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MECHANICAL PROPERTY AND FORMABILITY
STUDIES ON UNALLOYED PLUTONIUM

By

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ABSTRACT

The effect of temperature and testing speed on the tension and compression properties of unalloyed plutonium were studied in the alpha, beta, gamma and delta phases. Compressive formability data were obtained for a load of 100,000 pounds in the aforementioned phases. In addition, preliminary creep, tension impact and torsion data for alpha phase plutonium are reported.

Extrusion constants and pressures for the beta, gamma and delta phases were obtained. The room temperature tension and compression properties of the beta and gamma extruded plutonium were determined.

Metallographic studies were made to determine the effect of tension, compression and extrusion, in the indicated phases, on the microstructure of as-cast plutonium.

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MECHANICAL PROPERTY AND FORMABILITY STUDIES ON UNALLOYED PLUTONIUM

H. R. Gardner and I. B. Mann

INTRODUCTION

The mechanical properties of a material must be determined before it can receive extensive usage in engineering applications. In the case of plutonium the number of such applications is relatively small, but their importance places a high priority on mechanical property data. Accordingly, studies were initiated on tensile, compression, creep, tension impact and torsion properties. The effects of temperature and testing speed in tension and compression were determined.

To obtain data on the formability of plutonium, a study of the extrusion characteristics of the beta, gamma, and delta phases was initiated. The room temperature tensile and compression properties of beta and gamma extruded plutonium were determined.

SUMMARY AND CONCLUSIONS

The effect of temperature on the tension and compression properties of as-cast plutonium was determined in the alpha, beta, gamma, and delta phases. In general, the effect of increasing temperature is to decrease strength and increase ductility. The alpha phase is quite brittle, while the beta, gamma and delta phases are very ductile. The beta phase has the greatest ductility; at 160 C and a testing speed of 0.015 inch/minute, elongations up to 620 per cent and reductions in area of 100 per cent are obtained. Despite the apparent brittleness of the alpha phase, it is interesting to note that the elongation data obtained in

both tension and compression indicate that between 30 and 70 C a change in deformation mechanism, possibly caused by recrystallization, is taking place. In addition, the total plastic deformations obtained prior to fracture during compression testing in the alpha phase indicate that it may be possible to accomplish limited dimensional sizing operations without fracture.

As expected, the effect of increasing metal purity was to decrease strength values. Formability studies in compression indicated that the delta phase had the greatest formability. Metallographic observations indicate that forming in the beta, gamma and delta phases generally results in a non-uniform grain structure. Microcracks were also observed in formed specimens; however, since microcracking was present in most of the as-cast specimens, it is expected that this had a great influence on the microcracking observed after forming. It is concluded that forming operations should be supplemented by metallographic studies to evaluate the integrity of formed parts.

Determinations of the effect of testing speed on tension and compression properties in the alpha, beta and gamma phases produced varied results. In the alpha phase, strength values increased to a maximum and then decreased. Beta phase strength values increased rapidly with increasing testing speed, while the increase in gamma phase strength was relatively small. Elongation in the beta phase decreased rapidly with increasing testing speed, the effect on gamma phase elongation was much smaller.

Since gamma phase properties are not affected by testing speed as much as beta phase properties, the gamma phase would probably be more amenable to hot forming operations. However, it must be kept in mind that the degree of microcracking originally present in the as-cast microstructure may greatly influence the integrity of formed parts.

In view of the apparent effect of the Pu-Pu₆Fe eutectic in inhibiting microcracking it may be beneficial from a metal integrity standpoint to specify a certain amount of iron in plutonium to be used in forming operations.

During preliminary creep studies it was determined that alpha phase secondary creep rates are low, as are the total plastic deformations obtained. At a stress of 10,000 psi, creep rates varied from 15 to 330 x 10⁻⁴ in./in./10,000 hours for test temperatures of 31 and 100 C, respectively.

A brittle fracture was obtained in room temperature tension impact testing. Impact energy values ranged from 1.3 to 4.8 foot-pounds with an average of 2.6 foot-pounds.

An average of 52,500 psi was obtained for the ultimate shear strength in torsion.

Extrusion in the beta, gamma and delta phases was determined to be a feasible fabrication method for as-cast plutonium. Extrusion constants and pressures decrease as temperature is increased through the beta to delta phases. Non-uniform grain structures which may indicate the presence of deleterious residual stresses were present after extrusion. Room temperature tensile strength is increased approximately 10 per cent by extrusion, while compressive strength was not affected.

GENERAL EXPERIMENTAL TECHNIQUES

Specimen Preparation Procedure

Unless stated differently, the following specimen preparation procedures apply to all specimens used to obtain data for this paper.

Plutonium buttons of nominal purity were charged into MgO crucibles for melting. The metal charged for each casting heat ranged from 1200 to 3000 grams. The plutonium was melted in vacuo and held at 950 C for 30 minutes before pouring into a multicavity MgO coated graphite mold which had been heated to 300 C. When the mold cooled to 150 C, the castings were removed and cooled slowly to room temperature in the normal air atmosphere of the glove box.

Prior to machining to specimen dimensions at room temperature, the castings were cold treated for several hours at -23 to -34 C. Samples for chemical analysis were taken on the machining cut just before the finish cut on the specimens.

Metallographic Procedure

Metallographic specimens were taken from each casting heat and mounted in Thalco polyester resin which sets at room temperature. The initial surface preparation consisted of hand polishing on paper ranging from 180 to 600 grit using carbon tetrachloride as a lubricant. An acceptable as-polished surface was produced by automatic polishing on Syntron Vibratory polishers for two hours using a Linde A emulsion in carbon tetrachloride on billiard cloth. All photomicrographs

not containing grain structures, were taken of the as-polished surface under bright field illumination. Electropolishing for grain structure and electroetching for inclusion studies were both accomplished in a solution of 20 parts tetraphosphoric acid, 30 parts water and 50 parts 2-ethoxyethanol at 21 volts and 0.15-0.30 amperes. A 10-second time was used for electroetching while 60 seconds was sufficient for electropolishing. The grain structure of alpha plutonium is readily apparent under polarized illumination after the 60-second electropolish and a 5 to 15-hour oxidation period. Longer electropolishing times decrease the oxidation period.

METALLOGRAPHY OF AS-CAST PLUTONIUM

To evaluate the quality of the plutonium used, metallographic specimens taken from each casting heat were examined in both the as-polished and electropolished conditions. Microcracking which varied between the extremes illustrated in Figures 1 and 2 was observed in most of the specimens. As would be expected, as the size of the microcracks increases, density decreases. An unidentified spherical inclusion which was quite common in the microstructure is illustrated in Figure 3. In a few of the specimens a network of Pu-Pu₆Fe eutectic was present, Figures 4 and 5. In addition, unidentified small white particulate inclusions were present in casting heat 19-2-2, Figure 4. Plutonium nitride inclusions were also observed in a number of specimens.

Comparison of Figures 1 and 2 with Figures 4 and 5 indicates that the presence of a fairly large amount of Pu-Pu₆Fe eutectic, about 500 ppm Fe or greater, tends to inhibit the formation of microcracks. Russian investigators have found that Pu-Pu₆Fe has good ductility,^[1] and herein may lie the answer to its apparent inhibiting effect on microcracking. When the Pu-Pu₆Fe eutectic is present in sufficient quantities in the microstructures, the plastic strains accompanying the phase transformations during cooling after casting may be taken up in the Pu-Pu₆Fe and not the plutonium matrix. When the Pu-Pu₆Fe is not plentiful the plastic strains are dissipated in the plutonium with subsequent formation of microcracks. The typical grain structure present in all casting heats is illustrated in Figure 6. In all specimens, the as-cast average grain diameter ranged from 0.017 to 0.070 mm with an over-all average of 0.040 mm.

TENSILE PROPERTY STUDIES

Experimental Material and Testing Techniques

The chemical impurities, densities and grain sizes for the plutonium used in the tensile property studies are presented in Table I.

The 0.250-inch diameter tensile specimens, Figure 7, were tested on a 440,000 pound Baldwin-Lima-Hamilton Universal Testing Machine equipped with a glove box mounted between the adjustable and fixed crossheads. [2]

The effect of testing temperature was studied over a temperature range of -30 to 325 C at a testing speed of 0.015 inch/minute. Peanut oil was used as a heating medium for the elevated temperature work and tri-chloroethylene and dry ice for the low temperature work. Through vigorous agitation in the bath it was possible to maintain a temperature control of ± 1.5 C during testing.

In the alpha phase a linear differential transformer type extensometer was used to obtain a stress-strain curve [2] from which 0.01 per cent yield strength, modulus of elasticity and elongation data could be determined. All elongation data are based on a one-inch gage length.

In the beta, gamma and delta phases the large amount of thermal expansion that had taken place on heating from room temperature eliminated most extensometer systems from use. To gain an indication of yielding, a Baldwin Platen Deflectometer was used to obtain a graph of load versus displacement during testing. A typical curve is illustrated in Figure 24, curve (B). It was not possible to obtain an offset yield strength from curves of this type because of the low sensitivity of the deflectometer. However, since the curves have a straight line portion, the point of demarkation (C), from the straight line was defined as the yield strength. This type of yield strength data was obtained in the beta, gamma and delta phases.

Modulus of elasticity data in the beta, gamma and delta phases was obtained on 0.505-inch diameter tensile specimens with a Martins

Extensometer^[3], Figure 8. Elongation in the specimen is transmitted through four parallel rods to two mirrors which rotate as the specimen elongates. The rods are linked to the specimen through taper pins at either end of the two-inch gage length. The pins are inserted in tapered holes drilled through the gage diameter. The amount of mirror rotation is followed optically with a cathetometer and scale. A simple calibration using either a specimen of known elastic modulus or the geometry of the system relates mirror rotation to strain in the specimen.

Elongation, based on a one-inch gage length, and reduction in area in the beta, gamma and delta phases were obtained using the conventional techniques of punch marks and diameter at fracture measurements, respectively. Testing speed, the rate of platen motion, was controlled by a Baldwin Platen Motion Pacer.

Results and Discussion

1. Effect of Test Temperature

In general, as test temperature is increased through the alpha to delta phases, both strength and modulus of elasticity values decrease, Figures 9 and 10, Tables II and III. Note that the low temperature gamma region has somewhat higher strength and modulus values than the high temperature beta region. Since elongation in the alpha phase is less than 1 per cent, it is not possible to obtain elongation data by measuring between punch marks on the one-inch gage length after fracture. However, by drawing a line parallel to the elastic portion of the stress-strain curve, from the fracture point to its intersection with the strain axis, it is possible to obtain elongation data, Figure 11. Note that there is a 600 per cent increase in elongation from 0.065 per cent at 30 C to 0.46 per cent at 70 C. This may indicate that a change in the type of deformation mechanism is taking place, possibly caused by recrystallization. A typical brittle fracture was obtained at all alpha phase test temperatures.

In the beta phase, elongation and reduction in area are very high, Figure 12. The average elongation ranges from 295 to 570 per cent, while

the reduction in area is nominally 100 per cent. The decrease in beta phase elongation from the 570.4 and 503.2 per cent values at 160 and 180 C to the 325.9 per cent result at 190 C is attributed to the occurrence of beta to gamma transformation during testing and will be discussed later in the paper with the 200 C test results.

Both elongation and reduction in area are much lower in the gamma phase and little change occurs with increasing temperature. The average elongation ranges from 50.0 to 57.2 per cent while the reduction in area increases slightly from 75.0 to 82.8 per cent. The 67.3 per cent average elongation in the delta phase at 325 C is significantly greater than the 50.1 per cent average gamma phase elongation at 300 C. The average reduction in area in the delta phase, 98.0 per cent, is 19 per cent greater than the average gamma phase value at 300 C, 82.8 per cent.

The type of deformation and fracture exhibited in the beta, gamma and delta phases is illustrated in Figures 13, 14 and 15.

Metallographic samples were taken at the point of fracture from beta, gamma and delta phase tested specimens. A typical microstructure for the 160 C test temperature is illustrated in Figures 16 and 17. Note the large number of elongated microcracks, also the elongated Pu-Pu₆Fe eutectic and unidentified spherical inclusions. The accompanying grain structure is non-uniform with columnar grains in some areas and no alignment of grains in the tension direction, Figure 18. The axes of the columnar grains are perpendicular to the loading direction and they appear to be nucleated at the elongated inclusions and/or microcracks. Since nucleation at these imperfections would occur earlier than in the base metal, columnar grain growth would take place during the beta to alpha transformation. Any grain alignment in the tension direction which existed in the beta phase would probably be essentially erased by the beta to alpha transformation.

Three types of fractures were observed after gamma phase testing at 265 C, Figures 19, 20 and 21. The reason for the difference between the types in Figures 19 and 20 may be the size of microcracks originally present. The average size of microcracks in Figure 20 appear to be somewhat larger than those in Figure 19.

The effect of the presence of microcracks on the elongation and reduction in area in the gamma phase is illustrated in Figures 14, 19, 20 and 21. Microcracks were present before testing in the specimens illustrated in Figures 19 and 20, while the specimen in Figure 21 had an extensive network of Pu-Pu₆Fe eutectic and no microcracks. The upper specimen in Figure 14 had extensive Pu-Pu₆Fe eutectic and no microcracks, while the lower specimen had extensive microcracking. Thus, when microcracks are absent from the microstructure, greater elongation and reduction in area can be expected. In addition, the gamma phase strength data indicate that slightly higher strengths are obtained with specimens containing no microcracks.

The alpha phase grain structure observed after testing in the gamma phase at 265 C is uniform and has about the same grain size as observed in as-cast plutonium, Figure 22.

A typical fracture in the delta phase at 325 C is illustrated in Figure 23. Note the elongated microcracks along loading axis. The alpha phase grain structure after delta phase testing is uniform with about the same grain size as cast plutonium.

Note that in the foregoing discussion no mention has been made of the 200 C test temperature results, Table III. The reason for this is because of the rather unique properties obtained at this temperature. A typical stress-platen displacement curve for the 200 C test temperature, Curve (A), is illustrated in Figure 24 along with a typical curve for the beta, gamma and delta phases, Curve (B). For the 200 C curve, the stress initially increases to a maximum and then decreases slightly prior to increasing to a stress higher than the initial maximum. This phenomenon was not observed at any of the other test temperatures which have stress-platen displacement curves similar to Curve (B). An explanation for this can be offered if it is noted that the 2700 psi stress value corresponding to the first maximum in the 200 C curve falls on an extrapolation of the beta phase ultimate strength curve, Figure 9, while the 3800 psi stress at the second maximum falls between extrapolations of the beta and gamma phase ultimate strength curves at 200 C. This observation suggests the possibility of partial beta to gamma transformation occurring which would

result in the somewhat higher ultimate strength observed in the second maximum in the curve, since the low temperature gamma phase is stronger than the high temperature beta phase.

This argument is substantiated by recent British data^[4] which established the thermo-dynamic equilibrium temperature for the beta to gamma transformation as 184 C. Thus, considering the six to seven-hour duration of tensile tests at the 200 C temperature and also at 190 C, it is not surprising that partial transformation of beta to gamma plutonium occurred during testing. Since elongation in the gamma phase is much lower than in the beta phase the decrease in elongation observed at the 190 and 200 C temperatures is consistent with what would be expected.

2. Effect of Testing Speed

In the alpha phase, the effect of testing speed was studied at 30 and 110 C. At both temperatures the ultimate strength increases to a maximum at the 0.250 inch/minute testing speed and then decreases, Figure 25 and Table IV. The initial increase in strength as testing speed is increased can be attributed to strain hardening. The decrease at the higher testing speeds is probably the result of an increase in the notch sensitivity of plutonium which is characteristic of many metals at high testing speeds. Because of an extensometer limitation it was not possible to determine yield strengths over the full range of testing speeds.

Both ultimate and yield strength increase rapidly with testing speed for all test temperatures in the beta phase, Figure 26 and Table V. For the 130 and 160 C test temperatures, elongation decreases rapidly as testing speed increases. However, for the 190 C temperature, the elongation is lower at the 0.015, 0.060, and 0.250 in./min testing speeds than would be expected. This is caused by partial gamma transformation as explained in the preceeding section. At the 1.0 in./min testing speed the total testing time is too short to allow enough beta to gamma transformation to occur to influence the test results. Reduction in area at the 130 and 160 C temperatures decreases with increasing testing speed while at 190 C, elongation remains constant at approximately 100 per cent. The type of deformation and fracture exhibited at the different testing speeds at 160 C is illustrated in Figure 28.

In the gamma phase at 265 C, both ultimate and yield strengths increase by 100 per cent when testing speed is increased from 0.002 to 1.0 in./min. Elongation decreases by 40 per cent while reduction in area decreases by 25 per cent, Figures 26, 27 and Table V. The effect of testing speed on the deformation and fracture obtained in the gamma phase is illustrated in Figure 29.

Since gamma phase properties are not affected by testing speed as much as beta phase properties, the gamma phase would probably be most amenable to warm forming operations. However, it must be kept in mind that the degree of microcracking originally present in the as-cast microstructure may greatly influence the integrity of formed parts.

COMPRESSION AND FORMABILITY STUDIES

Experimental Material and Testing Techniques

Approximately 2/3 of the compression specimens used were machined from as-cast and cold-treated cylinders. The remaining specimens were machined from the strain free grip ends of previously tested 0.500-inch diameter tensile specimens. The average and range of chemical impurities, density, and grain size in the plutonium used are presented in Table VI.

A 440,000 pound Baldwin-Lima-Hamilton Universal Testing Machine equipped with a glove box mounted between the platen and the adjustable cross-head was used for the compression testing.

Prior to the study of the compressive properties of plutonium, it was necessary to establish the proper specimen height-diameter ratio. It is stated in the literature^[5] that the optimum height-diameter ratio for compression specimens should fall in the range of 1.5 to 10.0. Furthermore, a height-diameter ratio of 2.0 is most commonly employed. With this in mind, 0.500-inch diameter specimens with height-diameter ratios of 2.2 and 3.3 were prepared. During compression testing these specimens buckled at a stress of approximately 110,000 psi, Figure 30, which indicated that the height-diameter ratios were too high. Note that peripheral cracks were developed in the region of greatest bending.

To overcome buckling, specimens with height-diameter ratios of 1.0, 1.25, 1.5 and 1.75 were tested. The specimens with height-diameter ratios of 1.0 and 1.25 shattered violently and flew apart at ultimate compressive strengths ranging

from 162,000 to 178,000 psi, Figure 31. The specimens with an height-diameter ratio of 1.5 failed by shearing at an approximate 45° angle, at ultimate strengths of 175,200 and 178,600 psi, Figure 32a. The 1.75 height-diameter ratio specimens failed by shearing at strengths of 164,400 and 167,800 psi, however, they were observed to buckle slightly prior to failure. Since the 1.5 height-diameter ratio specimens, 0.500-inch diameter by 0.750-inch length, produced the desired 45° shear failure without buckling, this height-diameter ratio was selected as the standard for compressive strength determinations in the alpha, beta, gamma and delta phases. The relatively short length of this specimen eliminates most extensometer systems from use. Thus, the Platen Deflectometer, described earlier in this paper, was used to obtain load-platen displacement curves. Yield strengths for the alpha, beta, gamma and delta phase regions were obtained from these curves in the way described earlier.

To obtain 0.01 per cent yield strength and modulus of elasticity data at 30 C, a linear differential transformer type extensometer was used on specimens 0.500 inch in diameter by 2.75 inches long.

Both the elevated temperature and below room temperature testing were conducted in an open container which allowed both upper and lower compressive bearing surfaces to be heated or cooled to the desired test temperature. Heating and cooling mediums, as well as temperature control were the same as in the tensile work.

Results and Discussion

1. Compression Properties at 30 C

A total of 27 specimens with 1.5 height-diameter ratios were tested at 30 C to establish the ultimate compressive strength. Yield strengths were determined for approximately half of the specimens tested (see Table VII). Unfortunately the chemical analysis data obtained on the specimens were not accurate enough to use in a correlation of compressive strengths with impurity constituents. However, on each test specimen, accurate density data were obtained which reflect the quality of the plutonium. Accordingly, the ultimate strength data were separated into two groups, one for specimens with densities less than 19.50 g/cc and the other for densities equal to or greater than 19.50 g/cc, Table VII. The average ultimate compressive strength for the high density group is only 6,500 psi greater than the low density group. Thus the density variations in the alpha phase at 30 C had an almost

negligible effect on ultimate compressive strength. Sufficient data were not available to make the same comparison on a yield strength basis. Note that for most of the metal groups, the ultimate compressive strength values within any particular metal group agree very closely.

Modulus of elasticity and 0.01 per cent yield strength data at 30 C were obtained on five specimens with height to diameter ratios of 5.5, Table VIII.

In comparison with the 59,100 psi ultimate strength in tension^[5] the ultimate compressive strength, 175,000 psi, is 200 per cent higher. The average compressive 0.01 per cent yield strength, 38,200 psi, is 19 per cent higher than the tensile 0.01 per cent yield strength, 32,100 psi. The average values for the modulus of elasticity in both compression and tension are identical, at 14.3×10^6 psi.

Prior to failure in specimens with height-diameter ratios of 1.5 or less, extensive barreling is produced, Figure 32a. In particular, a specimen with a height-diameter ratio of 1.0 increased 8.2 per cent in diameter and decreased 11.5 per cent in length after loading to 164,000 psi and unloading for measurement and visual observation. No visible surface cracks were apparent and the specimen ultimately failed at 178,000 psi.

As indicated above, in addition to barreling, appreciable axial plastic deformation was produced in the specimens prior to failure. The total plastic deformation in length ranged from 18.6 to 26.4, with an average of 22.8 per cent.

2. Effect of Temperature

As illustrated in Figure 33 and Table IX, the effect of temperature on the compression properties of plutonium at a testing speed of 0.015 inch/minute is quite marked. In the brittle alpha phase, both the ultimate and yield strengths decrease approximately 60 per cent over the temperature range -30 to 110 C.

Ductility in the alpha phase is low compared to the beta, gamma and delta phases; a typical brittle, shear type fracture with some

barreling was obtained at all alpha phase test temperatures, Figure 32a and 32b. As reported in Table IX the total plastic decrease in length prior to fracture increased from 4.5 per cent at -30 C to 26.5 per cent at 70 C, a decrease to 18.3 per cent was observed at the 110 C test temperature.

During this study it was determined that increases in the density of compression specimens could be obtained by compression at 100 and 110 C. A specimen compressed to 83,000 psi at 100 C increased in density, measured at 30 C, from 19.41 to 19.55 g/cc, a 0.73 per cent increase. Another specimen compressed to 63,500 psi at 110 C exhibited 0.46 per cent density increase from 19.55 to 19.64 g/cc. No indication of fracture or impending failure could be observed during visual examination of the specimens.

While testing specimen D-5 at 70 C and an initial testing speed of 0.015 inch/minute, no indication of brittle failure was observed on the load-platen displacement curve. The test was continued at the original testing speed for approximately 10 minutes past the point where failure should have occurred. At this time it was decided to load the specimen to 100,000 pounds at a testing speed of roughly 1/2 inch/minute. After this loading the specimen had increased 300 per cent in area and decreased 75.8 per cent in height, Figure 34. Note the radial cracking at the periphery, and large radial crack extending almost to the center of the disk. To gain further information on this result a similar test was conducted with specimen E-1. This time an indication of brittle failure was obtained at 15,200 pound load or 118,400 psi. The testing speed was then increased to 1/2 inch/minute and loading was continued to 100,000 pounds. The flattened specimen E-1 is similar in appearance and dimensions to specimen D-5, Figure 34.

Figures 35, 36, 37, 38 and 39 illustrate the results of a metallographic examination of a sample from flattened specimen D-5. The extensive peripheral cracking present is illustrated in Figures 35 and 36. Toward the center of the disk, however, little cracking was apparent, Figure 37. Figures 38 and 39 illustrate the variation in grain structure

across the 0.18 inch thickness of the disk. Note the elongation of grains in the direction of flow.

The above experiment indicates that it is possible to appreciably compress plutonium at fairly high alpha temperatures without excessive fragmentation, especially toward the interior of the specimen. Thus it may be possible to accomplish limited dimensional sizing operations without fracture in the alpha phase.

Since a high degree of plasticity is present in the beta, gamma and delta phases ultimate strength data could not be obtained. Yield strength values in the beta and gamma phases decrease with increasing temperature. Referring to Figure 33, the beta phase yield strength is decreased 70 per cent as the temperature increases from 130 C to 190 C, while in the gamma phase the yield strength decreases 30 per cent over the 230 to 300 C temperature range. The yield strength in the delta phase at 330 C was the lowest of all temperatures studied.

For the beta, gamma and delta phases an indication of the effect of metal quality, i. e., impurity content and density, can be obtained from Figure 40 and Tables IX and X. In general, the higher quality metal, indicated by a higher density and a lower impurity content, has slightly lower yield strengths over the range of testing temperatures studied. No explanation can be offered for the apparent exception to this observation at 300 C.

3. Formability Studies

In the beta, gamma and delta phases a measure of plasticity or formability was obtained by loading the test specimens to 100,000 pounds at approximately 1/2 inch/minute after the yield strength had been obtained at the normal speed of 0.015 inch/minute. Decrease in length and increase in area data were determined as measures of formability, Figures 41, 42 and Tables IX and X. It can be seen that formability increases rapidly as the test temperature is increased through the beta, gamma and delta phases, the delta phase being the most formable.

To determine the effect of loading to 100,000 pounds on microstructure, a series of metallographic samples were selected from the flattened compression specimens. In the beta phase, a number of cracks had formed on the surfaces where the compressive load was being applied, Figure 43. All inclusions were strung out in the direction of flow, perpendicular to the compression direction, Figures 44 and 45. The effect of the 100,000 pound beta compression on resultant alpha grain structure is illustrated in Figures 46 and 47. In Figure 46 the non-uniform nature of the grain structure is apparent, the average grain size is 0.012 mm. An area containing columnar grains is illustrated in Figure 47. The axes of the columnar grains are parallel to the compression direction and perpendicular to the direction of metal flow during compression. A possible explanation for the columnar grain formation was presented in the tensile portion of this paper.

Compression to 100,000 pounds in the gamma phase also produced surface cracks similar to those produced in beta phase compression. In addition, interior cracks were produced which were aligned in the direction of flow during compression, Figure 48. Similar to the influence of beta forming on alpha grain structure, some areas of the gamma compressed specimens had a columnar grain structure like that illustrated in Figure 47. In addition, a columnar grain structure is present in some areas at the compression surface of the flattened specimen, Figure 49. Grain sizes ranged from 0.033 to 0.070 mm over the flattened section.

In the delta phase, at 330 C, compression to 100,000 pounds resulted in a number of large cracks aligned in the direction of flow, Figure 50. The alpha grain structure resulting from delta compression is uniform and has an average grain size of 0.0089 mm with no preferential grain alignment, Figure 51.

In summary of the above metallographic data:

- a. beta forming results in a few cracks at the compression surfaces; the grain structure is non-uniform with columnar areas.
- b. gamma forming results in interior cracking in addition to

cracks at compression surfaces; again the grain structure is non-uniform, with columnar grains at the compression surfaces and in scattered areas over the flattened section.

- c. delta forming results in severe interior cracking; the grain structure is uniform and very fine.

It must be remembered that some of the effects observed above are possibly the result of cooling through the appropriate transformations after forming.

4. Effect of Testing Speed

For the alpha phase, Figures 52, 53 and Table XI illustrate that testing speed has the same general effect on the ultimate and yield strength in compression as was observed in tension. As the testing speed is increased from 0.002 inch/minute to 1.00 inch/minute the strength values increase to a maximum and then decrease. As discussed in the section on tensile properties, this is probably the result of a competition of strain hardening and notch sensitivity factors.

In the beta phase, the yield strength increases almost linearly with increasing testing speed, Figure 53. Over the range of testing speeds studied the increase in yield strength is 350 per cent. For the gamma phase, a 70 per cent increase in yield strength from 2,620 to 4,500 psi is observed. Comparison with tensile data, indicates that for the beta and gamma phases the effect of testing speed on yield strength results is about the same for both tension and compression testing.

A further indication of the effect of metal quality on yield strength can be determined from data obtained at various testing speeds in the beta phase for low and high quality metal, Figure 54 and Table XII. At testing speeds ranging from 0.002 to 1.0 inch/minute, the yield strength for high quality plutonium is 20 to 30 per cent lower than that for low quality plutonium.

The effect of testing speed and test temperature on total plastic deformation of alpha phase plutonium prior to fracture is illustrated in Figures 55, 56 and Table XIII. For all testing speeds, as test

temperatures increase the amount of plastic deformation increases to a maximum and then decreases, Figure 55. This maximum occurs at 70 C for all testing speeds except 0.002 inch/minute where the maximum occurs at 30 C.

At -30 and 30 C, Figure 56, the effect of increasing testing speed is to decrease the total plastic deformation, which is generally the case for most metals. However, at the 70 and 100 C test temperatures, the total plastic deformation increases up to the 0.060 inch/minute testing speed and then decreases with increasing testing speed. The initial increase is probably the result of recovery which would have less effect as testing speed increases.

The effect of testing speed on the deformation characteristics of the specimens tested at 70 and 110 C is illustrated in Figures 57 and 58. Note that the 0.060 and 0.250 inch/minute speeds produce similar failures, i. e., barreling followed by a shear fracture. For the 1.0 inch/minute testing speed, the typical shear failure is obtained, however the barreling has been replaced by a localized bulge. This occurs for both 70 and 110 C temperatures at the 1.0 inch/minute testing speed, Figure 58, and is not observed at lower temperatures at this speed. This phenomenon is not unusual since it is known that as the rate of plastic deformation increases, deformation in the specimen becomes more localized. Thus bulging is produced at the high testing speeds during compression testing. Bulging is not observed at the lower test temperatures and high test speed because fracture occurs before extensive localized plastic deformation becomes apparent.

CREEP TESTING

Experimental Material and Testing Techniques

Densities and total impurity contents for the creep specimens tested are presented in Table XIV. The density of casting heat 18-10-12, 19.43 g/cc, is at the low end of the density range of specimens discussed earlier in the paper, however, the total impurity contents are about average.

Results and Discussion

Impact energy values ranging from 1.3 to 4.8 foot-pounds, with an average of 2.6 foot-pounds were obtained, Table XV. A typical brittle fracture resulted in each case. Seven of the specimens tested failed at both ends of the gage length, Figure 61, while one specimen failed only at one end of the gage length. The cause for failure at the ends of the gage length can probably be attributed to non-axiality of loading, since inspection of the radii at either end of the gage length showed that no uneven junctures were present.

TORSION TESTING

The experimental material for the torsion specimens was also comparable to that used in the tensile property study. Five tubular torsion specimens, with 0.250-inch inside diameter, 0.375-inch outside diameter and 2.50-inch gage length were fabricated. Testing was done at 30 C in a plastic encased fixture, Figure 62, on a non-glove-boxed Tinius Olsen Torsion Testing Machine. Four of the five specimens fractured brittly at ultimate shear strengths of 46,400, 54,700, 53,700 and 57,800 psi, Figure 63; the remaining specimen broke at a defect. Although accurate angle of twist data could not be obtained during testing, it was indicated that the stress-strain curve in torsion was quite similar to that for tension.

BETA, GAMMA AND DELTA PHASE EXTRUSION

Experimental Material and Procedure

Billets 18-12-3C, 18-12-4A and 19-1-4 were cast in vacuo into MgO coated graphite molds. Pouring temperature was 900 C and the mold was heated to 300 C prior to pouring. The billets were machined to size in preparation for extrusion. Billets 19-6-3 and 19-6-4 were poured at 740 C into a copper mold which had been heated to 550 C. These billets were cast to size and not machined prior to extrusion. Table XVI contains the chemical impurity and density data.

The extrusions were performed on a Baldwin Universal Testing Machine equipped with a glove box and a fixture which permitted extrusions at forces up to 50 tons. Two different types of extrusion dies were used, a shear die and a streamline flow die, Figure 64. All billets were extruded at a ram speed of 1.5 inches per minute at a 9 to 1 extrusion ratio. The billets were heated to the extrusion temperature in a peanut oil bath. No lubricant was used during extrusion and the atmosphere in the glove box was air.

Results and Discussion

The extrusion pressures and constants obtained for the beta, gamma and delta phases, Table XVII, reflect the elevated temperature tensile strength data previously obtained. The tensile strength was found to decrease in each higher temperature phase, which is also the case for the extrusion pressures and constants. The force versus platen displacement curves obtained during extrusion are comparable to those obtained for other metals.

During cooling of the extruded rods to room temperature, it was determined that decreases in diameter of 3.6, 4.5 and 7.8 per cent had occurred for extrusion in the beta, gamma and delta phases respectively. The over-all surface quality of the extruded rods was good, Figure 65. Note that bonding did not occur at the dead metal-flowing metal interface during the gamma extrusions with the shear die.

Metallographic specimens were taken at several positions along the length of extruded rods 18-12-4A, 18-12-3C and 19-1-4. Extrusion produced much the same effect on the microstructure as observed on the elongated tensile specimens. Microcracks, Pu-Pu₆Fe eutectic and PuN inclusions were all elongated in the extrusion direction.

Extruded rods 18-12-4A and 19-1-4 contained an unusually large number of PuN inclusions which is attributed to inadequate slagging action during casting. It is felt that if sufficient time is allowed between pouring and solidification, the PuN inclusions will float to the top of the melt where they can be adequately cropped after solidification. The top of cast billet 18-12-4A exhibited the interesting PuN configurations illustrated in Figure 66. A PuN cluster elongated in the extrusion direction is illustrated in Figure 67.

While examining a metallographic section taken along the extrusion direction of rod 18-12-4A it was determined that not all the microcracks were strung out in the extrusion direction. A number of microcracks were randomly oriented in the microstructure, Figure 68. This observation indicates that microcracking occurs during the beta to alpha transformation.

A wide variety of grain structure and grain size were present along the length of the beta extruded rod. Structures ranged from columnar near the rod periphery, Figure 69, to banded, alternate layers of fine and coarse grains throughout the cross section of the rod, Figures 70 and 71. In addition, a columnar alignment of grains similar to that observed in specimens tensile tested in the beta phase was observed to radiate from microcracks, Figure 72. There was no apparent preferential alignment or elongation of grains in the extrusion direction. Grain sizes throughout the rod ranged from 0.0062 to 0.025 mm. For comparison, the original as-cast structure, grain size 0.023 mm, is illustrated in Figure 73.

In the gamma extruded rods, variations were also present in the grain structure although not as marked as in the beta extruded rod. Columnar grains arranged in a swirly pattern were common throughout the cross section, Figure 74, as were randomly oriented grains similar

to those in Figure 73. As in the beta extruded rod, the alpha grains were not elongated in the extrusion direction, Figure 75. As indicated earlier, the over-all surface finish of the extruded rods was good, however during the metallographic examination a few blisters were observed on rods 18-12-4A and 18-12-3C; a typical blister is illustrated in Figure 76.

Tension, compression and hardness data were obtained on the rods extruded from billets 18-12-3C, 18-12-4A and 19-1-4. Average values for these properties are compared to as-cast data in Table XVIII. Except for the ultimate strength of the beta extruded rod, the general effect of extrusion was to increase both ultimate and yield strengths by roughly 10 per cent. The modulus of elasticity appears to be increased slightly, possibly because of orientation effects. The low ultimate strength in the beta extruded rod can be attributed to the relatively poor quality of the initial billet which became apparent during the metallographic examination.

The ultimate strength in compression may have been slightly lowered by extrusion. The poor quality of billet 18-12-4A was reflected in the compression properties of the beta extruded rod. Only one of the four compression specimens from this rod did not fail at a defect. Poor quality cast billets result in the presence of deleterious stringers of inclusions in the extruded rod which act as stress raisers during compression causing premature failure.

Density and hardness data from the extruded rods are comparable to as-cast plutonium. None of the properties studied seemed to vary appreciably along the length of the extruded rods.

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FIGURE 1

Typical Area, Casting Heat 19-6-4, Density 19.56 g/cc. Note Microcracking, 50X.

FIGURE 2

Typical Area, Casting Heat 18-1-6L, Density 19.47 g/cc. Note Larger Size Microcracks Than in Figure 1, 50X.

FIGURE 3

Same Sample as in Figure 1, Photographed at 250X to Show Spherical Unidentified Inclusions. Note that Some Appear to have a "Donut" Type Configuration, Arrow, 250X.

FIGURE 4

Typical Area for 19-2-1 and 19-2-2 Casting Heats, Average Density 19.43 g/cc, 1250 ppm Average Fe Content, Table V. Pu_6 Fe Eutectic (A), Unidentified Spherical Inclusions (B), and Unidentified White Particulate Inclusions Visible in Field (C). Note Absence of Microcracking, 250X.

FIGURE 5

Typical Area for Casting Heat 19-11-2E, Pu₆ Fe Eutectic in Plutonium Matrix, Density 19.47 g/cc, 1175 ppm Fe. Grain Size of Eutectic Network 0.033 mm, 10 Second Etch, 100X.

FIGURE 6

Specimen 19-7-2, Typical of Grain Structure in All As Cast Plutonium. Grain Size 0.047 mm, 250X.

FIGURE 7
Design for 0.250 inch Diameter Tensile Specimens

FIGURE 8
Martins Extensometer on
0.505 Inch Diameter Tensile
Specimen, 1/4X.

FIGURE 9
EFFECT OF TEMPERATURE ON TENSILE STRENGTH

FIGURE 10
EFFECT OF TEMPERATURE ON ELASTIC MODULUS

FIGURE 11

Effect of Test Temperature on Alpha Phase Elongation

FIGURE 12
EFFECT OF TEMPERATURE ON DUCTILITY

FIGURE 13

Beta Phase - 160°C , 0.015 Inch/Minute.

FIGURE 14

Gamma Phase - 265°C , 0.015 Inch/Minute. Upper Specimen Contained Pu_6Fe Eutectic, No Microcracks. Lower Specimen Contained Microcracks, No Pu_6Fe Eutectic.

FIGURE 15

Delta Phase - 325°C , 0.015 Inch/Minute.

FIGURE 16

Typical Beta Phase Tensile Fracture, 160°C, Specimen 19-9-7C. Note Cracks Elongated in Direction of Loading, 20X.

FIGURE 17

Area from Above Sample Illustrating, Elongated Cracks, Pu_6Fe Eutectic (A) and Unidentified Spherical Inclusions (B), 150X.

FIGURE 18

Grain Structure of Beta Phase Tested Specimen 19-9-7C, Note Columnar Grains Apparently Nucleated by Cracks or Inclusions. Average Grain Size 0.0089 mm, As Cast Grain Size 0.060 mm, 100X.

FIGURE 19

Specimen 19-5-6H, 44X.

FIGURE 20

Specimen 19-9-8H, 44X.

FIGURE 21

Specimen 19-11-3J, 20X.

The Above Figures Illustrate the Types of Fracture that Occurred During Gamma Phase Tensile Testing at 265°C. The Reason for the Different Types is Believed to be a Function of the Degree of Microcracking Originally Present in the As Cast Structure.

FIGURE 22

Same Area as in Figure 19 Illustrating Uniform Random Grain Structure. Grain Size 0.040 mm, which is Essentially the Same as the As Cast Grain Size, 50X.

FIGURE 23

Typical Delta Phase Tensile Fracture, 325°C, Specimen 19-9-7A. Note Elongated Cracks Along Loading Axis, 20X.

FIGURE 24
STRESS-PLATEN DISPLACEMENT CURVES

FIGURE 25
EFFECT OF TESTING SPEED ON ALPHA
PHASE TENSILE STRENGTH

FIGURE 26

Effect of Testing Speed
on Beta Phase Properties at 130, 160 and 190 C

FIGURE 27
Effect of Testing Speed on Gamma Phase Properties at 265 C

0.015 In./Min.
0.060
0.250
1.0
As Machined

FIGURE 28
Beta Phase - 160°C

0.002 In/Min.
0.060

0.250
1.0

As Machined

FIGURE 29
Gamma Phase - 265°C

Type of Deformation and Fracture at Indicated Temperatures and Test Speeds.

FIGURE 30

Compression Specimens with Height to Diameter Ratios of 3.3, Before and After Testing. Note Buckling and Peripheral Cracks which Occurred at a Stress of 110,000 psi.

FIGURE 31

Fragmentation Accompanying Failure of 1.0 and 1.25 h/d Ratio Specimens.

FIGURE 32a

FIGURE 32b

Illustration of 45° Shear Failure and Barreling Produced in 1.5 h/d Ratio Specimens at Test Temperatures of 30°C (Left) and 110°C (Right).

FIGURE 33
EFFECT OF TEMPERATURE ON AVERAGE
COMPRESSIVE STRENGTH FOR HIGH DENSITY
PLUTONIUM

FIGURE 34

Specimens Loaded to 100,000 lbs. at 70°C, 1X.

Compression Direction →

FIGURE 35

Peripheral Cracking in Specimen D-5 After Loading to 100,000 lbs., 50X.

FIGURE 36

Cracking in Specimen D-5 After Loading to 100,000 lbs., 50X.

FIGURE 37

Typical of Crack Free Area Toward Center of Specimen D-5 After Loading to 100,000 lbs., 50X.

Compression Direction

FIGURE 38

Variation in Grain Structure Across Thickness of Flattened Disc. Note Grain Elongation in Direction of Flow, 20X.

Compression Direction

FIGURE 39

Same Area as Figure 38, 50X.

FIGURE 40
EFFECT OF METAL QUALITY ON YIELD STRENGTH
IN THE BETA, GAMMA AND DELTA PHASES

FIGURE 41
EFFECT OF TEMPERATURE ON FORMABILITY
IN COMPRESSION

DETERMINED AFTER LOADING THE SPECIMEN
TO 100,000 LBS. THE INITIAL SPECIMEN
SIZE WAS 0.500 IN. DIA. X 0.750 IN. HEIGHT

FIGURE 42

Relative Degree of Formability at 100,000 lbs. Load for the 150, 230 and 330°C Test Temperature in the Beta, Gamma and Delta Phases, Respectively, 1/2X.

↓ Compression Direction ↓

FIGURE 43

Crack Formed During Compression to 100,000 lbs. at 150°C, 50X.

FIGURE 44

Elongation of Inclusions in Direction of Flow, During Compression to 100,000 lbs. at 150°C, 100X.

FIGURE 45

Elongation of Plutonium Nitride Cluster During Compression to 100,000 lbs. at 150°C, 250X.

↓ Compression Direction ↓

FIGURE 46

Non-uniform Grain Structure Present in Plutonium Compressed to 100,000 lbs. at 150°C. Grain Size - 0.012 mm, 100X.

FIGURE 47

Columnar Grains Aligned in Compression Direction, for Specimen Compressed to 100,000 lbs. at 150°C, 250X.

Compression Direction ↓

FIGURE 48

Interior Crack Developed During Compression to 100,000 lbs. at 230°C, 250X.

Compression Direction ↓

FIGURE 49

Columnar Grains at Compression Surface of Gamma Compressed Specimen, 300°C. Grain Size of Non-columnar Region - 0.047 mm, 100X.

Compression Direction ↓

FIGURE 50

Cracks Resulting from Delta Phase Compression to 100,000 lbs. at 330°C, 50X.

FIGURE 51

Typical Grain Structure of Delta Compressed Plutonium, 330°C. Grain Size, 0.0089 mm, 250X

FIGURE 52
EFFECT OF TESTING SPEED ON ULTIMATE
STRENGTH IN COMPRESSION

FIGURE 53
EFFECT OF TESTING SPEED ON YIELD STRENGTH
IN COMPRESSION

FIGURE 54

EFFECT OF METAL QUALITY ON YIELD STRENGTH
TEST TEMPERATURE, 175°C

FIGURE 55
EFFECT OF TEMPERATURE ON TOTAL PLASTIC
DEFORMATION PRIOR TO FRACTURE, WITH TESTING
SPEED AS A PARAMETER

FIGURE 56
EFFECT OF TESTING SPEED ON TOTAL PLASTIC
DEFORMATION PRIOR TO FRACTURE

0.060

0.250

1.0

FIGURE 57

Effect of Testing Speed on Deformation Characteristics at 110°C for the 0.060, 0.250 and 1.0 Inch/Minute Testing Speeds. Plane of Shear Fracture is 45° Back from the Plane of the Photograph. 1X.

70°C

110°C

FIGURE 58

Specimens Tested at 70 and 110°C at a Testing Speed of 1.0 Inches/Minute. Bulging is Apparent in the Specimens at the Left for Each Testing Temperature, While the Shear Type Failure is Illustrated in the Right Hand Specimens which are at a 90° Angle to those on the Left. 3/4X.

FIGURE 59
ALPHA PLUTONIUM CREEP CURVES

FIGURE 60

ALPHA PLUTONIUM CREEP CURVE

FIGURE 61

Typical Brittle Fracture Occurring in Tension Impact Specimens.

FIGURE 62

Fixture for Torsion Testing, at Left the Specimen Position is Illustrated, at Right the Fixture is Encased in the Plastic Container, 1/4X.

FIGURE 63

Brittle Fracture Occurring in
Torsion Specimen, 1X.

SHEAR EXTRUSION DIE

STREAMLINE EXTRUSION DIE

FIGURE 64
DIES USED IN PLUTONIUM EXTRUSION

FIGURE 65

Gamma Extruded Rod 18-12-3C.
Note that Bonding did not Occur
Between the Dead Metal-Flowing
Metal Interface, 1/2X.

FIGURE 66

Different Configurations of PuN Inclusions at Top of Cast Billet 18-12-4A,
250X.

FIGURE 67

Plutonium Nitride Aligned in Extrusion Direction of Rod 18-12-4A, 250X.
As Polished Surface, Bright Field, 250X.

Extrusion Direction →

FIGURE 68

Randomly Oriented Microcracks in Extruded Rod 18-15-4A, 250X.

Rod Periphery

FIGURE 69

Columnar Grain Structure Existing at Periphery of Beta Extruded Rod. Transverse to Extrusion Direction, 100X.

Rod Periphery

FIGURE 70

Banded Structure in Beta Extruded Rod. Note Coarse Grained Periphery, Fine Grained Layer, Then Fine and Coarse Grained Regions Tending to Align in Radial Direction. Transverse to Extrusion Direction, 100X.

FIGURE 71

Banded Structure Existing in Beta Extruded Rod. Fine Grain Size -0.0062 mm, Coarse Grain Size -0.025 mm. Transverse to Extrusion Direction, 100X.

FIGURE 72

Columnar Grains Radiating from Microcracks. Transverse to Extrusion Direction, 100X.

FIGURE 73

As Cast Grain Structure Prior to Beta Extrusion. Grain Size ~ 0.023 mm.
100X.

FIGURE 74

Columnar Grains Aligned in a Swirly Pattern in Gamma Extruded Rods
18-12-3C and 19-1-4, Grain Size ~ 0.028 mm. Transverse to Extrusion
Direction, 250X.

Extrusion Direction →

FIGURE 75

Non-alignment of Grains in Extrusion Direction of Gamma Extruded Rod 19-1-4, Grain Size - 0.040 mm, 100X.

FIGURE 76

Blister on Periphery of Gamma Extruded Rod Near Butt End, Transverse to Extrusion Direction, 50X.

TABLE I

CHEMICAL ANALYSIS⁽¹⁾, DENSITY AND GRAIN SIZE⁽²⁾ OF PLUTONIUM USED IN TENSILE STUDY

	<u>Al</u>	<u>Ca</u>	<u>Cr</u>	<u>Cu</u>	<u>Fe</u>	<u>Mg</u>	<u>Mn</u>	<u>Ni</u>	<u>Si</u>	<u>C</u>	<u>Total</u>	<u>Density (g/cc)</u>	<u>As Cast Grain Size mm</u>	<u>Number of Samples</u>
Min	3	2	5	2	51	2	10	2	1	40	-	19.43	0.024	-
Max	40	16	100	30	1175	20	100	50	20	290	-	19.60	0.070	-
Avg	14	5	22	7	252	15	47	19	3	136	520	19.53	0.046	21

(1) Reported in parts per million

(2) Reported as average grain diameter in millimeters

TABLE II

EFFECT OF TEMPERATURE ON TENSILE PROPERTIES OF ALPHA PHASE PLUTONIUM⁽¹⁾

	Test Temp. (C)	Ultimate Strength (psi)	0.01% Yield Strength (psi)	Modulus of Elasticity (10 ⁶ psi)	Elongation ⁽²⁾ Per Cent	Reduction In Area Per Cent	Number of Samples Tested
Min		52,500	46,700	14.0	0.016	-	
Max	-30	63,300	56,800	15.2	0.020	-	4
Avg		57,300	50,300	14.7 (12.7) ⁽³⁾	0.018	-	
Min		47,800	28,200	13.5	0.054	-	
Max	30	56,800	35,600	14.8	0.077	-	5
Avg		50,900	32,100	14.3	0.068	-	
Min		42,900	14,900	12.6	0.41	-	
Max	70	44,600	15,600	12.7	0.45	-	2
Avg		43,800	15,200	12.6	0.43	-	
Min		29,000	11,800	8.5	0.91	-	
Max	100	30,600	15,200	11.5	1.08	-	5
Avg		34,800	13,600	9.8 (9.2) ⁽³⁾	1.00	-	
Min		-	11,600	9.0	-	-	
Max	110	-	13,000	10.9	-	-	2
Avg		33,100	12,300	10.0	-	-	

(1) Testing speed: 0.015 inches/minute

(2) Based on one inch gage length

(3) Determined with Martins Extensometer

TABLE III

EFFECT OF TEMPERATURE ON TENSILE PROPERTIES
OF BETA, GAMMA AND DELTA PHASES⁽¹⁾

	Test Temp. (C)	Ultimate Strength (psi)	Yield Strength (psi)	Modulus of Elasticity (10 ⁶ psi)	Elongation ⁽²⁾ Per Cent	Reduction In Area Per Cent	Number of Samples Tested	Phase
Min		11,700	10,240	2.0	272.0	100.0		
Max	130	12,500	10,570	3.9	316.0	100.0	2	Beta
Avg		12,100	10,400	3.0	294.0	100.0		
Min		5,500	3,720	-	519.0	100.0		
Max	160	5,830	4,380	-	621.8	100.0	3	Beta
Avg		5,620	3,950	-	570.4	100.0		
Min		3,550	2,540	-	481.3	100.0		
Max	180	3,600	2,600	-	525.0	100.0	2	Beta
Avg		3,580	2,620	-	503.2	100.0		
Min		2,950	1,730	1.4	271.5	93.5		
Max	190	3,590	2,630	1.7	406.2	100.0	6	Beta
Avg		3,280	2,210	1.6	325.9	97.8		
Min		2,730	1,950	-	93.8	60.2		
Max	200	3,390	2,360	-	151.0	97.1	6	Beta
Avg		2,940	2,190	-	121.0	82.1		
Min		3,330	3,250	1.8	37.5	61.0		
Max	230	4,990	4,210	1.8	65.8	92.5	7	Gamma
Avg		4,420	3,860	1.8	50.0	75.0		

TABLE III (Contd.)

	Test Temp. (C)	Ultimate Strength (psi)	Yield Strength (psi)	Modulus of Elasticity (10 ⁶ psi)	Elongation Per Cent	(2) Reduction In Area Per Cent	Number of Samples Tested	Phase
Min		2,500	2,340	-	33.0	64.0		
Max	265	4,750	3,660	-	84.4	84.7	7	Gamma
Avg		3,470	2,900	-	57.2	77.0		
Min		1,540	1,360	0.9	37.5	57.9		
Max	300	2,630	2,100	1.2	68.8	98.6	8	Gamma
Avg		2,020	1,650	1.0	50.1	82.8		
Min		837	731	0.35	65.8	97.5		
Max	325	953	848	0.40	68.8	98.4	2	Delta
Avg		895	790	0.38	67.3	98.0		

(1) Testing speed: 0.015 inches/minute

(2) Based on one inch gage length

TABLE IV

EFFECT OF TESTING SPEED ON ALPHA PHASE STRENGTH

Testing Speed in /min	30° C					110° C				
	Sample No.	Density (g/cc)	Total Impurity (ppm)	Ultimate Strength (psi)	0.01% Yield Strength (psi)	Sample No.	Density (g/cc)	Total Impurity (ppm)	Ultimate Strength (psi)	0.01% Yield Strength (psi)
0.002	19-9-1A	19.56	439	42,600	23,000	19-4-11 ⁽¹⁾	19.53	384	21,500	---
	19-9-1B	19.56	439	44,800	24,600	19-4-10 ⁽¹⁾	19.53	384	23,200	7800
	19-11-2G	19.47	1476	51,300	35,300					
0.015	19-5-8N	19.60	377	56,800	35,600					
	19-4-2P	19.43	780	50,500	---	19-3-4G	19.51	328	33,100	13,000
	19-3-4E	19.51	328	47,800	---	19-3-4H	19.51	328	---	11,700
	19-9-1C	19.56	439	---	29,300	---	---	---	---	---
	19-3-4F	19.51	328	48,100	28,200					
0.060	19-9-2E	19.49	380	54,800	31,800	19-5-3A	19.48	504	33,400	12,800
	19-9-4L	19.53	468	49,200	29,700	19-5-3B	19.48	504	37,400	---
	19-9-6U	19.52	616	50,700	25,700	19-4-1M	19.53	384	32,600	13,400
	19-9-3K	19.56	295	47,000	---	19-5-3C	19.48	504	39,500	---
0.250	19-9-5Q	19.55	616	56,500	28,100	19-5-3D	19.58	504	38,600	---
	19-9-6V	19.52	616	54,000	36,600	19-4-1L	19.53	384	33,300	---
1.0	19-9-6X	19.52	616	51,700	---	19-5-6G	19.57	486	31,500	---
	19-9-6Z	19.52	616	46,800	---	19-5-5E	19.60	295	29,800	---

(1) Unlike the specimens tested at faster speeds at this temperature, the load dropped off gradually just before failure indicating that some necking may have taken place. However, the degree of necking was so small that it could not be measured with a micrometer caliper.

TABLE V
EFFECT OF TESTING SPEED ON BETA AND GAMMA PHASE TENSILE PROPERTIES

Test Speed	Ultimate Strength (psi)		Yield Strength (psi)		Elongation ⁽¹⁾ (%)		Reduction in Area (%)		Number of Samples Tested
	Average	Range	Average	Range	Average	Range	Average	Range	
Beta Phase - 130 C									
0.002	7,000	-----	3,920	-----	---	---	---	---	-
0.015	12,100	11,700-12,500	10,400	10,200-10,600	294.0	272.0-316.0	100	---	2
0.060	17,300	-----	---	-----	181.5	---	100	---	1
0.250	19,800	-----	16,900	-----	43.5	---	55.2	---	1
1.00	28,800	27,800-29,800	21,700	19,100-24,300	31.5	---	35.5	---	2
Beta Phase - 160 C									
0.002	3,400	-----	2,550	-----	---	---	---	---	1
0.015	5,600	5,500-5,830	3,950	3,720-4,380	570.4	519.0-621.8	100	---	3
0.060	8,500	8,170-8,840	6,200	5,920-6,480	360.9	315.6-406.2	100	---	2
0.250	12,400	11,900-12,900	9,900	9,600-10,200	251.6	196.9-306.2	98.6	98.3-98.9	2
1.00	18,700	18,600-18,800	15,200	14,800-15,700	110.9	78.1-143.7	70.0	61.1-79.0	2
Beta Phase - 190 C									
0.002	2,400	-----	1,520	-----	---	---	---	---	1
0.015	3,280	2,950-3,590	2,210	1,730-2,630	325.9	271.5-406.2	97.8	93.5-100	6
0.060	5,230	4,970-5,510	4,030	3,610-4,410	331.5	---	100.0	---	3
0.250	8,180	6,740-9,880	5,890	4,070-8,360	243.5	---	100.0	---	9
1.00	10,600	10,000-11,500	7,820	6,370-9,280	212.5	---	100.0	---	3
Gamma Phase - 265 C									
0.002	3,250	-----	2,280	-----	75.0	---	90.9	---	1
0.015	3,400	2,500-4,750	2,750	2,340-3,650	59.3	33.0-84.4	79.6	71.2-84.7	6
0.060	3,910	3,280-4,240	3,300	3,100-3,540	49.6	40.7-64.1	68.6	49.4-99.0	3
0.250	4,500	3,710-5,200	4,030	3,520-4,600	42.7	31.3-50.0	69.2	52.3-85.6	3
1.00	4,940	4,160-5,350	4,720	4,050-5,070	44.8	37.5-53.2	69.3	38.0-93.2	3

(1) Based on one-inch gage length.

TABLE VI
CHEMICAL ANALYSIS,⁽¹⁾ DENSITY AND AS-CAST GRAIN SIZE⁽²⁾ OF PLUTONIUM STUDIED

High Density⁽⁴⁾

	Al	Ca	Cr	Cu	Fe	Mg	Mn	Ni	Si	C	O ⁽³⁾	H ⁽³⁾	N ⁽³⁾	Total	Density (g/cc)	Grain Size(mm)	No. of Samples
Min.	2	3	1	2	50	10	5	1	1	58	81	1	1	415	19.52	0.024	---
Max.	20	50	200	20	500	50	200	200	20	210	190	13	40	1024	19.59	0.050	---
Avg.	6	8	34	10	216	22	45	38	5	140	132	6	11	666	19.55	0.040	14

Low Density⁽⁵⁾

Min.	2	5	2	5	100	5	10	20	1	60	64	1	1	457	19.34	0.016	---
Max.	13	13	100	20	2000	200	500	200	50	600	200	11	10	3468	19.48	0.053	---
Avg.	4	8	51	14	483	62	97	97	28	172	123	8	4	1140	19.44	0.033	10

(1) Reported in parts per million.

(2) Reported as average grain diameter in millimeters.

(3) The average for the O, H and N impurities are based on 5 samples for the high density group and 7 samples for the low density group.

(4) Equal to or greater than 19.50 g/cc.

(5) Less than 19.50 g/cc.

TABLE VII
COMPRESSION PROPERTIES OF PLUTONIUM⁽¹⁾ AT 30 C
Density Less Than 19.50 g/cc

Specimen Number	Density (g/cc)	Ultimate Strength (psi)	Yield Strength (psi)	Diamond Pyramid Hardness (10 kg load)	Plastic Decrease In Length Prior To Failure (2) Per Cent	Metal Group
17-12-1G1	19.42	178,600	-	272	-	1
17-12-1G2	19.42	175,200	-	272	-	
18-1-1A	19.34	163,900	-	255	-	2
18-1-1B	19.47	175,600	-	255	-	3
18-1-4G1	19.43	177,000	-	267	-	4
18-1-4G2	19.43	177,800	-	267	-	
18-1-6L1	19.47	156,600	-	265	-	5
18-1-6L2	19.47	149,000	-	265	-	
18-1-7M1	19.43	163,200	-	256	-	6
18-1-7M2	19.43	172,000	-	256	-	
18-1-7N1	19.46	165,600	-	275	-	7
18-1-7N2	19.46	164,400	-	275	-	
AVERAGE(3)	19.43	168,500	-	260	-	--

TABLE VII (Contd.)

Density Equal to or Greater Than 19.50 g/cc

Specimen Number	Density (g/cc)	Ultimate Strength (psi)	Yield Strength (psi)	Diamond Pyramid Hardness (10 kg load)	Plastic Decrease In Length Prior To Failure (2) Per Cent	Metal Group
18-1-3F1	19.55	177,600	-	265	-	8
18-1-3F2	19.55	175,600	-	265	-	
18-1-6K1	19.56	166,800	-	256	-	9
18-1-6K2	19.56	169,000	-	256	-	
18-8-1D1	19.55	168,200	102,400	-	21.3	10
18-8-1D2	19.55	164,000	109,100	-	18.6	
18-8-4P1	19.56	184,000	103,200	259	24.0	11
18-8-4P2	19.56	178,000	109,800	259	22.6	
18-8-5Q1	19.55	183,000	99,800	-	23.4	12
18-8-5Q2	19.55	181,000	112,700	-	23.4	
18-8-5Q3	19.55	189,000	107,600	-	25.0	
18-8-5R1	19.55	169,200	109,900	258	20.6	13
18-8-5R2	19.55	189,100	101,700	258	25.6	
19-7-3-G2	19.53	167,500	113,200	-	26.4	14
19-8-2-C5	19.55	178,000	106,300	-	20.3	15
AVERAGE(3)	19.55	175,000	107,400	263	22.8	--

(1) Testing speed: 0.015 inches/minute.

(2) Determined from load-platen displacement curve at point of failure.

(3) All average values were obtained by first finding the average within each metal group and then averaging these values for an over all average. This was done because the material tested in each metal group came from the same casting heat. It was felt that a more representative and unbiased over all average could be obtained in this way.

TABLE VIII
YIELD STRENGTH AND MODULUS OF ELASTICITY IN
COMPRESSION⁽¹⁾ AT 30° C

Specimen No.	0.01% Yield Strength (psi)	Modulus of Elasticity (10 ⁶ psi)	Density (g/cc)	Diamond Pyramid Hardness (10 kg load)
18-8-1C	47,300	13.9	19.49	261
18-8-1D	39,600	14.5	19.55	---
18-8-4O	34,200	14.7	19.56	---
18-8-4P	32,100	14.2	19.56	259
18-8-5R	37,500	14.0	19.55	258
Average	38,200	14.3	19.54	259

(1) Testing speed: 0.015 inches/minute; h/d: 5.5

TABLE IX
COMPRESSIVE STRENGTH⁽¹⁾ AND RELATED DATA FOR HIGH DENSITY PLUTONIUM

Specimen Number	Test Temp. (C)	Ultimate Strength (psi)	Yield Strength (psi)	Increase In Area ⁽²⁾ PerCent	Plastic Decrease In Length (%)	Density (g/cc)	Total Impurity Content(ppm)
19-7-3-E4	-30	194,200	161,600	-	4.7 (4)	19.53	745
19-7-3-E5	-30	190,300	160,600	-	4.5 (4)	19.53	745
(3)	30	175,000	107,400	-	22.7 (4)	19.55	-
19-7-2-D5	73	-	74,200	-	26.5 (4)	19.54	324
19-7-3-E1	70	118,400	80,200	-	-	19.53	745
19-7-3-E2	110	78,300	65,400	-	18.3 (4)	19.53	745
19-7-3-E3	110	77,200	64,800	-	-	19.53	745
19-5-4-B4	128	-	-	392	79.8 (2)	19.59	266
19-5-4-A3	130	-	20,900	409	79.9 (2)	19.59	266
19-5-4-A4	130	-	24,100	498	82.2 (2)	19.59	266
19-6-4-H4	131	-	24,600	497	83.3 (2)	19.56	412
19-6-4-G1	130	-	17,700	436	81.6 (2)	19.56	412
19-5-4-B3	149	-	11,650	557	84.8 (2)	19.59	266
19-5-4-A2	149	-	12,000	557	84.5 (2)	19.59	266
19-5-4-C3	151	-	11,970	592	85.2 (2)	19.59	266
19-5-4-C1	176	-	8,170	625	86.0 (2)	19.59	266
19-5-4-C2	176	-	8,770	625	85.5 (2)	19.59	266

TABLE IX (Contd.)

Specimen Number	Test Temp. (C)	Ultimate Strength (psi)	Yield Strength (psi)	Increase In Area ⁽²⁾ Per Cent	Plastic Decrease In Length(%)	Density (g/cc)	Total Impurity Content(ppm)
19-5-4-A1	189	-	6,820	658	86.6 (2)	19.59	266
19-5-4-D4	190	-	7,130	658	86.3 (2)	19.59	266
19-6-4-H3	191	-	6,910	661	86.5 (2)	19.56	412
19-4-3-C1	230	-	4,930	945	89.1 (2)	19.55	310
19-4-3-B1	231	-	5,110	841	87.7 (2)	19.55	310
19-5-4-B5	232	-	4,530	800	88.5 (2)	19.59	266
19-5-4-B2	266	-	3,970	957	90.3 (2)	19.59	266
19-6-4-H2	266	-	4,340	942	90.3 (2)	19.56	412
19-7-1-A3	300	-	3,430	1145	91.4 (2)	19.56	343
19-5-4B	300	-	3,380	1353	92.6 (2)	19.59	266
19-4-3-B2	300	-	3,500	1196	92.2 (2)	19.55	310
19-4-3A	330	-	816	1593	93.8 (2)	19.55	310
19-7-1-A1	331	-	1,265	1610	92.8 (2)	19.56	343

- (1) Testing speed: 0.015 inches/minute
- (2) After exceeding the yield strength the load was increased at a rapid rate to 100,000 pounds. The increase in area and decrease in length data were taken after unloading and cooling to room temperature.
- (3) A total of 15 specimens were tested at this temperature. The average values are reported.
- (4) Total plastic decrease in length was determined from load-platen displacement curve at point of failure.

TABLE X

COMPRESSIVE STRENGTH⁽¹⁾ AND RELATED DATA FOR LOW DENSITY PLUTONIUM

Specimen Number	Test Temp. (C)	Ultimate Strength (psi)	Yield Strength (psi)	Increase In Area ⁽²⁾ (%)	Plastic Decrease In Length (%)	Density (g/cc)	Total Impurity Content(ppm)
(3)	30	168,500	-	-	-	19.43	-
19-2-2-7	100	97,500	68,000	-	-	19.41	1467
19-2-2-10	100	90,000	67,000	-	-	19.41	1467
19-2-2-3	150	-	10,880	-	-	19.41	1467
19-2-2-9	150	-	14,120	-	-	19.41	1467
19-2-2-11	150	-	12,500	-	-	19.41	1467
19-2-2-12	150	-	15,300	599	-	19.41	1467
19-2-2-19	150	-	15,300	613	86.1	19.41	1467
19-2-2-1	175	-	8,750	-	-	19.41	1467
19-2-2-4	175	-	8,160	683	86.8	19.41	1467
19-2-2-2	190	-	5,870	-	-	19.41	1467
19-2-2-17	190	-	5,900	725	87.7	19.41	1467
19-2-2-5	230	-	6,120	958	89.3	19.41	1467
19-2-2-14	230	-	6,830	907	89.2	19.41	1467
19-2-2-16	230	-	7,490	853	89.2	19.41	1467

TABLE X (Contd.)

Specimen Number	Test Temp. (C)	Ultimate Strength (psi)	Yield Strength (psi)	Increase In Area ⁽²⁾ (%)	Plastic Decrease In Length(%)	Density (g/cc)	Total Impurity Content(ppm)
19-2-2-15	265	-	5,400	1069	91.7	19.41	1467
19-2-2-18	265	-	4,700	1110	91.7	19.41	1467
19-2-1-4A	300	-	2,600	-	-	19.45	2300
19-2-1-3A	300	-	-	1072	92.7	19.45	2300
19-2-2-25	330	-	2,350	1473	94.2	19.41	1467
19-2-1-1A	330	-	2,575	-	-	19.45	2300

- (1) Testing speed: 0.015 inches/minute
- (2) After exceeding the yield strength the load was increased at a rapid rate to 100,000 pounds. The increase in area and decrease in length data were taken after unloading and cooling to room temperature.
- (3) A total of 12 specimens were tested at this temperature. The average values are reported.

TABLE XI

EFFECT OF TESTING SPEED IN ALPHA, BETA AND GAMMA PHASES ON
COMPRESSIVE STRENGTH

Testing Speed (in /min)	Alpha Phase								Beta Phase	Gamma Phase
	-30 C		29 C		70 C		110 C		175 C	265 C
	Ultimate Strength (psi)	Yield Strength (psi)	Ultimate Strength (psi)	Yield Strength (psi)	Ultimate Strength (psi)	Yield Strength (psi)	Ultimate Strength (psi)	Yield Strength (psi)	Yield Strength (psi)	Yield Strength (psi)
0.002	190,700	145,200	142,000	95,300	95,700	69,000	63,500	48,100	3,900	2,620
	---	---	149,000	95,900	96,000	69,000	68,600	46,900	3,870	---
0.015	190,300	161,600	178,000	106,300	118,400	80,200	77,200	64,800	8,170	3,970
	194,200	160,600	167,500	113,200	---	---	78,300	65,400	8,770	4,340
0.060	179,800	158,600	156,750	123,000	123,200	85,400	85,000	64,800	8,930	3,630
	186,400	161,000	165,500	117,200	125,800	79,000	85,000	69,500	8,910	---
0.250	183,200	158,500	136,500	112,100	117,800	83,700	75,400	68,300	14,700	4,040
	184,000	166,000	147,600	112,800	114,100	86,000	75,900	70,400	15,600	---
1.00	176,800	140,000	140,100	111,500	107,000	---	77,500	63,500	16,900	4,420
	175,200	139,000	141,300	107,300	103,400	76,300	75,250	61,200	20,200	4,500

TABLE XII

EFFECT OF METAL QUALITY ON YIELD STRENGTH
OVER A RANGE OF TESTING SPEEDSLow Quality Metal

<u>Testing Speed (inch/minute)</u>	<u>Specimen No.</u>	<u>Yield Strength (psi)</u>	<u>Density (g/cc)</u>	<u>Total Impurity Content (ppm)</u>
.003	19-2-2-22	6650	19.41	1467
.007	19-2-2-24	7650	19.41	1467
.015	19-2-2-4	8700	19.41	1467
.015	19-2-2-1	8960	19.41	1467
.060	19-2-2-20	14,480	19.41	1467
.125	19-2-2-21	17,190	19.41	1467
.250	19-2-2-23	20,400	19.41	1467

High Quality Metal

.002	19-7-1-A-4	3900	19.56	343
.002	19-7-1-A-5	3870	19.56	343
.015	19-5-4-C-1	8170	19.59	266
.015	19-5-4-C-2	8770	19.59	266
.060	19-7-1-A-6	8930	19.56	343
.060	19-7-1-B-1	8910	19.56	343
.250	19-7-1-B-3	15,600	19.56	343
.250	19-7-1-B-4	14,700	19.56	343
1.00	19-7-1-B-5	16,900	19.56	343
1.00	19-7-1-B-6	20,200	19.56	343

TABLE XIII

TOTAL PLASTIC DEFORMATION IN ALPHA PHASE⁽¹⁾

Testing Speed (in. /min)	Total Plastic Decrease in Length ⁽²⁾ (%)			
	-30° C	30° C	70° C	110° C
0.002	7.3	27.7	23.3	15.7
	---	---	---	---
0.015	4.7	26.4	26.5	18.3
	4.3	20.3	---	---
0.060	2.7	15.5	28.3	20.0
	2.3	18.8	---	18.3
0.250	3.0	21.0	24.7	12.0
	2.3	17.7	26.0	18.3
1.00	3.0	9.0	11.0	7.7
	2.3	9.0	---	7.7

(1) Testing speed: 0.015 inches/minute.

(2) Total plastic decrease in length determined from load-platen displacement curve at point of failure.

TABLE XIV
CREEP DATA

Specimen Number	Test Temp. (C)	Applied Stress (psi)	Secondary Creep Rate (1)	Total Strain (10^{-4} in/in)	Duration of Test (Hours)	Density (g/cc)	Total Impurity Content(ppm)
18-10-12A	31.0	10,000	15.0	4.2	1370	19.43	520
19-3-2A	26.0	8,000	15.2	4.3	1850	19.49	486
19-3-2A	42.3	8,000	28.2 ⁽²⁾	-	870	19.49	486
18-10-12B	100.0	10,000	330.0	41.0	570	19.43	425

(1) 10^{-4} in/in/10,000 hours

(2) Obtained during 870 hour testing period after raising temperature to 42.3 C from 26.0 C

TABLE XV

TENSION IMPACT DATA AT 30° C

Specimen No.	Tension Impact Value (ft-lb)	Density (g/cc)	Total Impurity Content (ppm)
18-9-8C	1.4	19.48	446
18-9-8D	1.6	19.48	475
18-9-12E	3.5	19.41	1755
18-9-12F	4.2	19.41	1638
19-2-2A	2.3	19.51	---
19-2-2B	4.8	19.51	---
19-3-1A	2.1	19.53	773
19-3-1B	1.3	19.53	773
Average	2.6	19.48	976

TABLE XVI
DENSITY AND CHEMICAL ANALYSIS⁽¹⁾ DATA FOR EXTRUSION BILLETS

Billet Number	Al	Ca	Cr	Cu	Fe	Mg	Mn	Ni	Si	C	Total Impurity	Total Plutonium Per Cent	As Cast Density (g/cc)	Density After Extrusion (g/cc)
18-12-4A	2	2	20	30	500	66	20	66	13	130	853	-	-	19.49
18-12-3C	4	2	35	8	425	40	8	100	35	478	1130	-	-	19.55
19-1-4	5	5	15	10	100	125	75	35	50	135	561	-	-	19.50
19-6-3	-	-	-	-	-	-	-	-	-	-	800	99.92	19.55	19.50
19-6-4	-	-	-	-	-	-	-	-	-	-	1500	99.85	19.40	19.43

(1) Reported in ppm.

TABLE XVII
EXTRUSION DATA

Billet Number	Billet Temp. (C)	Container Temp. (C)	Maximum Extrusion Pressure (psi)	Extrusion Constant ⁽¹⁾ (psi)	Billet Dia. (in)	Billet Length (in)	Rod Dia. Produced (in)	Rod Length Produced (in)	Type Extrusion Die ⁽²⁾	Extrusion Die Throat ID (in)
<u>Beta Phase Extruded</u>										
18-12-4A	168	185	37,400	17,000	1.50	2.75	0.487	22.0	Shear	0.505
<u>Gamma Phase Extruded</u>										
18-12-3C	267	288	24,700	11,300	1.50	2.75	0.483	21.0	Shear	0.505
19-1-4	283	291	25,400	11,600	1.50	2.75	0.483	21.0	Shear	0.505
19-6-4	235	300	27,200	12,000	2.39	2.25	0.749	9.5	Streamline	0.784
<u>Delta Phase Extruded</u>										
19-6-3	330	400	8,200	3,700	2.37	2.50	0.723	12.5	Streamline	0.784

(1) Based on maximum extrusion pressure and obtained from the relation:

$$P = k \ln \frac{D_0^2}{D^2}$$

(2) Illustrated in Figure 64.

TABLE XVIII
AVERAGE MECHANICAL PROPERTY DATA AT 30 C⁽¹⁾

Billet Number	Phase Extruded	Ultimate Tensile Strength (psi)	Tensile 0.01% Yield Strength (psi)	Ultimate Compres- sive Strength (psi)	Total Plastic Length Decrease In Compression Prior to Failure Per Cent	Modulus of Elasticity In Tension (10 ⁶ psi)	Diamond Pyramid Hardness (10 kg load)
18-12-4A	Beta	59,600	35,300	169,000 ⁽²⁾	27.4 ⁽²⁾	14.9	257
18-12-3C	Gamma	68,900	36,500	176,000	30.6 ⁽²⁾	14.1	267
19-1-4	Gamma	73,000	38,200	166,300	28.5	14.8	269
AVERAGE		62,800	33,000	175,000	22.8	13.6	262

(1) Testing speed: 0.015 inches/minute

(2) Single result

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