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FUNDAMENTAL AND APPLIED RESEARCH AND DEVELOPMENT IN METALLURGY. EXTRUSION BY HYDROSTATIC PRESSURE

Final Report for the Period July 1, 1960 Through June 30, 1961

By

R. N. Randall J. M. Siergiej

D. M. Davies P. Loewenstein

July 13, 1961

Nuclear Metals, Inc.
Concord, Massachusetts

UNITED STATES ATOMIC ENERGY COMMISSION • DIVISION OF TECHNICAL INFORMATION

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METALS, CERAMICS, AND MATERIALS

Fundamental and Applied
Research and Development in Metallurgy

Extrusion by Hydrostatic Pressure

Final Report to the
United States Atomic Energy Commission
for the Period July 1, 1960 through June 30, 1961

R. N. Randall, D. M. Davies,
J. M. Siergiej and P. Loewenstein

July 13, 1961

Nuclear Metals, Inc.
Concord, Massachusetts

Contract No. AT(30-1)-1565

A. R. Kaufmann
Technical Director

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ABSTRACT

Experimental extrusions were made from a container in which the billets were surrounded by a fluid under hydrostatic pressure. Copper, aluminum, mild steel, yttrium and beryllium billets were extruded at room temperature at various reductions. Attempts to extrude at 900°F from a container filled with liquid lead were unsuccessful because of the failure of the containers at pressures greater than 100,000 psi. The pressures required for extrusion of copper and aluminum were approximately the same as were required for extrusion by conventional means.

I. INTRODUCTION

Under Contract No. AT(30-1)-1565 with the United States Atomic Energy Commission, Nuclear Metals, Inc. has conducted experimental work on the extrusion of metals by use of a fluid under hydrostatic pressure. Interest in new techniques has arisen because of the increased need for methods of fabrication suitable to the more refractory metals and alloys. The use of a liquid medium for the transmittal of hydrostatic pressure to the piece to be deformed can be valuable for at least two reasons: (1) if an extrusion billet is surrounded by a high pressure liquid, friction between the billet and the container will be eliminated; and (2) it should also be possible to reduce the friction at the die, if the fluid passes through the die and forms a barrier between the die and the deforming material. British investigators have been able, through the use of a lubricant under high pressure, to draw wire at high speeds through a die with no contact between the die and the wire. The increased ductility which high hydrostatic pressure has been found to impart to many materials could also aid fabrication. Many normally brittle and unworkable materials can be deformed if the deformation is conducted under hydrostatic pressure.

II. SUMMARY

Pressures up to 100 tons/sq.in. were used by Nuclear Metals, Inc., to extrude aluminum, copper, beryllium, mild steel and yttrium billets from a container in which the billet was surrounded and acted upon by a high pressure fluid. These extrusions were made at room temperature. Attempts to extrude copper from a container filled with liquid lead at 900°F were unsuccessful because of failure of the containers. In addition, during preliminary experiments, plasticene billets were extruded at low pressures from a plexiglas container in order that the behavior of the plasticene and the fluid during extrusion might be directly observed.

The results of the extrusion experiments indicate that apparently the friction between the container and a well-lubricated billet during conventional extrusion is slight, for the extrusion constant, k, in the

formula $P = k \ln R$, where P is the pressure required for extrusion and R is the extrusion reduction ratio, was the same for both the hydrostatic and the conventional extrusion of aluminum and copper at room temperature. Good lubrication was as necessary for hydrostatic extrusion as for conventional extrusion.

The successful extrusion of brittle materials requires that the billet and the extruding section be kept under pressure. The material being deformed is thus held in compression, and cracking caused by tensile stresses is prevented. The normal extrusion arrangement in which the extruding section coming out of the die is under no pressure higher than atmospheric is imperfect in this respect, and brittle materials will still fail despite the high hydrostatic pressure in the fluid surrounding the billet. Future work will be done on equipment modified so that the material can be completely surrounded with high pressure, and studies will be made on the effect of the high hydrostatic pressure on the ductility of materials during fabrication.

III. LITERATURE SURVEY

A search of the pertinent literature was made at the start of the program and continued concurrently with the experimental work during the course of the contract.

Bridgman(1) has described the history of the work with high pressure and summarized his own work over the past fifty years. He discusses variour seals, pressure gages, and other experimental equipment. A seal designed to utilize the principle of unsupported area was the most satisfactory for both static and dynamic applications. Seals made according to this principle were effective because they were always subject to a greater pressure than was the fluid which they contained, the difference in pressure being produced by the unsupported area of the seal. He used soft rubber or lead, depending upon the application, in the construction of the seal. Pressure was measured most successfully at the higher pressures by measuring the change in resistance of a non-inductively wound coil of manganin wire located in the pressure vessel. Manganin is a copper-manganese-nickel alloy with a positive pressure coefficient of resistivity linear to at least 280,000 psi.

Suitable fluids for use in high pressure equipment were discussed. The compressibility of the fluid, which may be as high as 25 to 30 percent at 150,000 psi, and the rise in the freezing point temperature of a liquid under high pressure were two important characteristics affecting the choice of a fluid for the pressure-transmitting medium.

Bridgman examined many materials, some normally ductile and some normally brittle. Beryllium was one of the normally brittle materials he subjected to a tensile test under high hydrostatic pressure. It showed considerable ductility and increased tensile strength. The beryllium used, which fractured at atmospheric pressure at 28,000 psi with negligible elongation, exhibited a 20.6 percent reduction in area and a tensile strength of 76,000 psi under a hydrostatic pressure of 250,000 psi. Under a 390,000 psi hydrostatic pressure, a reduction in area of 48 percent and a tensile strength of 110,000 psi was observed. Other brittle materials examined were cast iron, phosphor bronze, sapphire, and some other ceramic materials. Both cast iron and phosphor bronze showed greatly increased ductility in tensile tests conducted under hydrostatic pressure. Some ductility was also found in tests of ceramic materials.

In another work[(2)], Bridgman describes experiments conducted to determine the behavior of steel and copper when drawn or extruded in an atmosphere of hydrostatic pressure. His equipment was designed for operation at a pressure of 170,000 psi. He drew piano wire 0.076 inch diameter to 0.026 inch diameter in six passes with no intermediate anneals. Similar wire drawn at atmospheric pressure with no anneals required 15 passes, and exhibited no ductility at the end. The wire drawn under hydrostatic pressure still showed some ductility after drawing. Bridgman believes higher pressures would be necessary before any striking enhancement of properties would be evident.

Bridgman successfully extruded copper at a reduction of 16X. In this experiment the billet was in a container and was surrounded by a liquid; the die opened to the atmosphere. A ram applied force against the liquid which in turn applied pressure to the billet. He reported that at too great reductions at high pressures the metal tended to spit out through the die in gulps or to break along shear planes at the mouth of the die.

In the USSR, Beresnev, Vereschagin and Ryabinin have published several papers[3,4,5] covering their experiments involving hydrostatic pressure. Their equipment appears to be modeled on Bridgman's. They have performed rolling, drawing and extrusion experiments using pressures up to 142,000 psi. They reported that for aluminum appreciably less pressure was required for hydrostatic extrusion than for mechanical extrusion[4]. (A comparison of their results with ours indicates that the pressure required for hydrostatic extrusion was not low but rather, the pressure required for conventional extrusion was very high.) They have extruded several other metals, including beryllium. They found that a die with a 30^{o} included angle in the conical approach required the lowest extrusion pressures. They found in experiments with copper at low reduction that the hardness across a cross-section of a rod extruded hydrostatically was essentially constant but that the hardness across a rod extruded mechanically decreased continuously from the outside to the center[4]. The hardness at the outside was greater and the hardness at the center was less on the mechanically extruded rod than on the hydrostatically extruded rod, which had been reduced the same amount.

A principal advantage of the process, in their view, was the decreased friction between billet and tools caused by the fluid under hydrostatic pressure. Friction between liner and billet was completely eliminated. They found, however, that lubrication was necessary even under hydrostatic extrusion conditions. They reported that deformation under hydrostatic pressures resulted in increased strength with greater ductility than would be found in material deformed to the same degree mechanically.

H. Ll. D. Pugh and D. Green[6] at the Mechanical Engineering Research Laboratory, Glasgow, have used a different approach in an attempt to apply the benefits of hydrostatic pressure, concentrating on the extrusion of brittle materials which could not otherwise be deformed. Their equipment consists of a standard mechanical extrusion ram, die and container with a pressurized chamber at the exit end of the die. With this apparatus they have successfully extruded magnesium and bismuth at room temperature. The fluid in their exit chamber was at pressures up to 70,000 psi. In this application pressure is utilized to prevent the formation of cracks as the metal is deformed, and thereby prevent failure. The metal is subjected to pressure on all sides, by the ram, the container, the die, and the pressurized fluid, and is held in compression during deformation. No tensile stresses can develop to cause cracks either at a surface or in the interior of the specimen undergoing deformation and therefore tensile failure cannot occur.

IV. EXPERIMENTAL WORK

A. Plasticene Extrusions

In order that information on the behavior of the material and the fluid during hydrostatic extrusion might be gained quickly at the start of the program, preliminary experiments were carried out using a plexiglas container and die in which the extrusion of billets made of plasticene could be directly observed. Plasticene was chosen because it is a material with a stress-strain curve similar to one for a metal and it is easily available in different grades with different strengths. It has previously been effectively used to study the extrusion process[7].

The "press" consisted of a cylinder of plexiglas 4-1/2 inches OD by 2 inches ID clamped between two steel end plates. The die, which was inserted in one end of the cylinder, bore against one end plate and was sealed with an O-ring so that there would be no leakage around the OD of the die. Water from a pump was admitted through the other plate at pressures up to 2000 psi. A sketch of the experimental arrangement is shown in Fig. 1(a).

With the plasticene press it was quickly discovered that the proper seating of the billet in the die was extremely important. Any slight irregularity would allow water to pass. The pressurized water did not cause the billet to seal the irregularity, but rapidly eroded the billet and enlarged the opening.

Some reduction occurred in the billet before it contacted the conical entrance to the die. The deformation was not uniform around the circumference of the billet, but under the best conditions it accounted for about a 20 percent reduction in the billet cross-sectional area. This tendency for the billet to be reduced in cross-section is sketched in Fig. 1(b). A photograph of a partially extruded plasticene billet is shown in Fig. 2.

It was thought that the use of a flat-faced shear type die would emphasize the effect and that almost all of the deformation would occur in the pressurized water. When a flat-faced die was tried, the deformation did not occur before contact was made with the die. The conical nose of the billet came down flat against the die when extrusion began. Some of the billet material stagnated there and in effect formed a cone; the remainder of the billet sheared away from this material and extruded through the die. Figure 3 shows a sketch of the plasticene billet's behavior when extruded through a flat-faced die. The only technique that was found to increase the "dieless deformation" was the use of restraint at the rear of the billet (see Fig. 4) so that there were tensile forces along the length of the billet between the die and the rear of the billet. These tensile forces caused the billet to reduce in cross-sectional area near the entrance to the die. If the restraint were too great, the billet would deform too much and the pressurized fluid would escape through the die.

The pressurized fluid was not completely successful as a lubricant. Although there was no sticking of the billets to the dies, the billets would extrude unevenly. Lubrication is still a problem.

The plasticene press was used also for some experiments with lead. Lead rods were drawn at small reductions through a die as sketched in Fig. 5. The lead was drawn rather than extruded because the material in the die, where the deformation occurs, was completely surrounded by the high pressure water. The lead could be deformed but there was no reduction in force from that required for conventional drawing. Again it appeared that lubrication is still important and that lubricants must be used.

B. Metal Extrusions

Extrusions were made with metals both at room temperature and at 900°F. A 100-ton vertical hydraulic press was used to supply the force necessary. The press ram travel and pressure in the press hydraulic circuit were recorded. The experimental arrangement is shown in Fig. 6. The details of the piston and die design are shown more clearly in Fig. 7. The seals were designed to utilize the principle of unsupported area. An 0.112-inch diameter die was used for all the experiments. The extrusion reduction was varied by changing the billet diameter. The ID of the container was 1.100 inches, thus large enough to permit very high reductions with the die size used.

1. Room Temperature Extrusions

Aluminum, copper, steel, beryllium and yttrium billets were extruded from the container filled with a fluid under high pressure. The Table presents data on the reductions achieved and the pressure required for the various materials. Initially, kerosene was used as the fluid because of its good high pressure characteristics, its noncorrosive nature, and lubrication properties. However, it was discovered that clouds of kerosene vapor would be ejected if there were any failures of the seals. Because of the fire and explosion hazard created by this kerosene vapor, water was substituted for kerosene as the high pressure fluid. Sodium nitrite was added to the water to inhibit corrosion.

The pressure in the container was measured indirectly by measuring the pressure in the hydraulic line moving the ram on the 100-ton press. Despite the losses due to friction in seals this method is standard for the measurement of the force exerted by an extrusion ram. As the ram is in direct contact with the piston which is compressing the fluid it is possible to calculate the pressure in the fluid from the knowledge of the force on the piston and the area of the circular cross-section of the container. The actual pressure in the container will be less because of friction between the container wall and the seal of the piston.

Attempts were made to measure the pressure of the fluid more directly by measuring the change of resistance in a coil of manganin wire immersed in the fluid. These were unsuccessful because of failure of pyrophyllite insulating seals around the contacts through which the circuit was brought out of the container.

Another method of measuring the pressure involved the direct measurement of the amount of compression of the water in the container when force was applied to the piston. As the compressibility of water is known, the pressure can be determined by measuring the change in volume of the water and comparing it with data on the compressibility of water. A plot of the volume change of water with pressure based on Bridgman's data is shown in Fig. 8. Measurements of the volume change of the water in the container gave pressure values in good agreement with the values calculated from the pressure in the press hydraulic system. This indicates that the force used to overcome friction between the piston seal and the container wall is slight compared to the force compressing the water.

Dies having a conical approach with a 90^{o} included angle were used for the majority of the extrusions. Some extrusions of aluminum were made with dies having a 120^{o} included angle in the approach and one was made with a flat-faced die (180^{o} included angle). The latter dies were used in conjunction with tapered billets to see if some deformation would occur in the billet before it contacted the die. In billets extruded through conical dies, little if any deformation occurred before contact was made between the die and the billet. The billet extruded through the flat-faced die did not deform at all on one side but came down flat on the die. On the other side the billet deformed into a rough parabolic shape reducing its diameter to the die size. The water pushed through the die on this side before much of the billet had extruded, causing the extrusion to stop for lack of pressure.

Billets were designed with a nose which fitted into the die. Early extrusions were made with the billets press-fitted into the dies; this arrangement provided a good seal and permitted the slow application of pressure. However, high pressures were required to start the extrusions.

Later extrusions were made with the billets slip-fitted into the dies, and although it was necessary to apply pressure rapidly in order to overcome the leak at the die, reduced pressures were required. Apparently press-fitting caused some galling or seizing of the billet to the die.

Lubrication of the billets in hydrostatic extrusion was found to be as necessary as it is for conventional extrusion. It was found that a coating of Teflon baked onto the die and billet surfaces provided good lubrication. Earlier extrusions had been made with coatings of oil or grease on the billets. Oil did not prevent seizing of the billet to the die; grease was fairly satisfactory, but extrusions lubricated with grease were erratic and required higher pressures than did the extrusions lubricated with Teflon.

A standard procedure was used in preparing the extrusion experiments. The billet was first lubricated and then assembled together with the die. The die and billet assembly were then inserted into the container. A measured amount of fluid was added to the container and the piston was inserted in the container. Care was taken to avoid the entrapment of air in the container. The press ram was then brought down, forcing the piston into the container and building up pressure in the fluid. When the pressure reached a sufficient value the billet extruded. A greater pressure was required to start the extrusion than was necessary to maintain extrusion.

Pressure was applied both slowly and rapidly. When the pressure was applied slowly, the billets extruded in one of two ways depending upon the quality of the lubrication. When lubrication was poor, very high pressure was necessary to start the extrusion because of the friction between billet and die. Once friction was overcome the billet would extrude very rapidly because of the excess energy stored in the compressed liquid. When lubrication was good, extrusion would begin at a lower pressure because of the reduced friction. Since there was little excess energy stored in the compressed water, after the billet had extruded a short section the extrusion would stop. When the slowly moving piston had again built up pressure sufficient to start extrusion, the cycle repeated. Figure 9 presents a reproduction of the record of pressure vs piston travel obtained from an extrusion made slowly with good lubrication.

When the pressure was applied rapidly, the effect of lubrication was indicated only by the degree of pressure required. At the end of the extrusion when the billet cleared the die and the pressure in the fluid was released, a loud bang would occur. If the extrusion occurred rapidly the extruded rod would issue from the die with considerable force and at high speeds. An extruded rod of Type 1100 annealed aluminum penetrated a 1-inch thick wooden board five feet from the die.

a. Aluminum and Copper Extrusions

Aluminum and copper were the principal metals extruded. Hydrostatic extrusions were made with billets of various sizes in order to determine the pressures required at various reductions. Figure 10 presents data on the pressures required for the extrusion of aluminum at various reductions, and Fig. 11 presents the same data for copper. At any one reduction, particularly in the case of aluminum, there is a spread of pressure values, a variation believed to be due to variation in the quality of the lubrication.

If the pressure and reduction are related by the equation $P = k \ln R$, values of k can be determined for different materials under different conditions. A line has been drawn through the best values on both graphs in order to determine a k value for hydrostatic extrusion for purpose of comparison with the extrusion constant, k, for extrusion of copper and aluminum at room temperature by conventional means.

Extrusions of aluminum were made by conventional means at reductions of 13.7X, 20.2X, and 28.5X from a 1.100-inch diameter liner. A mixture of powdered lead and oil was used as a lubricant. The die had a 90° included angle conical approach so that the aluminum extruded in a streamline fashion. The extrusion ram speed was 150 in./min. The extrusion constant, k, was calculated from the force required and averaged 15.6 tsi; it was essentially the same for the extrusions at all three reductions. This compares with a value of k = 16 tsi obtained from Fig. 10.

Conventional extrusions of copper were made at reductions of 4X and 9.9X using a mixture of powdered graphite and oil as the lubricant. A die with a 90° included angle conical approach was used. The average value of k calculated from the data for these two copper extrusions was 43.5 tsi, which compares with the value of 40 tsi obtained from Fig. 11. The hydrostatic extrusions became heated to a greater or lesser extent during deformation. The copper extrusions were discolored, and had contracted to a diameter less than the die diameter. From the oxide color and from thermal expansion data it was estimated that the copper extrusions must have been heated to over 500°F. The aluminum extrusions were frequently too warm to handle with bare hands.

b. A151 1020 Steel

Hydrostatic extrusions of steel billets were made at reductions up to 4X at room temperature. The surfaces of the extruded rod were good. Higher reductions could not be obtained because of the high pressures required.

c. Yttrium

A tapered billet of yttrium was hydrostatically extruded at room temperature. The tapered billet was used in order to determine the maximum reduction that could be achieved. The billet increased in cross-sectional area along its length and so likewise the extrusion reduction increased continuously as the billet extruded. The billet stalled at a point equivalent to a reduction ratio of 24X. The extruded yttrium rod broke free from the remainder of the billet. It was hot enough to ignite the wad of cotton cloth used to slow down and stop the extruded rod. The surface was very poor, being heavily scored. There was also considerable pickup in the die.

A coating of Celvacene grease on the billet and die was the lubricant used.

d. Beryllium

Hydrostatic extrusions of beryllium were made at reductions of 1.2X and 1.5X. The extruded rods were found to be fractured in two or three pieces. It is not known whether they fractured during extrusion or while being decelerated as they passed through a wad of cotton cloth after extrusion. The surfaces of the rods were good and showed no evidence of scoring.

A coating of Teflon was used on both the billets and the die for lubrication.

e. Magnesium

Attempts were made to hydrostatically extrude magnesium billets, but the billets continuously fractured as they passed through the dies. This is typical of the behavior of magnesium when extruded at room temperature by conventional means. Because of the success of the British investigators(6) in using a conventional extrusion tooling arrangement with the addition of a vessel containing a pressurized fluid at the exit end of the die, it appeared that the extruding magnesium must be restrained. A die with a land 1/2-inch long, as compared with the normal 1/8-inch long land, was tried in the hope that the increased friction of the extruding rod against the die would act as a restraining force and prevent the fracture of the magnesium. Although the billet again fractured there was some indication that the long land had been of some effect at the start of the extrusion.

2. High Temperature Extrusions

Hydrostatic extrusions of copper at temperatures of 800°-900°F were attempted preliminary to the planned extrusion of beryllium. Beryllium is extruded in this temperature range by conventional means and it would be significant if higher extrusion reductions could be obtained through the use of hydrostatic extrusions. Lead was used as the pressure-transmitting medium. Lead melts at 621°F at atmospheric pressure and it has been determined both experimentally(8) and by calculation that the melting point rises to 750°-800°F at 200,000 psi. The lead would therefore still be liquid at the operating temperature. As far as is known, beryllium has good resistance to attack by molten lead at 900°F.

The equipment arrangement is the same as that shown in Fig. 6 for the room temperature extrusions. The seal on the piston is shown in Fig. 7(a). Copper, steel and aluminum washers were used in combination on the Bridgman type seal. Initially, when aluminum washers were not used the lead leaked around the piston and pressure could not be built up; the insertion of the aluminum washers gave a good seal. No special seal was used on the die; it was simply shrunk into the container.

In preparation for an extrusion the container assembly was heated to 900°F in a furnace. The die with the billet pressed in was shrunk into the container assembly; lead was added. The container assembly was then placed in the extrusion press, and the piston was inserted. Force was applied by the extrusion press through the ram. Three attempts were made, but there were no successful extrusions. In all cases, when force was applied and the pressure in the lead reached approximately 100,000 psi, the liner cracked, the lead leaked out, forming a cloud of lead oxide, and the extrusion was stopped. The copper billets partially extruded during the pressure build-up before the liners failed. For purposes of calculation, the maximum pressure was used, and the extrusion constant, k, was found to be approximately the same as it would be for conventional extrusions of copper at 900°F. A container assembly designed to have increased compressive stress at the ID of the liner was ordered. A container with an iron-plated liner was also ordered. It was hoped the iron plate might provide a barrier if failure was occurring because of contact between lead and the alloy steel. Iron was reported[9] to have fairly good corrosion resistance to lead at 900°F.

Because of manufacturing difficulties and the room temperature work, these liners were delayed and were not tested. Future work will include tests of these liners and increased emphasis on hydrostatic extrusion at elevated temperatures.

V. DISCUSSION

The extrusions made with plasticene indicated that some deformation will occur in the billet before the billet contacts the die, producing a reduction in the billet cross-sectional area. Similar deformation was noticed to a slight extent on the butt of some of the copper and aluminum extrusions but to a lesser extent than on the plasticene. It appears that the amount of the reduction will be affected by the strength of the material relative to the pressure, the work hardenability of the material, and the design of the die and billet.

The results obtained with aluminum were contrary to those reported by Beresnev, of the USSR[4]. An analysis of Beresnev's data indicates that the Soviet experimenters were able to extrude aluminum hydrostatically at pressures close to those used in the work reported here. However, in Beresnev's experiments considerably more pressure was required to extrude aluminum conventionally than was required at Nuclear Metals, Inc. In other words, the pressure required for hydrostatic extrusion was not low; rather, the pressure required for conventional extrusion was high. Thus, the reduction in pressure achieved by the Soviet investigators was not a result of the use of hydrostatic pressure but was, apparently, simply the result of improved lubrication.

The pressures reported by Beresnev et al for the hydrostatic extrusion of aluminum, copper, and beryllium were in good agreement with the pressures required at Nuclear Metals, Inc.

One factor which affects room temperature extrusion is the heating of the billet produced by the deformation of the material and the friction of the billet with the die. At high extrusion rates there can be a large temperature rise, as was noticed in the copper and yttrium extrusions especially. This increase in temperature affects the extrusion characteristics and, if sufficient, could also destroy the strengthening effect resulting from the cold work introduced by the room temperature deformation.

The reductions of 1.2X and 1.5X achieved in the hydrostatic extrusion of beryllium were low for reduction by extrusion, but are equivalent to reductions in area of 16.6 and 33.4 percent, respectively. These are much higher than can be obtained in a single pass by drawing. Likewise, the reduction of the yttrium was equivalent to a reduction in area of over 90 percent. Yttrium can normally be reduced only about 40 percent by drawing before an anneal is necessary.

The experiments with magnesium tend to confirm the work of the British experimenters who showed that magnesium and bismuth, both brittle at room temperature, could be successfully deformed by extrusion when pressure was applied at the exit end of the die to restrain the extrusion of the billet and keep the deforming material in compression.

The failure of the liners during the high temperature extrusions was disappointing and difficult to understand. The pressure of 100,000 psi in the liner corresponded to a tensile hoop stress of 115,000 psi at the ID of the liner. The actual stress at the ID of the liner was less because of the compressive stress introduced when the liner was shrunk into the container. For the container and liner used, this compressive stress was calculated to be 55,000 psi. The tensile stress was therefore only 60,000 psi, or about 1/3 the yield strength of the steel at $900^{\circ}F$. Thus, the failure cannot be laid to the decrease in yield strength at elevated temperatures.

It was suspected that corrosion by the liquid lead might be causing stress concentrations which would lead to the liner failures, although the lead was molten in the container for only 15 to 30 minutes. The liner was made from AlSl H-12 steel, an iron-chromium-tungsten alloy. There are some data to indicate that tungsten is seriously attacked even at low temperatures, and therefore it was possible an iron-chromium-tungsten alloy might have poor resistance. However, metallographic examination revealed no intergranular penetration by the lead, nor other signs of corrosive attack on the liner.

Recently, the work of Rostoker, McCaughey, and Markus[10] has come to our attention. They argue that no corrosion is involved in the embrittlement of certain solid metals by particular liquid metals but that the embrittlement is caused by a change in surface energy conditions when the solid metal is wet by a particular liquid metal. Embrittlement by such a mechanism can occur simultaneously with the wetting, and failure can occur immediately if there is a stress sufficiently high. If a reason for the failures lies in this explanation, then it will be necessary to use a different liquid metal which will not cause embrittlement, or to use sufficient compressive stress in the liner so that no tensile stress sufficient for failure can be reached.

VI. CONCLUSIONS

(1) For aluminum and copper the pressure required to extrude a billet from a container filled with a pressurized fluid was the same as that required to extrude a well lubricated billet in a conventional way at room temperature, under the experimental conditions used.

(2) The successful extrusion of brittle materials requires a restraining pressure at the exit end of the die.

(3) Beryllium and yttrium were reduced by hydrostatic extrusion in a single step much more than is possible by drawing.

(4) An extruded section will be heated by the operation to a greater or lesser extent depending on the material, friction conditions, and the rate of deformation.

VII. TABLE AND FIGURES

TABLE

Pressures Required to Extrude Various Materials

Material	Maximum Reduction	Pressure at Maximum Reduction (tsi)	Extrusion Constant $k = \frac{P}{\ln R}$ (tsi)
Aluminum (annealed)	50X	68	17.3
Copper (annealed)	20X	107	35.7
AlSl 1020 Steel	4X	110	79
Beryllium (hot extruded)	1.5X	67	167
Yttrium (annealed)	24X	105	33

$$\text{Reduction, } R, = \frac{\text{Area before}}{\text{Area after}}$$

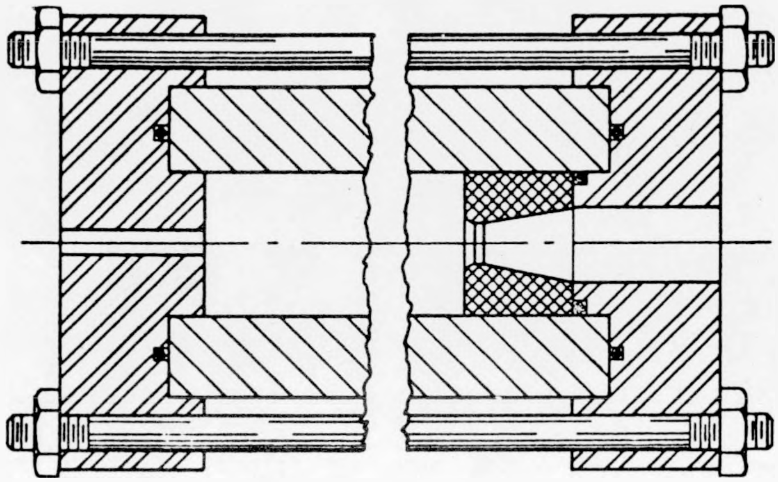


Fig. 1(a) - Hydrostatic extrusion press for plasticene extrusions. Drawing No. RA-1805

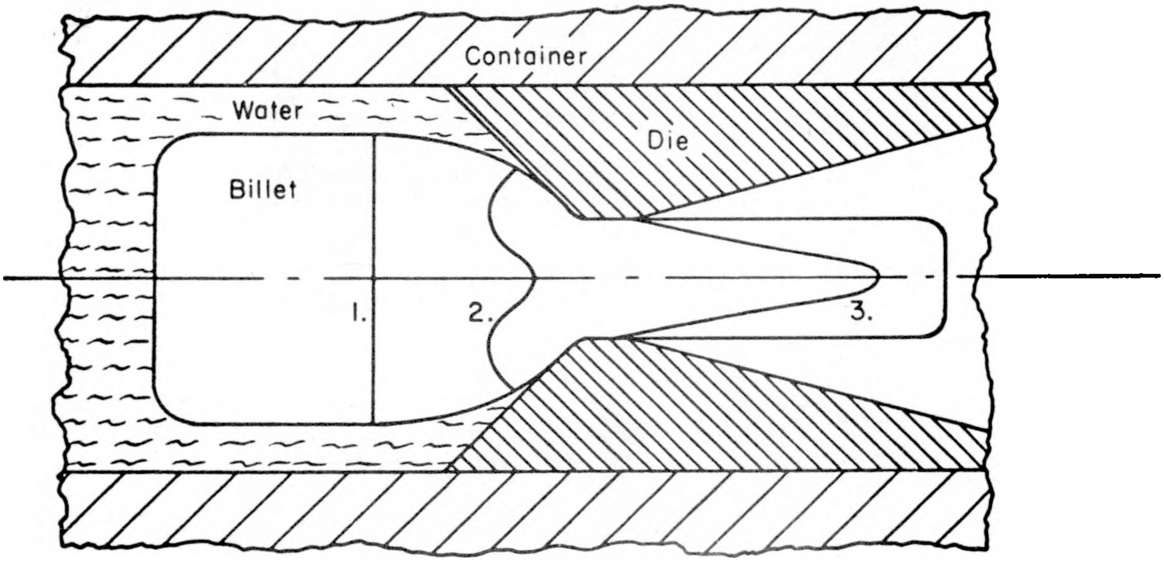
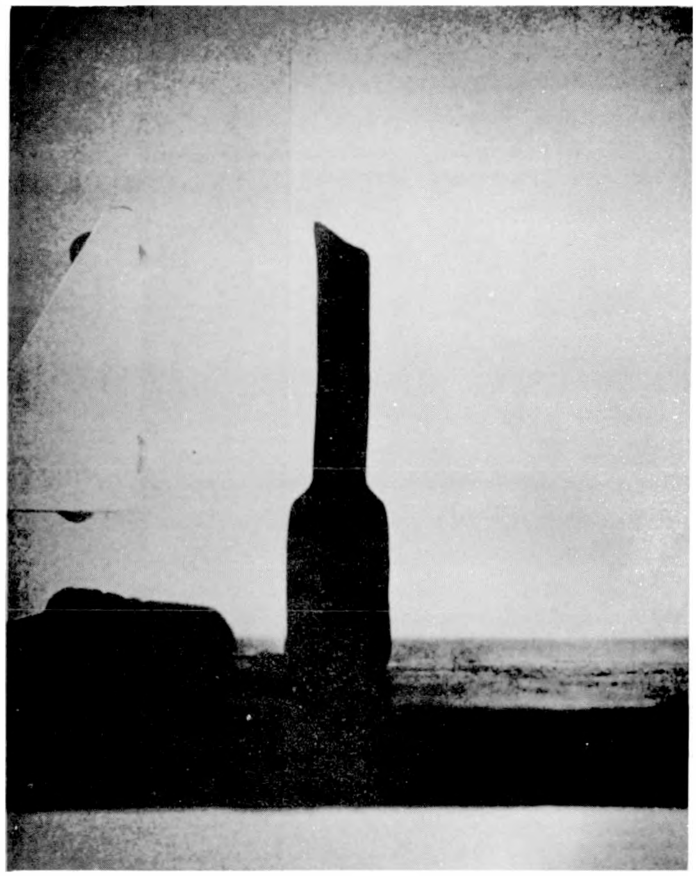
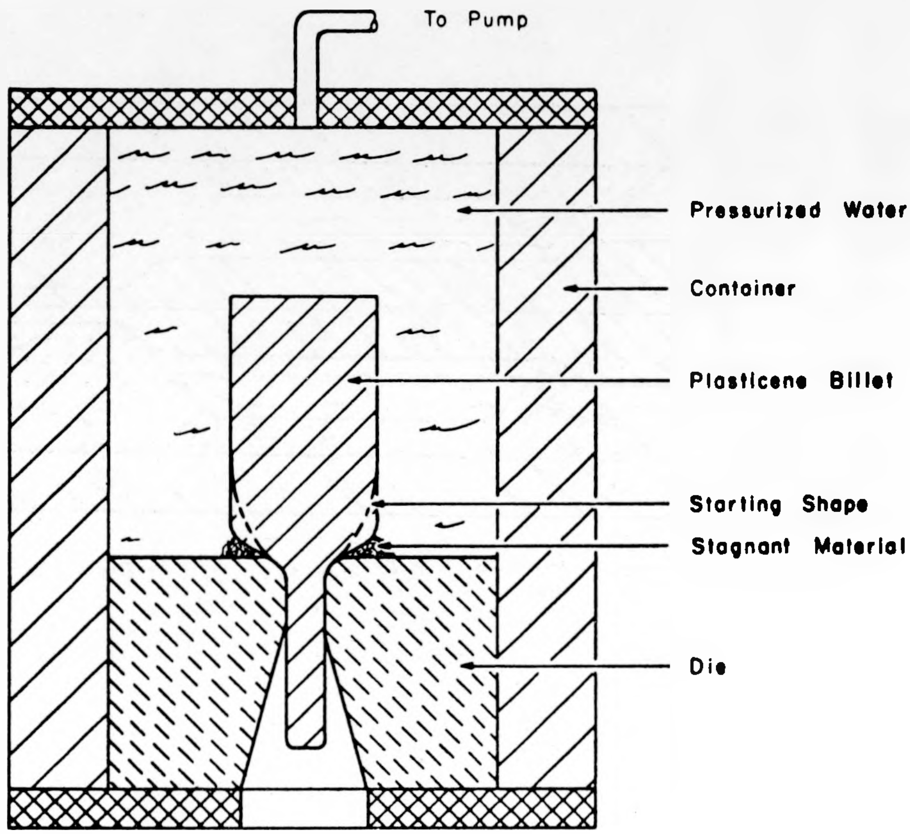


Fig. 1(b) - Section of a plasticene billet and the die in which it was partly extruded. When sectioned, the billet had the cross-section shown. The billet was made of alternate layers of two colors; lines 1, 2 and 3 are the boundaries between them. Drawing No. RA-1805.



RF-7869

Fig. 2 - Plasticene partially extruded, showing reduction in billet diameter before contact with die.



<u>**Fig. 3**</u> - Sketch showing behavior of plasticene billet when extruded through a flat-faced die. Dotted line indicates conical shape on front of billet at start of extrusion. Drawing No. RA-2051

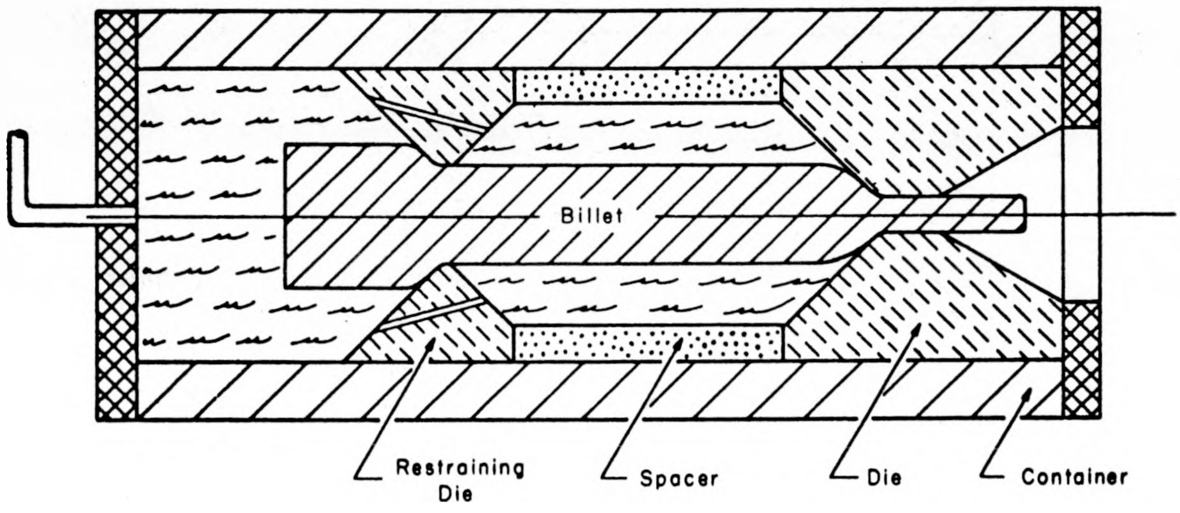


Fig. 4 - Sketch of experimental arrangement using a restraining die to increase the amount of deformation occurring in the billet before contacting the die. The pressure in the fluid is the same both in front and behind the restraining die. Drawing No. RA-2050

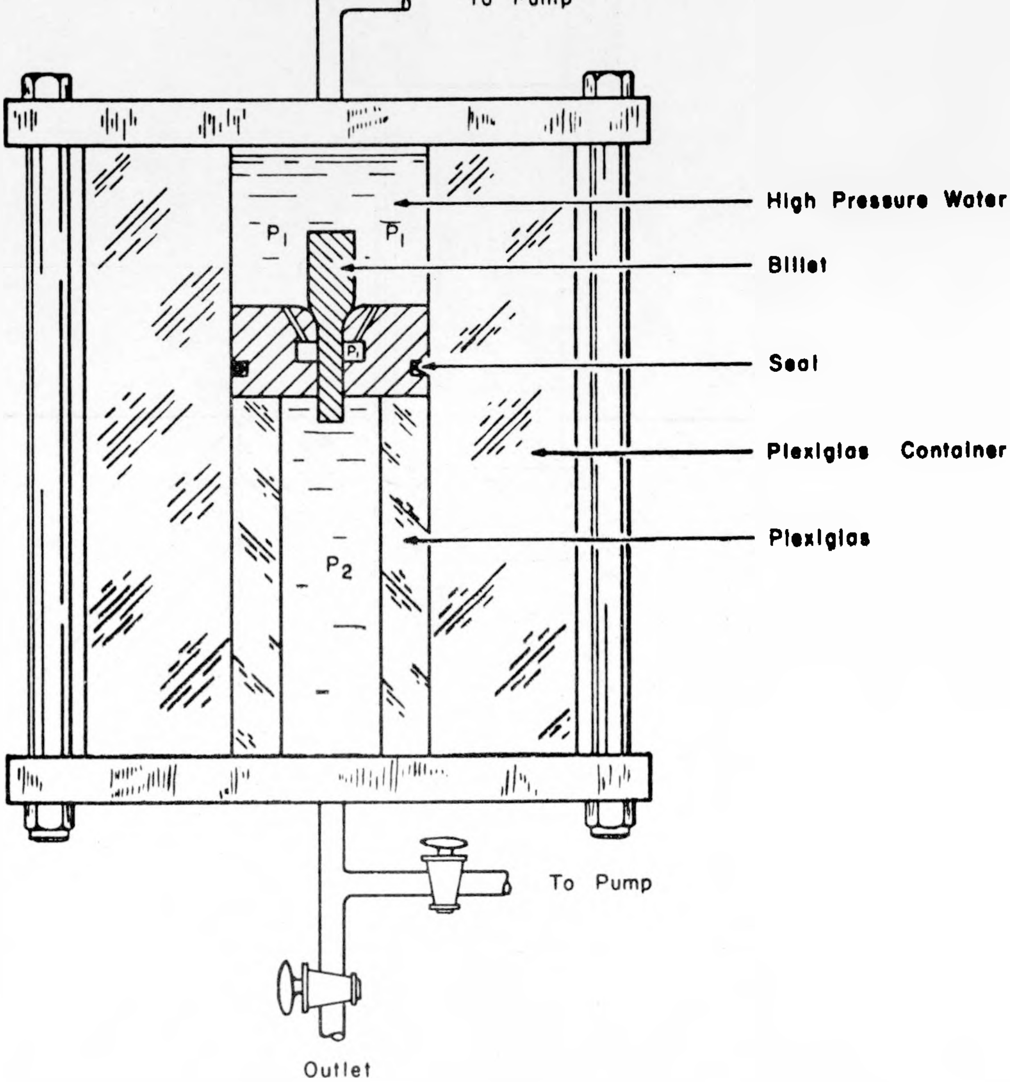


Fig. 5 - Sketch of equipment used for hydrostatic drawing experiments. Pressure $P_1 > P_2$
Drawing No. RA-2048

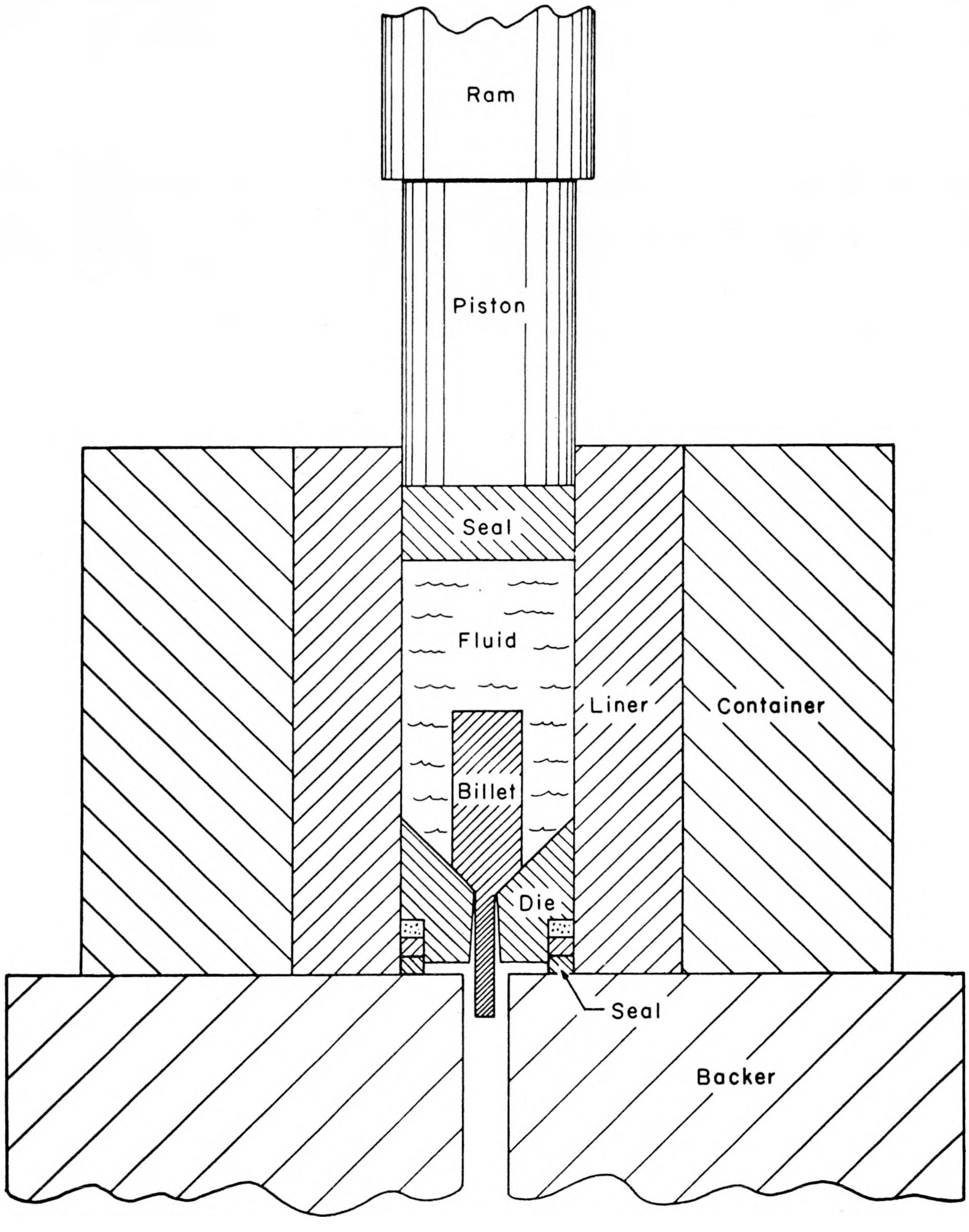
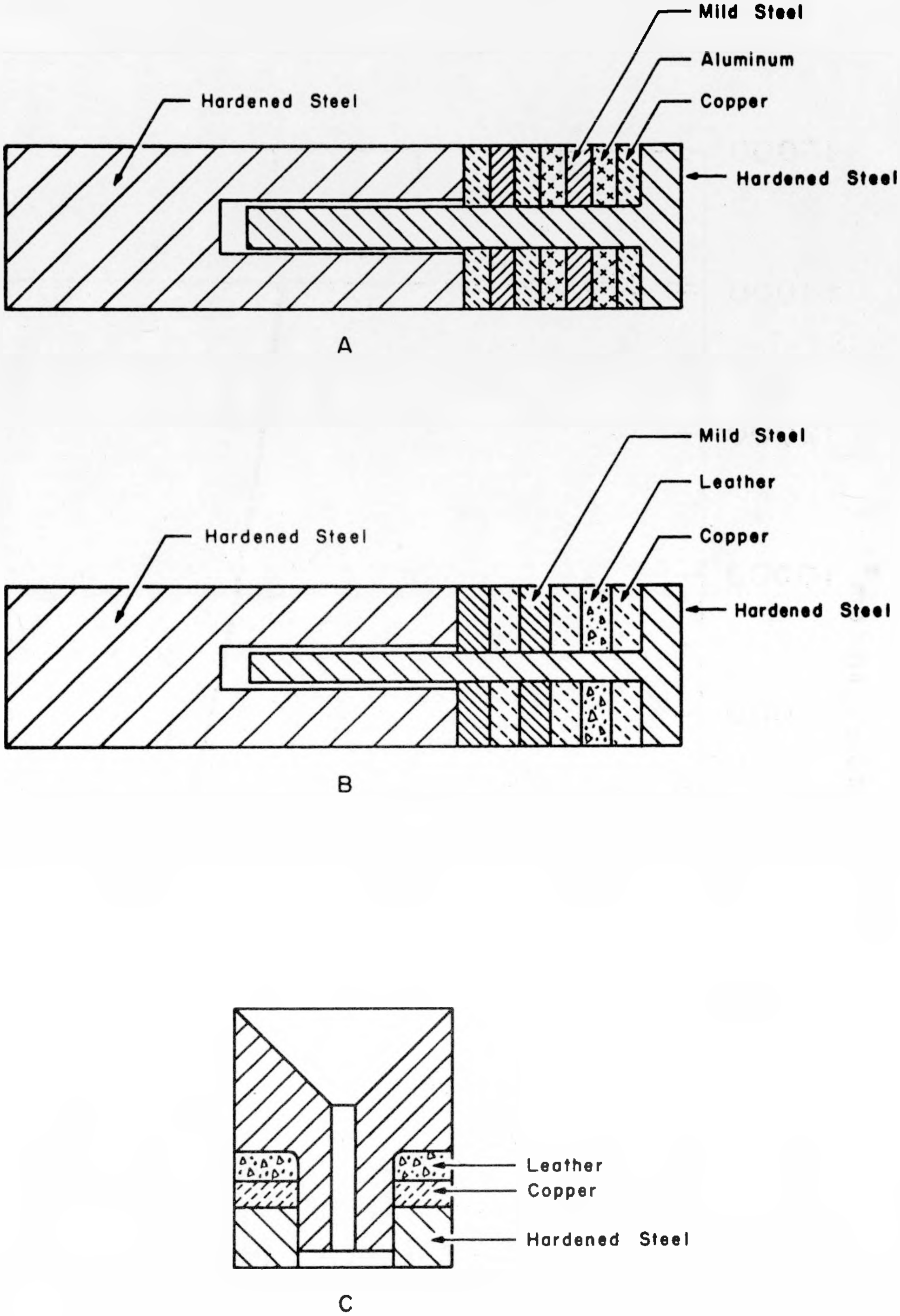


Fig. 6 - Diagram of tooling used in 100-ton vertical extrusion press for hydrostatic extrusion. Drawing No. RA-1912



<u>Fig. 7</u> - Details of piston and die designs showing seals using principle of unsupported area.

A. Piston with seal for use at 900^{o}F.

B. Piston with seal for use at room temperature.

C. Die with seal for use at room temperature.

Drawing No. RA-2045

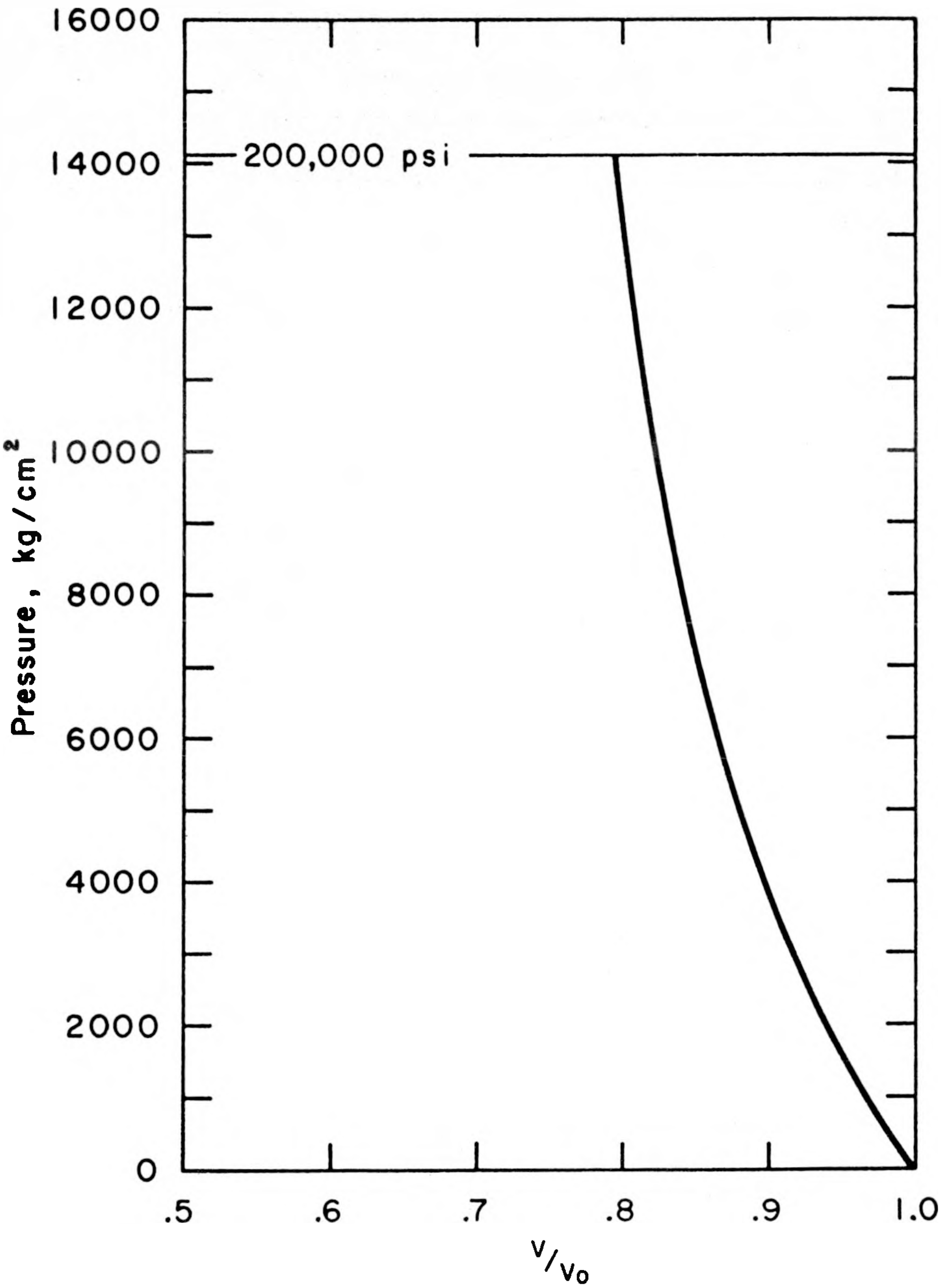


Fig. 8 - Graph of compressibility of water at 50°C (from Bridgman, Ref. 1) Drawing No. RA-2043

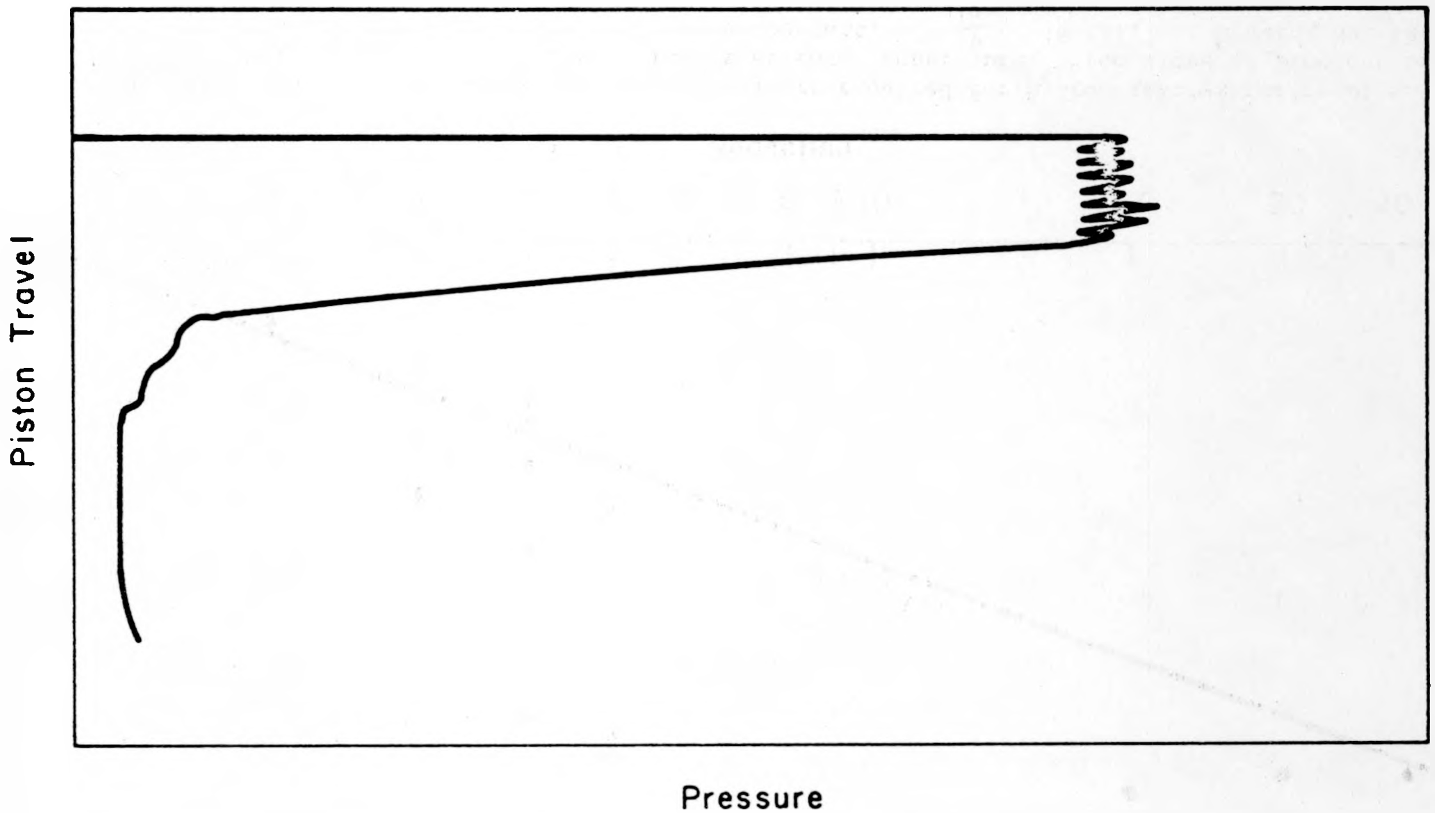


Fig. 9 - Plot of pressure vs piston travel, pressure applied slowly, for hydrostatic extrusion of aluminum. Jagged character of curve indicates repeated start and stop of extrusion. Drawing No. RA-2044

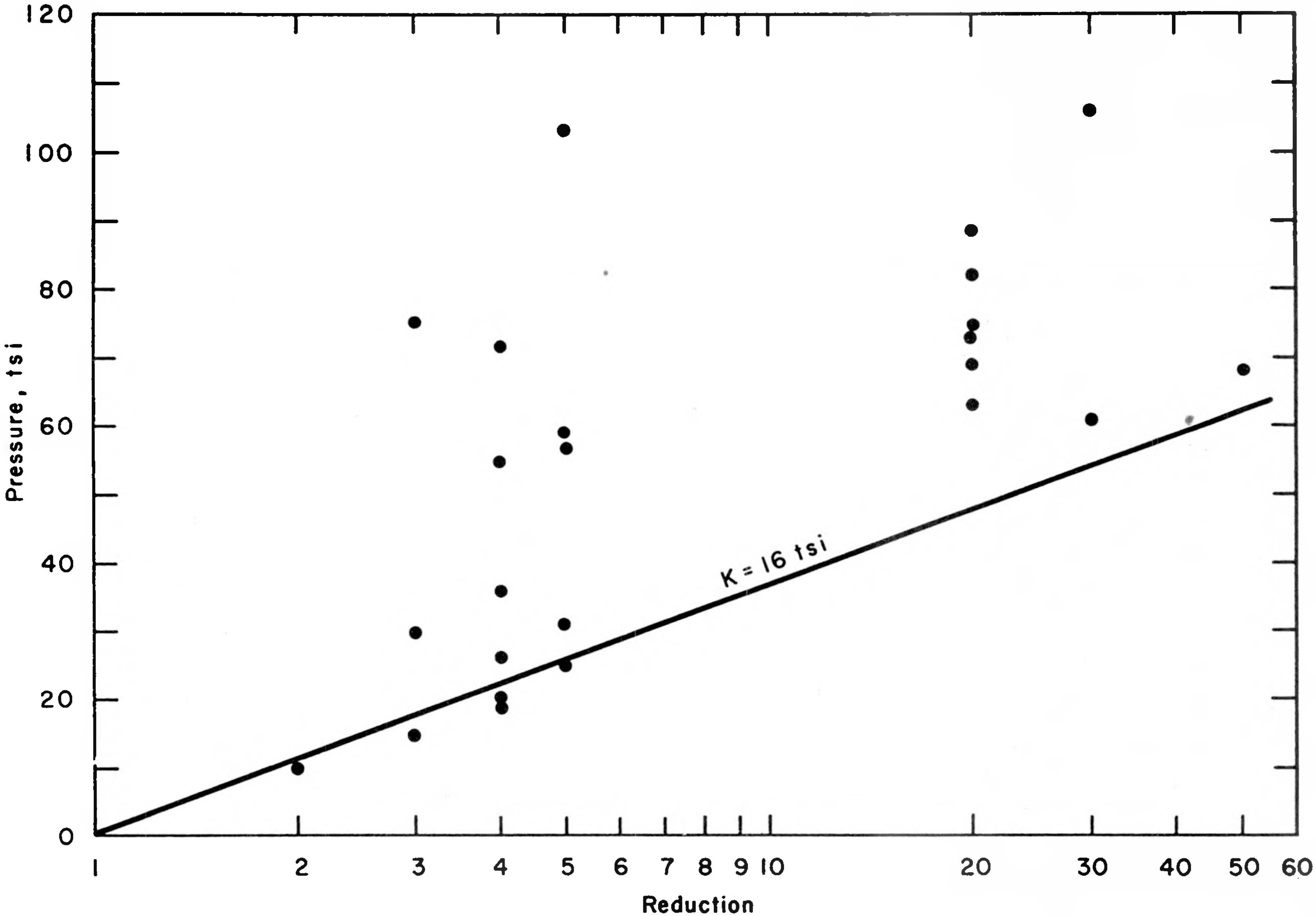


Fig. 10 - Plot of extrusion reduction vs pressure required for hydrostatic extrusion of annealed Type 1100 aluminum billets at room temperature. From slope of line can be calculated best average extrusion constant, $k = \frac{P}{\ln R}$ = 16 tsi. Drawing No. RA-2046

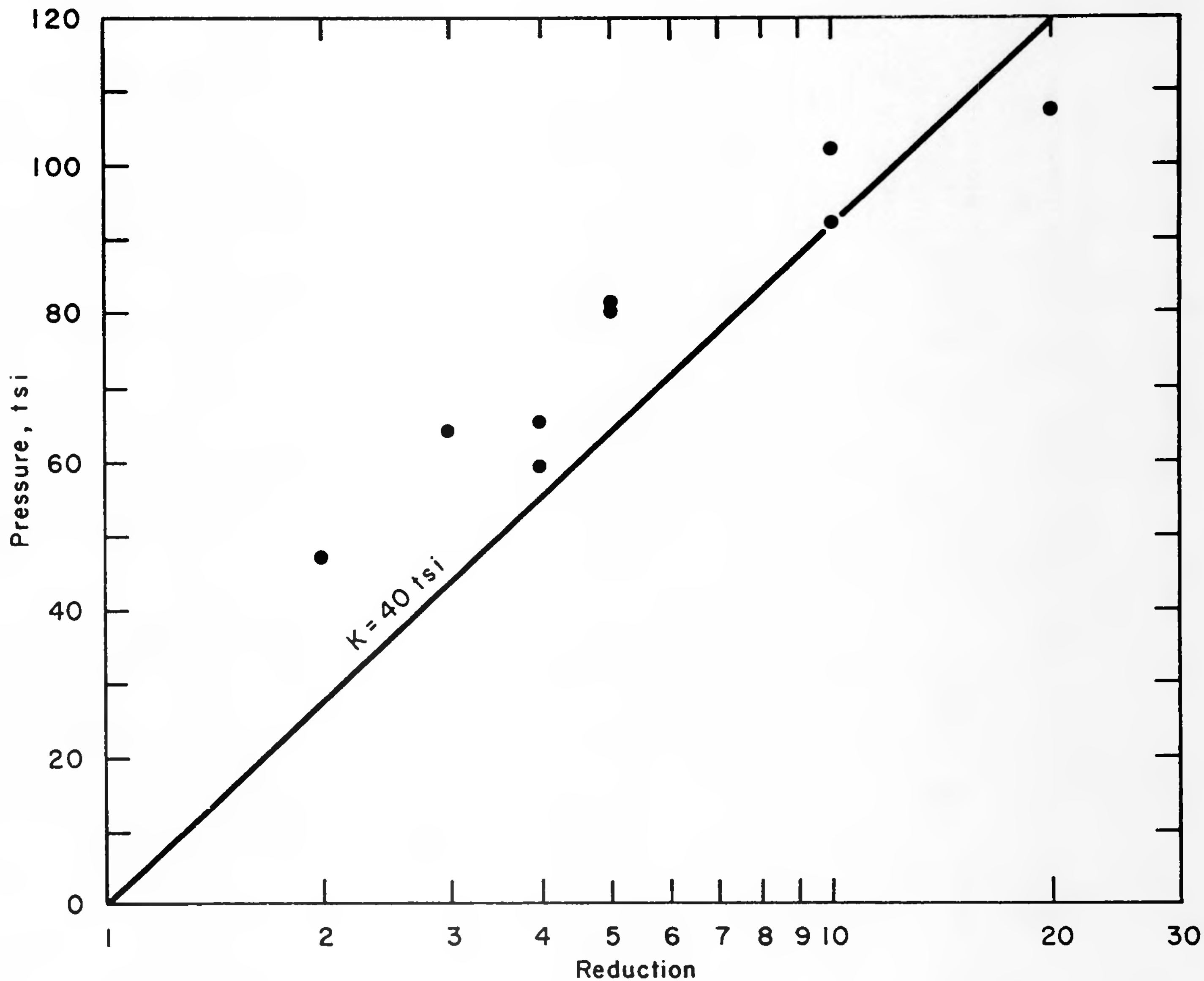


Fig. 11 - Plot of extrusion reduction vs pressure required for hydrostatic extrusion of annealed copper billets at room temperature. From slope of line can be calculated best average extrusion constant, $k = \frac{P}{\ln R} = 40$ tsi. Drawing No. RA-2047

VIII. REFERENCES

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