher strength can be obtained by heat treatment at 1250°F to form $\beta$, quenching, and aging at 450°F to decompose the $\beta$ into $\alpha + \beta'$ (ordered $\beta$). Unfortunately, ductility is exhausted and the strip warps badly during quenching. Varying heat treatment conditions to provide a better combination of strength and ductility has been extensively studied but has thus far been unsuccessful. Increasing aging temperature to 700-900°F produces a sharp drop in hardness (from >70 to $<50R_B$) as aging time is increasing. Producing an alloy with intermediate hardness (strength) by this technique might therefore be difficult to control. Another method of accomplishing this is to control the cooling rate from 1250°F so that part of the $\beta$ is decomposed during cooling into a comparatively coarse structure. As shown on the next page, little change in hardness in the T6 temper was effected when cooling rate was decreased from 1920 to 212°F/sec. in spite of the fact that considerable decomposition of $\beta$ occurred at the lower rates. Decreasing the cooling rate to 68°F/sec. and below did reduce hardness.

| Cooling Method | Cooling Rate | Hardness - $R_B$ | |
|---|---|---|---|
| | | As-Cooled | Aged |
| Cold Water | $\sim 1900^{\circ}$F/sec. | 43,41 | 85,88 |
| Oil | $\sim 1600$ | 50,37 | 82,84 |
| Hot Water | $\sim 700$ | 51,44 | 83,88 |
| Between Cu Plates | 268 | 50 | 83 |
| Between Steel Plates | 212 | 50 | 88 |
| Forced Air | 68 | 67 | 75 |
| On Platen | 42 | 59 | 67 |
| Still Air | 28 | 64 | 65 |
| Sandwiched in Steel | 0.4 | — | 51 |

Since intermediate hardness was obtained by simply air cooling Mg-30Sc from $1250^{\circ}$F, we selected this condition for testing. The cooling rate ($38^{\circ}$F/sec.) and hardness ($69R_B$) of the test strip (6 1/2" long) were somewhat higher than the values obtained with small pieces but still quite suitable. More important was the fact that the air-cooled strip warped as badly as the water-quenched sample. This suggests that warping is due primarily to the $\alpha - \beta$ transformation rather than thermal strain introduced by rapid quenching. To avoid warpage of the test bar and still obtain the desired cooling rate, we sandwiched the sample between two flat strips of 1/16" steel, welded the steel strips together, heated the composite to $1250^{\circ}$F, and quickly placed it between two copper plates about 1/2" thick. A cooling rate of $37^{\circ}$F/sec. was obtained, and the Mg-30Sc strip remained flat. The hardness of the Mg-30Sc strip was $68R_B$ after cooling and $74R_B$ after aging 24 hours at $450^{\circ}$F. Tensile testing yielded 3.5% elongation, 43 ksi yield and 49 ksi ultimate strength. It is interesting to compare these results with those obtained in the as-extruded condition. In spite of higher hardness the heat treated strip is not as strong nor as ductile.

Since heat treatment failed to improve the room temperature properties of Mg-30Sc, we decided to use the as-extruded condition for more extensive testing of Mg-30Sc. These tests are described on the next page.

Modulus - The modulus of Mg-30Sc determined from conventional tensile tests has varied from 6.7 to 7.5 x $10^6$ psi. More accurate measurement of strain with Tuckerman gages yielded a value of 8.0 x $10^6$ psi for the as-extruded condition and 7.0 and 7.5 x $10^6$ psi for the bar cooled at 37°F/sec. from 1250°F.

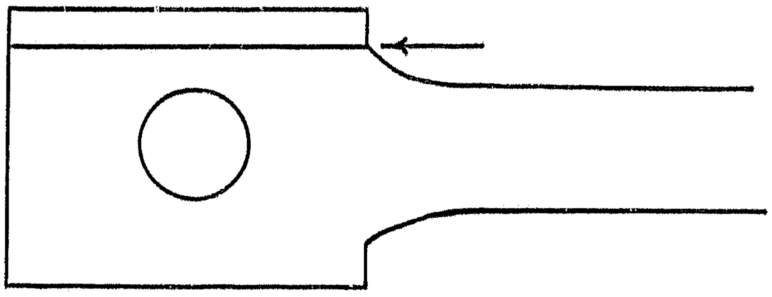
Minimum Bend Radius - Samples from the nose and butt of the Mg-30Sc extrusion were bent 90° longitudinally over a mandrel with a radius of 3/32" (1.5 t) without cracking. Cracking occurred with a radius of 1/16" (1 t). The minimum bend radius of 1.5 t for Mg-30Sc compares favorably with that of extruded AZ31B-F (2.4 t) and particularly 7075-T6 (4-6 t).

Notch-bend Toughness - The relative toughness of Mg alloys is determined by the energy required to break a notched bar. A specimen about 3" long and 1/16" thick is notched (60°V, 0.004" radius) on one end to form a reduced section 1/2" wide. This end of the bar is clamped at the notches and the other end is gradually raised until fracture occurs in bending. Integration of the load-deflection curve obtained gives the energy required for rupture. As shown below, the notch-bend energy of Mg-30Sc is well above that of other Mg alloys.

| Alloy | Energy - in. lbs. |
|---|---|
| Mg-30Sc | 16.7,13.4 |
| AZ31B-H24 | ~11 |
| AZ61A-H24 | ~4 |

Notch Sensitivity - To determine notch sensitivity a 60°V-notch (0.0004" radius) was machined from each side in the 1" wide reduced section of a tensile specimen to a width of 0.7". During testing failure occurred at 1576 pounds (43 ksi) through the pin hole in the shoulder of the bar. When the bar was rerun using conventional grips, failure occurred at 1380 pounds (37.7 ksi) through the notches. (This lower value can be ignored because it merely means that the bar was not properly aligned when tested with conventional grips). If we use the first value, we get a notched/unnotched ratio of tensile strength of >0.73. The Mg-30Sc extrusion, therefore, is not particularly notch-sensitive when tested in the longitudinal direction.

Stress-Corrosion - Tensile bars of Mg-30Sc were loaded to stresses of 20 and 30 ksi in a rural atmosphere ($\sim$5 miles away from Midland). Failure occurred within 10 days at 30 ksi and within 17 days at 20 ksi. The bar loaded at 30 ksi broke through the pin hole in the shoulder, while the one loaded at 20 ksi broke through the reduced section. These tests indicate that the stress corrosion resistance of the alloy is not good. A part of the shoulder of one bar was found to have broken off longitudinally. The plane of fracture corresponded to the intersection of the reduced section with the flat shoulder of the bar (see sketch). This observation indicates the need for further tests in the transverse direction on this material.



### Evaluation of Mg-Sc-Li

Evaluation of many Mg-Sc ternaries on a mini-scale (Table I) indicated that Mg-10Sc-5Li was perhaps the most promising one. Its high strength (52 ksi CYS) and low density (1.61 g/cc) make it attractive on a strength/density basis and equivalent to 7075 Al with a yield strength of $\sim$ 90 ksi. One possible disadvantage of the alloy is the rapid decomposition of the $\beta$ phase. Partial decomposition of $\beta$ occurs even during water quenching from 950°F. More extensive decomposition of $\beta$ and lower strength may be encountered when larger sections are quenched. The relatively low temperatures at which the alloy must be aged (250-275°F for one day) to achieve maximum strength suggest poor thermal stability and perhaps poor creep resistance at room temperature.

In an attempt to solve the potential disadvantages of Mg-10Sc-5Li, we studied alloys containing more Sc or less Li. Increasing the Sc level to 20% appeared to slow the decomposition of β during water quenching but did not prevent it nor improve properties. Reducing the Li content to 3% completely eliminated β formation at 10% Sc and markedly reduced strength. A Li level of 4% provided only a small amount of β. A completely β alloy was obtained with a Li content of 4.5% and properties were much improved. However, the CYS of Mg-10Sc-4.5Li (41 ksi) was not as high as that of Mg-10Sc-5Li (49 ksi), apparently due to greater decomposition of β during quenching. These results were puzzling until we obtained chemical analyses on all the Mg-Sc-Li ternaries. The results, shown below, indicate that Li efficiency was much higher than the 80% figure we used in preparing the alloys. They also indicate that Sc content markedly affects the strength of the β alloys.

| | Nominal | | Analyzed | | Max. |
|---|---|---|---|---|---|
| Alloy No. | %Sc | %Li | %Sc | %Li | CYS |
| 100,639 | 10 | 5 | 10.5 | 5.7 | 49 |
| 100,899 | 20 | 5 | 14.4 | 5.4 | 46 |
| 101,773 | 10 | 3 | -- | 3.8 | 29 |
| 102,024 | 10 | 4 | 8.8 | 4.4 | 32 |
| 102,129 | 10 | 4.5 | 8.0-8.4 | 6.0 | 41 |

Note that alloy 100,639 with 10.5% Sc is stronger than alloy 102,129 with 8.2% Sc although the latter contains slightly more Li. Based on these results we decided to evaluate Mg-10Sc-5Li on a normal laboratory scale.

Mg-10Sc-5Li was processed in essentially the same way as Mg-30Sc. We decided to add 11% Sc and 5.5% Li in hopes of retaining at least 10% Sc and 5% Li in the final alloy. Pure Mg was first melted in the alumina crucible. The Sc was added and the melt was held for 2.5 hours at 1450°F to dissolve the Sc. The Li was then added and the melt was stirred briefly prior to pouring. After an analytical sample and almost three inches of billet (Fig. 1) were poured, the melt stopped flowing from the crucible.

When the crucible was examined, attack of the crucible along the melt line was quite evident. When the crucible was lifted by the top, it separated at the melt line. Part of the metal remaining in the crucible was scraped into a sludge pan. It burned vigorously and could not be extinguished in spite of the application of copious amounts of flux. Another look at the crucible indicated that the alumina crucible had disappeared. All that was left was a large amount of sludge in the steel container. In spite of the trouble encountered with this melt, chemical analysis of the last metal poured indicated a Sc content of 9.8% and a Li content of 5.5%.

The reaction of the melt with the alumina crucible was surprising because no attack was encountered in preparing Mg-30Sc at much higher temperatures. Mg-Li alloys are not known to attack alumina, and several Mg-Sc-Li ternaries were previously prepared in small alumina crucibles without incident. Microprobe examination of the sludge indicated particles of alumina dispersed in a metallic phase. The metal phase contained a substantial amount of an Sc-Al intermetallic compound. The Sc content of the metallic matrix was nil. The distribution of Li in the sludge is unknown because this element cannot be detected by the probe.

We attempted to duplicate the reaction between the Mg-10Sc-5Li melt and alumina by holding 100 gram melts for 15 minutes in a small alumina crucible. There was no obvious attack on the crucible after the Sc was alloyed, and the metal was relatively clean when a melt sample was taken just after the Li was alloyed. Another melt sample taken 15 minutes later revealed numerous inclusions in the metal. No obvious crucible attack was apparent during this period. Metal quality degenerated further during holding in the steel pot. The final melt contained a very high concentration of inclusions. Only about 20 grams of metal was recovered from an initial charge of 100 grams. The final analysis of the melt - 5.80% Sc and 2.15% Li indicate a loss of $\sim$ 50% of these elements during holding. The analysis also revealed the presence of 0.11 Al. Careful examination of the alumina crucible revealed a layer of metal which could not be separated from the bottom of the crucible. Rupture of the crucible in this area revealed excellent bonding of the metal and ceramic and significant penetration of the melt into the crucible wall.

These results indicate that alumina is attacked by molten Mg-10Sc-5Li even on a small scale although at a much slower rate. One significant difference between the large and small alumina crucibles is porosity. The thicker walls of the large crucible have 30% porosity compared to only 15% for the small crucibles. The rapid reaction noted with the large crucible may have been due to penetration of the melt through the dense outer surface (cracking of the crucible?) into the porous core, where the high porosity and hence high surface of the alumina may have accelerated the reaction. In any event we plan to use magnesia crucibles in any future melts of this alloy.

Because the Mg-10Sc-5Li billet was very short, we decided to extrude 1/16" x 7/8" strip instead of 1/16" x 1 1/4" strip. Use of the narrower strip almost doubled the length of extrusion obtained and should not seriously interfere with the testing program. The Mg-10Sc-5Li billet was extruded into 1/16" x 7/8" strip at 650°F and one foot per minute. Extrusion at higher speeds (e.g., 10 fpm) caused severe die loading as shown in Fig. 1. Additional work would be required to determine if this is an inherent limitation of the alloy or primarily a problem of die design and/or processing conditions. Comparison of the extrusion temperature of Mg-10Sc-5Li (650°F) with that of Mg-30Sc (950°F) clearly reveals the difference in their high temperature properties. Mg-10Sc-5Li is designed for high strength at room temperature. Even AZ31B, the work-horse Mg extrusion alloy, required a temperature of 700°F under the same extrusion conditions.

In the as-extruded condition the strip had 8.5% elongation, 30 ksi TYS, 36 ksi CYS, and 39 ksi TS. The modulus determined from this stress-strain curve (5.7 x $10^6$ psi) was lower than that obtained with Tuckerman gages (6.6 and 6.5 x $10^6$ psi). Heat treatment at 950°F and quenching produced a structure that was largely, but not completely, $\beta$. Increasing the solution temperature to 1050°F eliminated the residual $\alpha$. Partial decomposition of $\beta$ during water quenching from both temperatures was noted. Properties of the heat treated extrusion will soon be determined.

A final attempt was made to modify the composition of the Mg-Sc-Li ternary in order to inhibit the decomposition of the $\beta$ phase. We felt that higher properties and greater freedom in processing would result if this could be accomplished. In order to reduce diffusivity in the alloy and effect this objective, it appeared logical to increase Sc and minimize Li. Prior data suggested that as little as 4% Li might be adequate to produce an all-$\beta$ structure in Mg containing 15% Sc. This alloy was therefore evaluated on the mini-scale. The results shown in Table I are gratifying. Note that Mg-15Sc-4Li is stronger than any Mg-Sc-Li ternary prepared thus far. Its CYS of 50 ksi as-extruded and 65 ksi after heat treatment are well above similar values obtained with the other compositions. Although failure occurred in tension without yielding, a modulus of $8.0 \times 10^6$ psi was obtained. Metallographic examination confirms the formation of $\beta$ at 950°F and indicates no obvious decomposition of the $\beta$ during water quenching. Note also that maximum CYS (65 ksi) is obtained by aging at 300-350°F and that of a CYS of over 50 ksi is retained after exposure to temperatures as high as 500°F. If we use the calculated density of 1.70 g/cc, we find that the strength/density ratio of Mg-15Sc-4Li is equivalent to that Mg-30Sc and to that of 7075 Al with a CYS of 108 ksi. Although this alloy contains more Sc than the one selected for laboratory-scale evaluation, its higher strength makes it, too, worthy of consideration for more intensive study.

## Mini-Scale Evaluation of Mg-Sc-Ag and Mg-Sc-Y

The Mg-Sc-Ag and Mg-Sc-Y ternaries have been extensively evaluated (Tables II and III, respectively) on a mini-scale in order to determine the optimum composition of each system and to select the most promising alloy for more intensive study. One of the first alloys prepared, Mg-20Sc-6Ag, has steadfastly defied our efforts to surpass its excellent properties. As shown in Fig. 2, we have finally achieved slightly higher CYS in the T6 temper with less Sc (15%) by increasing the Ag content to 9%. This difference cannot be considered significant because of the greater sensitivity of Mg-15Sc-9Ag to processing conditions (Table II) and the limited accuracy of the small compression tests. The calculated densities of the two alloys are essentially the same (2.01 g/cc for Mg-20Sc-6Ag and 2.02 g/cc for Mg-15Sc-9Ag). Mg-20Sc-6Ag is much stronger than Mg-15Sc-9Ag in the as-extruded condition, apparently due to the presence of $\beta$ at the higher Sc level. Mg-15Sc-9Ag has a relatively low solidus temperature ($<950^{\circ}$F) and must be extruded at low temperatures and speeds to avoid hot shorting.

Because of the similarity between Y and Sc, considerable effort has been expended in the study of Mg-Sc-Y ternaries. The results shown in Table III indicate that Y can be substituted for a considerable amount of the Sc without impairing properties. In fact, Y appears to be equivalent on a weight basis to Sc. Note, for example, the properties of Mg containing 20 or 30% (Sc + Y) listed below:

|  |  | As-Extruded |  |  |  |  | CYS |  |
|---|---|---|---|---|---|---|---|---|
| %Sc | %Y | %E | TYS | CYS | TS | Modulus | T4 | T6 |
| 20 | -- | 15 | 40 | 41 | 49 | 7.4 | 29 | 31 |
| 10 | 10 | 9 | 45 | 44 | 52 | 7.0 | 35 | 38 |
| 30 | -- | 7 | 58 | 54 | 63 | 8.2 | 42 | 42 |
| 18 | 12 | 3 | 54 | 54 | 59 | 7.6 | -- | -- |
| 15 | 15 | 0.3 | 58 | 58 | 59 | 7.5 | 44 | 49 |

Part of the difference in CYS in the T4 and T6 temper may be due to the longer time (16 vs 1/2 hours) at $950^{\circ}$F used for the Mg-Sc alloys. The Mg-Sc-Y ternaries are not as ductile as the Mg-Sc binaries because part of the Y is present as Mg-Y intermetallic compound. Because of the limited solid solubility of Y in $\alpha$, this difference becomes more pronounced as the Y level is increased. The use of Y instead of additional Sc does provide some age hardenability but this is small compared to the pronounced solid solution strengthening afforded by Y and/or Sc.

The formation of $\beta$ in the two alloy systems is also similar. Mg-30Sc, Mg-15Sc-15Y, and Mg-18Sc-12Y have an $\alpha$ matrix when heat treated at 950°F, but $\beta$ is formed in each alloy at higher temperatures. These Mg-Sc-Y ternaries cannot be converted entirely to $\beta$ like Mg-30Sc because melting limits the solution temperature to 1150-1200°F. It is interesting to note that the Mg-Y intermetallic compound which is present in abundance at 950°F, disappears at higher temperatures as $\beta$ is formed. Higher solubility in the $\beta$ than in the $\alpha$ phase has been noted for Ag and Li as well as Y.

In an attempt to produce a $\beta$ alloy without increasing the Sc content beyond 15%, ternaries with higher Y levels have been prepared—first 18% and then 21%. Since a considerable amount of $\beta$ was formed by heat treating Mg-15Sc-15Y, we assumed that the higher Y levels would provide an all-$\beta$ structure. Increasing the Y content to 18% produced a disappointingly small increase in $\beta$, and an all-$\beta$ structure was still not obtained at 21% Y. The Sc level was then increased to 18% and combined with 18% Y. This alloy still contained residual $\alpha$ when heat treated at 1150°F. Mg-36Sc, on the other hand, would be converted to $\beta$ by heat treatment at 1050°F. This means that Y is not as effective as Sc in forming $\beta$ at high alloy levels or that the actual Sc and/or Y levels in these alloys are well below the nominal values. This will be determined before additional alloys are prepared.

Perhaps the most serious disadvantage of the Mg-Sc-Y alloys is the large amount of Mg-Y intermetallic compound which may be formed in the alloys. The rather poor ductility of these alloys in the as-extruded condition is attributed to this factor.

Since the best combination of properties of Mg-30Sc is obtained in the as-extruded condition, this could be a major problem for the Mg-Sc-Y ternaries. Therefore an attempt was made to improve the ductility of the Mg-Sc-Y extrusion by varying the processing conditions. The cast billets of Mg-15Sc-15Y and Mg-15Sc-18Y were heat treated at 1150°F to dissolve the Mg-Y compound for improved ductility and to maximize $\beta$ formation for increased strength. Part of the billet was extruded at the minimum temperature (950°F due to pressure limitations), while the other part was extruded at the maximum temperature (1125-1150°F due to hot shorting). As shown in Table IIIA, ductility was improved by extruding at the high temperature, but strength was sharply decreased. The good combination of properties obtained with Mg-30Sc was not approached in any case. Metallographic examination of the extrusion indicates marked decomposition of $\beta$ during extrusion at 950°F. This produces high strength but poor ductility. Extrusion at the highest temperature apparently produces a predominantly $\beta$ structure as the extrusion passes through the die, but the slow cooling rate caused by the slow speeds employed produces a rather coarse $\alpha - \beta$ structure which is neither strong nor ductile. More rapid cooling of the extrusion and/or intermediate extrusion temperatures will be tried in the hope of producing the fine $\alpha - \beta$ structure characteristic of the Mg-30Sc extrusion.

## TABLE I

## Properties of Mg-Sc-Li Ternaries

### A) As-extruded

| | Nominal | | Ext. | | $10^3$ psi | | | $10^6$ psi |
|---|---|---|---|---|---|---|---|---|
| Alloy No. | %Sc | %Li | Temp. | %E | TYS | CYS | TS | Modulus |
| 101,773 | 10 | 3 | 800 | 6 | 36 | 35 | 44 | 8.2 |
| 102,024 | 10 | 4 | 700 | 14 | 40 | 40 | 46 | 7.1 |
| 102,129 | 10 | 4.5 | 650 | 12 | 28 | 29 | 35 | 6.2 |
| 100,639 | 10 | 5 | 700 | 2 | 29 | 33 | 37 | 6.0 |
| 102,222 | 15 | 4 | 750 | -- | -- | 50 | 41 | 8.0 |
| 100,899 | 20 | 5 | 700 | 2 | 36 | 41 | 42 | 6.1 |

### B) CYS ($10^3$ psi) After Heat Treatment

| | Nominal | | Solution | | T6** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Alloy No. | %Sc | %Li | Temp. | T4* | 250F | 300F | 350F | 400F | 450F | 500F |
| 101,773 | 10 | 3 | 950F | 26 | -- | 29 | 29 | 28 | 23 | -- |
| | | | 1050 | 24 | -- | 26 | 26 | 25 | 24 | -- |
| 102,024 | 10 | 4 | 950 | 30 | -- | 32 | 32 | 32 | -- | -- |
| 102,129 | 10 | 4.5 | 950 | 36 | -- | 38 | 33 | 31 | 29 | 27 |
| | | | 1050 | 41 | -- | 38 | 41 | 35 | -- | -- |
| 100,639 | 10 | 5 | 800 | 36 | -- | -- | -- | -- | -- | -- |
| | | | 950 | 49 | 52 | 49 | -- | -- | 34 | -- |
| | | | 1100 | 48 | -- | -- | -- | -- | 35 | -- |
| 102,222 | 15 | 4 | 950 | 45 | 60 | 65 | 65 | 58 | -- | 51 |
| 100,899 | 20 | 5 | 950 | 36 | -- | 46 | 41 | 37 | 38 | |
| | | | 1050 | 28 | -- | 47 | 29 | 37 | -- | |

*Solution heat treated 1/2-1 hour, water quenched, and naturally aged up to one month.

**Same as T4 except artificially aged after quenching at indicated temperature for 24 hours.

# TABLE II

## Properties of Mg-Sc-Ag Ternaries

### A) As-extruded

| | Nominal | | Ext. | | $10^3$ psi | | | $10^6$ psi |
|---|---|---|---|---|---|---|---|---|
| Alloy No. | %Sc | %Ag | Temp. | %E | TYS | CYS | TS | Modulus |
| 100,407 | 2 | 6 | 760 | 25 | 27 | 25 | 40 | 7.6 |
| 100,571 | 10 | 6 | 850 | 8 | 42 | 42 | 50 | 6.3 |
| 100,210 | 10 | 7.5 | 800 | 7 | 44 | 43 | 53 | 7.0 |
| 100,211 | 10 | 9 | 820 | 7 | 44 | 43 | 53 | --- |
| 102,130 | 15 | 4.5 | 860 | 11 | 46 | 46 | 56 | 6.9 |
| 102,087 | 15 | 6 | 880 | 3 | 47 | 46 | 48 | 7.2 |
| 102,131 | 15 | 7.5 | 860 | 5 | 50 | 48 | 57 | 6.9 |
| 102,209 | 15 | 9 | 850 | 4 | 47 | 46 | 56 | 7.6 |
| 102,086 | 20 | 4.5 | 880 | 9 | 52 | 51 | 61 | 7.3 |
| 100,897 | 20 | 6 | 825 | 3 | 62 | 65 | 66 | 7.4 |
| 102,026 | 20 | 7.5 | 800 | 6 | 50 | 54 | 59 | 7.0 |
| 101,774 | 20 | 9 | 850 | 5 | 52 | 52 | 59 | 8.6 |

## TABLE II (Continued)

### Properties of Mg-Sc-Ag Ternaries

### B) CYS ($10^3$ psi) After Heat Treatment

| | Nominal | | Solution | | T6** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Alloy No. | %Sc | %Ag | Temp. | T4* | 300F | 350F | 400F | 450F | 500F |
| 100,407 | 2 | 6 | 950F | 10 | 15 | 10 | 11 | | |
| 100,571 | 10 | 6 | 1100 | 28 | 37 | 32 | 34 | -- | |
| 100,210 | 10 | 7.5 | 850 | 37 | | 42 | | | |
| | | | 900 | 39 | | 43 | | | |
| | | | 950 | 36 | 44 | 44 | 37 | 32 | -- |
| 100,211 | 10 | 9 | 850 | 38 | | 43 | | | |
| | | | 900 | 40 | | 46 | | | |
| | | | 950 | 37 | 47 | 45 | 37 | 31 | -- |
| 102,130 | 15 | 4.5 | 850 | 39 | | 40 | | | |
| | | | 900 | 37 | | 40 | | | |
| | | | 950 | 38 | 39 | 40 | 38 | 36 | 36 |
| | | | 1050 | 36 | 39 | 40 | 38 | -- | -- |
| 102,087 | 15 | 6 | 850 | 41 | | 48 | | | |
| | | | 900 | 38 | | 46 | | | |
| | | | 950 | 40 | 47 | 48 | 45 | | |
| 102,131 | 15 | 7.5 | 850 | 39 | | 51 | | | |
| | | | 900 | 42 | | 54 | | | |
| | | | 950 | 39 | 50 | 54 | 43 | 38 | 37 |
| 102,209 | 15 | 9 | 850 | 44 | | 50 | | | |
| | | | 900 | 43 | | 58 | | | |
| | | | 950 | 39 | 52 | 56 | 47 | 39 | |
| 102,086 | 20 | 4.5 | 850 | 41 | | 46 | | | |
| | | | 900 | 39 | | 44 | | | |
| | | | 950 | 42 | 44 | 47 | 45 | | |
| 100,897 | 20 | 6 | 850 | 46 | | 56 | | | |
| | | | 900 | 45 | | 56 | | | |
| | | | 950 | 46 | 51 | 56 | 45 | 45 | |
| | | | 1050 | | | 49 | | | |
| 102,026 | 20 | 7.5 | 850 | 44 | | 52 | | | |
| | | | 900 | 36 | | 46 | | | |
| | | | 950 | 44 | 52 | 55 | 49 | | |
| 101,774 | 20 | 9 | 850 | 43 | | 54 | | | |
| | | | 900 | 36 | | 54 | | | |
| | | | 950 | 42 | 49 | 49 | 42 | 43 | |

*Solution heat treated 1/2-1 hour, water quenched, and naturally aged up to one month.

**Same as T4 except artificially aged after quenching at indicated temperature for 24 hours.

## TABLE III

### Mg-Sc-Y Ternaries

### A) As-extruded

|  | Nominal* |  | Ext. |  | $10^3$ psi |  |  | $10^6$ psi |
|---|---|---|---|---|---|---|---|---|
| Alloy No. | %Sc | %Y | Temp. | %E | TYS | CYS | TS | Modulus |
| 100,752 | 10 | 5(4.8) | 900F | 18 | 43 | 45 | 50 | 7.0 |
| 100,938 | 10 | 8(4.1) | 930 | 16 | 42 | 42 | 50 | 8.6 |
| 101,776 | 10 | 12(6.2) | 925 | 13 | 44 | 40 | 51 | 7.6 |
| 102,025 | 10 | 10(9.2) | 860 | 9 | 45 | 44 | 52 | 7.0 |
| 102,132 | 10 | 15 | 930 | -- | -- | 57 | 51 | 8.2 |
| 102,205 | 15 | 12 | 950 | 0.2 | 57 | 58 | 57 | 7.2 |
| 102,232 | 15 | 15 | 950 | 0.3 | 58 | 58 | 59 | 7.5 |
|  |  |  | 950*** | --- | -- | 59 | 54 | --- |
|  |  |  | 1130*** | 2 | 47 | 47 | 56 | --- |
| 102,277 | 15 | 18 | 930 | --- | -- | 70 | 40 | 9.4 |
|  |  |  | 950** | --- | -- | 76 | 38 | --- |
|  |  |  | 1150** | ~0.5 | 47 | 48 | 52 | 7.2 |
| 102,292 | 15 | 21 | 950 | --- | -- | 83 | 33 | --- |
| 102,259 | 18 | 12 | 960 | 3 | 54 | 54 | 59 | 7.6 |
| 102,304 | 18 | 18 | 950 | --- | -- | 73 | 30 | 7.4 |

*Analyzed Y content in parentheses

**Soaked at 1150°F for 1/2 hour prior to extrusion

***Soaked at 1150°F for 11 hours prior to extrusion

TABLE III (Continued)

Mg-Sc-Y Ternaries

B) CYS ($10^3$ psi) After Heat Treatment

| | Nominal*** | | Solution | | T6** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Alloy No. | %Sc | %Y | Temp. | T4* | 300F | 350F | 400F | 450F | 500F |
| 100,752 | 10 | 5(4.8) | 950F | 26 | | | | 27 | |
| | | | 1100 | 25 | | | | 26 | |
| 100,938 | 10 | 8(4.1) | 950 | 25 | 27 | 26 | 26 | -- | -- |
| | | | 1050 | 25 | -- | 26 | -- | 26 | -- |
| 101,776 | 10 | 10(6.2) | 950 | 28 | 29 | 29 | 29 | 28 | |
| 102,025 | 10 | 10(9.2) | 950 | 35 | 36 | 37 | 38 | | |
| 102,132 | 10 | 15 | 950 | 41 | 43 | 44 | 44 | 45 | 44 |
| | | | 1050 | 37 | 41 | 42 | 39 | 39 | |
| 102,205 | 15 | 12 | 950 | 39 | 40 | 42 | 43 | 44 | 43 |
| | | | 1050 | 32 | 37 | 40 | 40 | 40 | 40 |
| | | | 1200 | | | | | 47 | |
| 102,232 | 15 | 15 | 950 | 44 | 45 | 46 | 49 | 47 | 45 |
| 102,277 | 15 | 18 | | | | | | | |
| 102,292 | 15 | 21 | | | | | | | |
| 102,259 | 18 | 12 | | | | | | | |
| 102,304 | 18 | 18 | | | | | | | |

*Solution heat treated 1/2-1 hour, water quenched, and naturally aged up to one month.

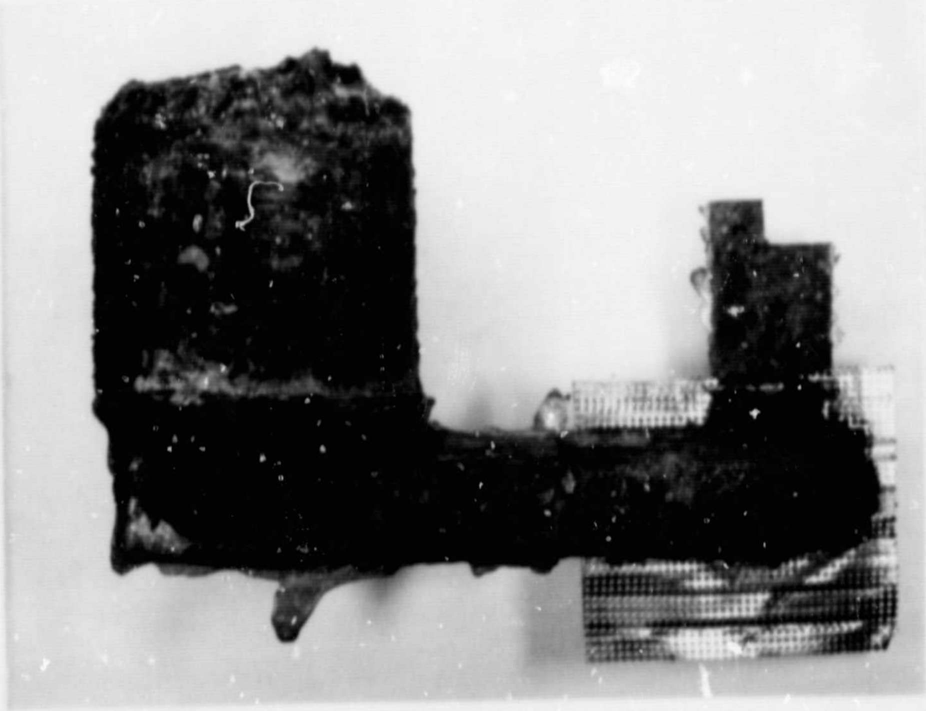
**Same as T4 except artificially aged after quenching at indicated temperature for 24 hours.

***Analyzed Y content in parentheses

FIGURE 1

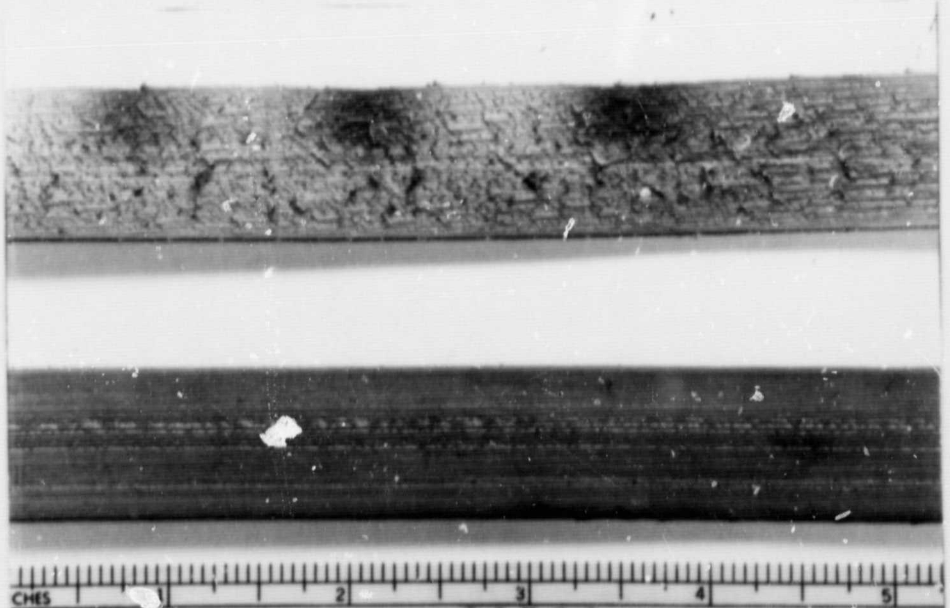
Mg-10Sc-5.5Li Casting and Extrusion

Alloy No. 102,223



Negative No. 66018

a) 3" Diameter Billet

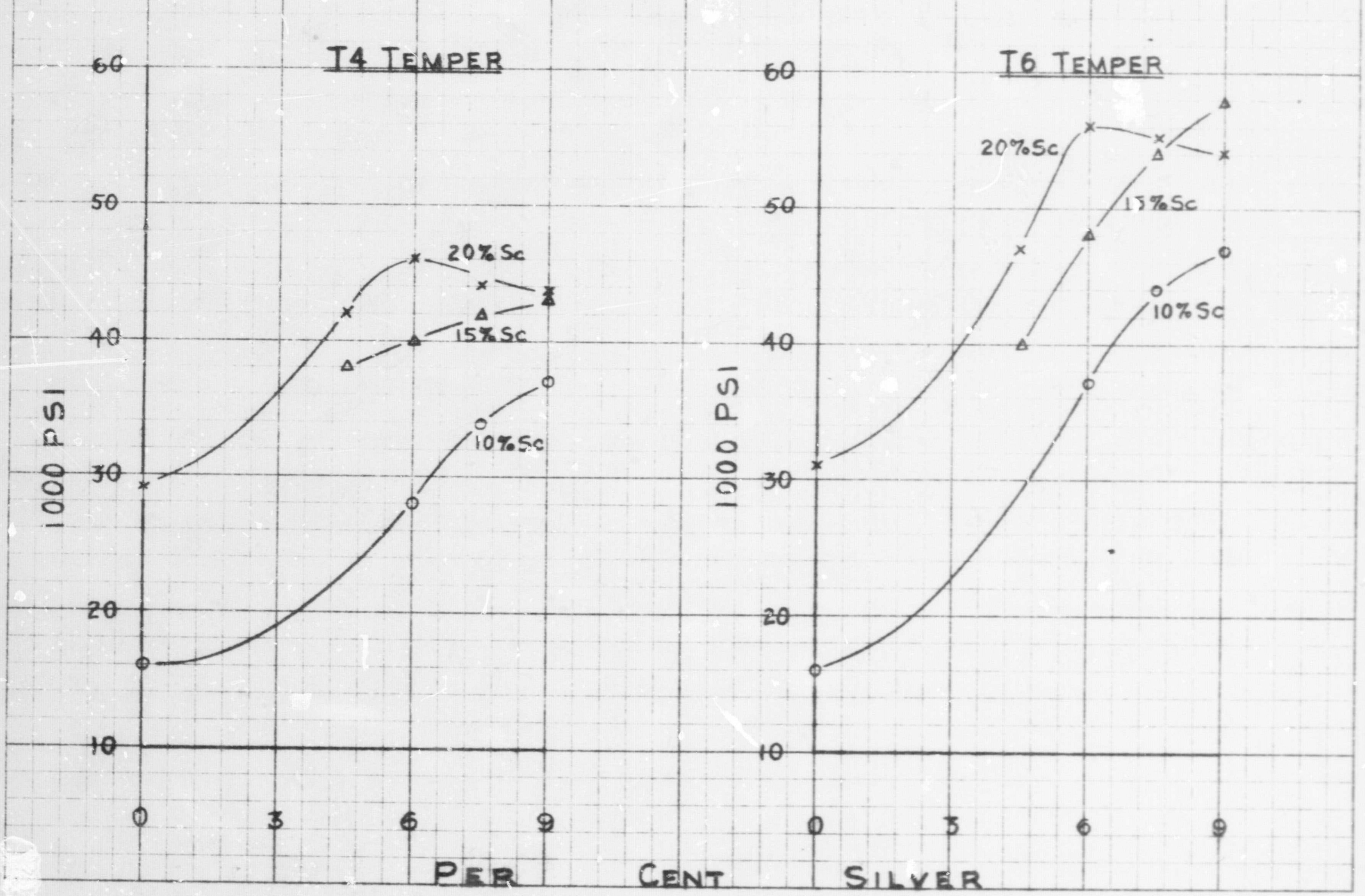


Negative No. 66027

b) 1/16" x 7/8" Extrusion

10 feet per minute (top)
1 foot per minute (bottom)

FIG. 2 CYS OF MG-SC-AG TERNARIES



5-19-65
Bef