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AUSTRALIAN ATOMIC ENERGY COMMISSION
RESEARCH ESTABLISHMENT
LUCAS HEIGHTS

EXPERIMENTS IN EXTRUSION

PART 3. THE MECHANICS OF EXTRUSION OF BERYLLIUM

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ABSTRACT

The extrusion pressures determined for beryllium and mild steel over a wide range of reductions in area at temperatures between 750 °C and 1050 °C are significantly lower than those reported previously. This is attributed to better control of temperature in the work reported. The effects of container friction were assessed and the coefficient of friction between tooling and billets was estimated as 0.03 – 0.035 when using graphite lubricants.

The flow of metal in extrusion through various dies was examined using gridded billets; the velocity profiles and extent of the plastic field were determined. The work was applied to a study of the shapes developed from plane interfaces in the billets during extrusion; the interface shape necessary in the original billet to produce a plane interface in the extruded section was determined and applied in the basic extrusion technique to improve the yield of product.

CONTENTS

(continued)

CONTENTS (continued)

1. INTRODUCTION

This report is the third of a series dealing with experiments on the extrusion of beryllium; the work was done at the Research Establishment of the Australian Atomic Energy Commission as part of a programme to investigate the suitability of beryllium as a material for application in high-temperature gas-cooled reactor systems.

The major objectives were:

(i) To develop a satisfactory technique for the extrusion of beryllium metal which was required for related projects including irradiation testing (Hickman and Stevens 1963) and chemical studies (Draycott et al. 1961).

(ii) To determine the mechanical properties of beryllium metal and the variation of these properties with extrusion conditions.

(iii) To extend the technique to the tandem and co-extrusion of (U Th)Be_{13} – beryllium dispersions clad in beryllium, such as would be suitable for H.T.G.C.R. fuel elements, and to determine the limitations of the extrusion technique in relation to this aim.

In Part 1 (Wright 1964) the theories of extrusion are reviewed. Part 2 (Wright et al. 1964) deals with the basic technique and equipment for beryllium extrusion.

Previous work, (Wright and Silver 1961; Wright et al. 1964) on the hot extrusion of beryllium within a sheath, emphasised two major problems; these were associated with the relatively high pressures and temperatures involved and the difficulties in predicting the flow behaviour of the metal and hence control of dimensions.

Part 3 (this report) deals with the pressures and flow behaviour in beryllium extrusion.

2. EXTRUSION PRESSURES

2.1 Experimental

Extrusion pressures for 4-inch and 2-inch diameter sheathed beryllium billets were determined as a function of reduction in area at temperatures between 750 °C and 1050 °C. The technique of billet preparation and extrusion is given in Part 2 (Wright et al. 1964); the die angle in all cases was 140° and graphite grease was used as lubricant on the container and die.

Autographic records of pressure during the extrusion stroke were obtained through a strain gauge transducer, responding to oil pressure variations in the main cylinder of the press; the transducer signal was fed to a fast pen recorder with a full-scale response of 50 cycles per second. The transducer and recorder were calibrated against a Class 1 standard Bourdon gauge at intervals during each run; drift in the amplifiers driving the pen was checked by a Wheatstone bridge circuit before each extrusion. The accuracy of pressure measurement was limited finally by the size of the recorder chart and was typically ± 1500 p.s.i. on the extrusion pressures for 4 inch billets or ± 2000 p.s.i. for the 2 inch billets.

Typical autographic records of the pressure for 4 inch billets are shown in Figure 1. For direct extrusion the pressure decreased as the frictional area of the billet on the container was reduced; this variation (between C and D in Figure 1) was about 2000 p.s.i. per inch ram movement but varied between 0 and 5000 p.s.i. for individual cases. Between D and E in Figure 1 the pressure was normally constant or rising slightly, suggesting some cooling of the billets. Random variations in pressure of ± 2000 p.s.i. were noted with most extrusions; these were short to medium term fluctuations attributed to variations in frictional conditions due to variable lubrication or residual oxide scale on the billets. The mean value of the extrusion pressure between the points C and D was adopted for consistency and to avoid the effects of cooling in the later stages of extrusion.

Autographic records on 2 inch diameter billets normally showed an increase in pressure during the stroke, varying from 10,000 to 20,000 p.s.i. This increase was attributed to cooling of the billets during the stroke as discussed below.

2.2 Results

The pressures required for the direct extrusion of 2 inch and 4 inch sheathed powder billets of beryllium are shown in Figures 2 and 3. For both billet sizes, the extrusion pressures were related to extrusion ratio by an expression of the form:

$$P = K \log_e R .$$

This expression was obeyed within experimental accuracy for extrusion ratios as low as 4 : 1 at 1050 °C and at least to 7 : 1 at other temperatures.

The values of K (extrusion constant) are shown in Table 1 for various conditions and are compared with those of Loewenstein, Kaufmann, and Arnold (1955). The billet size used by Loewenstein et al. was probably 2 inches and the ram speed was probably one inch per second (although this was not clearly stated in their report).

The values of the extrusion constant of 4-inch diameter billets determined in this work ranged from 32 per cent. lower at 1050 °C to 4 per cent. lower at 750 °C than those reported by Loewenstein et al. On the other hand, values for 2-inch billets ranged from only 15 per cent. lower at 1050 °C to 8 per cent. higher at 850 °C. These trends suggest that the smaller billets in both investigations were cooling rapidly during transfer between the furnace and press or during the stroke; the general agreement in values at the lower temperatures supports this view since the rate of radiant heat loss would be reduced by about 65 per cent. at the lower temperature, and the rate of heat transfer by conduction to the tooling would be less.

Comparison of the values obtained by Loewenstein et al. with the values for 4-inch diameter billets in this work suggests that there was an error in the previous work of about 200 °C in billet temperature at 1050 °C; this may not be excessive if the rates of billet transfer and extrusion were slow as suggested by their report. A similar error of about 100 °C for the 2-inch billets extruded in this work was generally confirmed by measurements of the temperature of the emergent rods using an optical pyrometer. The extent of cooling of the 4-inch diameter billets during extrusion at 1050 °C was also checked with an optical pyrometer; within the reproducibility of measurements, which was about ± 30 °C, no cooling was detected.

A further check was made on the possible error in temperatures of the billets by fitting the values of extrusion pressure to an expression (Schishokin 1929, Pearson and Smythe 1931) of the form:

$$P = A e^{-\lambda T} ,$$

where P = extrusion pressure,

λ, A are material constants, and

T = temperature.

This expression has been found to be valid for a range of aluminium and copper alloys (Pearson and Smythe 1931); Figure 4 shows the values for mild steel between 900 °C and 1200 °C (Cook 1957) which also obey this relationship. Thus, although no physical explanation has been put forward, the expression may adequately predict conditions for beryllium and other metals over a limited temperature range.

The extrusion pressure for 4-inch beryllium billets fitted the expression reasonably well (Figure 4) and, by extrapolation from the low temperature values, the error at 1050 °C may not exceed 5 per cent. On the other hand, the results from 2-inch billets showed a marked departure at 1050 °C on extrapolation from the low temperature results, which again suggested cooling of these billets.

The extrusion pressure determined for sheathed billets, as above, was the composite pressure required for extrusion of the $1/8$ inch thick mild steel sheath and beryllium core. Kaufmann, Gordon, and Lillie (1950) stated previously that the extrusion properties of mild steel and beryllium are similar and little error is introduced in accepting the pressures from sheathed billets as the true pressure for beryllium. This has been confirmed by extruding 0.15 per cent. carbon steel billets over the temperatures and range of reductions of interest. Results are shown in

Figures 5 and 6. The values of the extrusion constant for mild steel are above those for beryllium for both billet sizes under comparable conditions (Table 2), but the extrusion constants do not vary by more than 10 per cent. at 750 °C or 5 per cent. at 1050 °C; the results in Figures 2 and 3 were not corrected for this factor.

2.3 Effects of Friction

In the direct extrusion of 4-inch diameter billets, the extrusion pressure was noted to decrease by 10,000 – 12,000 p.s.i. as the unextruded billet length was reduced from about six inches to one inch, and this was attributed to reduced container friction. This effect was confirmed by the inverted extrusion at 1050 °C of 4-inch diameter billets, 7 inches long; by this technique, container friction was avoided and pressures were generally 12,000 – 15,000 p.s.i. lower than for direct extrusion.

The coefficient of friction between container and billet was calculated as 0.03 – 0.035 from Equation 1 below (see Wright 1964).

$$\frac{P_L}{P_o} = \frac{\left[(a + b \log_e R - 1) \exp \frac{4\mu L}{D}\right] + 1}{(a + b \log_e R)} \qquad (1)$$

The values for substitution are:

(i) when $R = 16, L = 5$, then $\frac{P_L}{P_o} = \frac{80000}{69000} = 1.16$,

and (ii) when $R = 16, L = 7$, then $\frac{P_L}{P_o} = \frac{80000}{66500} = 1.20$.

Sejournet (1956) found values of "about 0.05" for the friction coefficient in the extrusion of various steels using graphite and talc as lubricants.

Further experiments (Wright and Silver unpublished) on the direct extrusion of 4-inch mild steel billets at 1050 °C using a lead-base glass as lubricant gave results for extrusion pressures which were 10 – 12 per cent. lower than for graphite as shown in Figure 6. The conditions of friction with molten glass lubricants probably approach hydrodynamic conditions where the apparent friction coefficient is very low (< 0.01); Chadwick (1959) tends to confirm this by stating that the friction coefficients with glass lubricants are "negligible". The results with glass lubrication thus tend to support the value of friction coefficient derived for graphite as shown above.

Using the value of 0.03 – 0.035 for friction coefficient, the pressure loss by friction on the die face may be estimated as 2 – 3 per cent. of the total pressure from the equation (Wright 1964):

$$\Delta P = \frac{\mu_2 P_o}{\sin \alpha / \cos \alpha} \left(1 - \frac{1}{R}\right) \qquad (2)$$

The values of the extrusion constants for beryllium and mild steel quoted in Tables 1 and 2 and for the pressures given in Figures 2 and 3 were not corrected for the effects of friction. The corrected values for the extrusion constants on 4-inch diameter billets based on the above assumptions are given in Table 3.

3. FLOW PATTERNS

With the sheathed billets used for beryllium extrusion, equilibrium flow conditions must be attained as soon as possible after the start of extrusion if a predictable uniform cladding thickness is to be achieved. Extensive retardation of metal on the die face and particularly the formation of a true dead metal zone, will result in variable cladding thickness and variable dimensions of the beryllium. In the extreme case of sheathed extrusion through an unlubricated shear die, the original zone of dead metal will contain both steel and beryllium as shown in Figure 7(a); under these conditions the danger exists of stripping the cladding from the extruded section or at least reducing the cladding to an undesirable thickness. As extrusion proceeds, the beryllium in the dead zone will be displaced by steel as shown in Figure 7(b) and the dimensions of clad and beryllium will be modified. In the final stage (Figure 7(c)), the dead zone will contain only steel and a constant cladding thickness will be achieved by shear across the dead metal boundary; if the volume of dead metal now remains constant, the proportions of cladding to beryllium in the extruded section will be the same as in the original billet and these dimensions will be fully predictable. The danger exists however, that the billet will not be long enough to allow these equilibrium conditions to be achieved, in which case the cladding thickness will vary continuously along the extruded section.

The desirable conditions of flow across the die face are therefore associated with minimum retardation of the skin, uniform acceleration over the die face, and the absence of dead metal zones. The extent to which these conditions were met was examined using gridded billets; the associated problem of the correct shape to be adopted on the back plug of sheathed billets to compensate for unequal elongation across the section was also examined.

3.1 Velocity Conditions and Extent of the Plastic Field

For this study, 4-inch diameter steel billets were prepared as two half cylinders; one half of each billet was inscribed with a ¼ inch x ¼ inch grid, and 0.022 inch Inconel wire was hammered into machined grooves. The halves were coated with graphite and then assembled by tack welding; excess weld metal was removed by turning. The diameter of the assembled billets was calculated to fit the container accurately when hot.

The billets were extruded at 1050 °C through 0.72 inch conical dies with 140°, 90°, and 70° included angles using the techniques described previously; the extrusion stroke was interrupted before all the gridded section of the billet had entered the die. After extrusion, the unextruded portion of the billet was broken open to reveal the original and distorted grid as shown in Figure 8. Mean values of the position of the grid intercepts were transcribed from enlarged photographs onto drawing paper as shown in Figures 9 - 11. The velocities along the flow lines were taken from the distances between nodal points and referred to a ram velocity of unity. Profiles of equal velocity were drawn and the extremes of the plastic field were broadly defined by the upper profile for unit velocity.

Further definition of the shape of the plastic field was obtained by a modification of the technique used by Thomsen (1956).

The velocity vectors along each side of the grid were determined and their resultant indicated the extent and direction of maximum shear; by definition, the α-slip lines are tangential to these directions and hence the limiting α-slip line and the extent of the plastic region were defined.

The directions of maximum shear are shown in Figures 9 - 11 as crosses. The sensitivity of this technique for determining the slip-line field was rather low mainly because of the large grid size used in this work; nevertheless, the directions of maximum shear were generally as expected and in particular the angle of approach to the boundaries (container and centre of billet) was approximately 45° as required for frictionless conditions.

The upper boundary of the plastic field was a diffuse zone about 1/8 - 1/4 inch wide as shown. The poor definition could have arisen from the technique used to define the field or from a tendency of the material to work-harden in crossing this boundary; both causes probably contributed in this case. The plastic field for the 70° die was almost entirely within the cone of the die while for the 140° die the field extended for an appreciable distance into the container; for all dies, the outer layer of the billet did not appreciably deform until the die-container junction was reached.

There was some evidence of retardation of flow along the wall of the container relative to the centre of the billet, even before the grid lines entered the plastic field. The extent of retardation was small however, the velocity at the container face being about 3 per cent. less than in the centre of the billet. This variation was attributed to frictional forces on the container wall as discussed in Section 2.2. A major variation in grid pattern at the container wall is shown for the 90° die in Figure 8(a); in this case, the press pad was slightly under size and displaced to one side, thus allowing some metal to flow back between the pad and container.

The flow pattern with the 140° die showed a zone of retardation (Figure 11) near the top corner of the die with the outside skin velocity as much as 20 per cent. lower than the ram velocity; this zone extended inwards with decreasing severity for about ¼ of the billet diameter. A similar pattern was noted for the 90° die except that the retardation was not more than 10 per cent. and the zone was not as extensive. On the other hand, no retardation was noted with the 70° die and the outside skin accelerated regularly along the die face to the limit of these observations, although at a slower overall rate than the centre.

The presence of the retarded zones on the 90° and 140° dies did not involve a hold-up of material; for example, two particles A' and A'' in Figure 11 were retarded at different rates and for different times, but as far as detected, these particles emerged from the retarded zone at B', B'' together, and then accelerated as indicated by the velocity profiles.

The requirements for streamline flow of sheathed billets thus appeared to be met by all three die shapes. This was confirmed in the extrusion of billets in which the proportions of cladding to beryllium in the final shape were correctly calculated from the proportions in the billet. The extrusion pressures obtained from the 70° and 90° dies were within 5 per cent. of those obtained with the 140° die; the increase in die frictional losses with these long acute-angled dies was presumably balanced by the decrease in redundant work.

3.2 Compensation for Unequal Elongation

The velocity profiles in Figures 9 – 11 show that in each case the centre of the billet travelled faster along the stream lines than the outside; the outside grids were sheared towards the centre while the centre grids were largely deformed by pure tensile straining. Thus a plane interface in the original billet was deformed into a curved surface in the extruded rod. For the sheathed beryllium billets with a plane mild steel back plug, this unequal elongation across the section gave rise to some intrusion of the steel from the plug into the beryllium with consequent lower yield of product.

The extent of intrusion of the plane mild steel plug into the beryllium of the 4-inch billets was measured from radiographs of the extruded sections and is shown in Table 4.

Measurements of the spacing of grids along the centre-line of the billets showed that the axis of the billets deformed by tensile elongation only and hence the relative increase in length of intrusion (I/R) shown in Table 4 must reflect more extensive retardation of the outer fibres with increasing extrusion ratio; these results reflect the changes in the shape of the plastic field and possibly frictional conditions on the die face which would be predicted in general terms from the previous Sections.

The shape developed in the intrusion was also determined from radiographs of the interface and from gridded billets; the radiographs of the interfaces of billets extruded at 4 : 1 and 31 : 1 reduction are shown in Figures 12(a) and 12(b) and those measured at other reductions are shown in Figures 12(c), 12(d), and 12(e). The distortion of the intrusion at A–A' which was particularly evident with low extrusion ratios arose from the sheath which normally finished near that point.

The proportions of the intrusion measured at various extrusion ratios were reasonably constant, although these measurements were subject to errors due to the low sensitivity of the radiographs in detecting thin intrusions of steel (normally encountered at high extrusion ratios) and the distortion due to the sheath noted above. Figure 13 shows the shapes developed at extrusion ratios of 4, 11, and 21, plotted in non-dimensional units, that is, the co-ordinates of the intrusion were converted to ratios of length in each case. The shape of the intrusion could be represented by a parabolic equation of the form:

$$y = N\,(1 - x^2) ,$$

where y is the length co-ordinate of the interface measured as shown in Figure 13, x is the width co-ordinate, and N is a constant, whose values are shown in Table 4.

The determination of a parabolic shape for the interface is in agreement with previous work (Pearson and Parkins 1960) although no theoretical justification for the development of this shape has been put forward.

The correction to be applied to the plug-beryllium interface in the original billet to achieve minimum intrusion in the extruded section was calculated from Table 4 for various reductions, assuming a parabolic form as discussed above. These corrections are shown in idealised form in Figure 14. Because of the difficulties in machining the parabola on the plug, approximations were made to a full cone or a truncated cone and a series of billets were extruded to determine the extent of correction achieved.

With a full cone on the back plug, the centre of the extrusion was excessively retarded as expected and the beryllium formed a conical intrusion into the steel as shown in Figure 15. The use of a truncated cone achieved excellent correction (Figure 16) with less than 1½-inches of defect length on sections extruded at ratios of 11 : 1 and about 2½-inches for ratios above 11 : 1. (The "intrusion" of beryllium along the outer skin of the extrusion arises from the 2° taper on the plug to facilitate fitting into the sheath). The maximum error in shape was associated with the corners of the cone, as illustrated, and further correction could be achieved by varying the cone angle. The error in plug shape at these points calculated from the radiograph was 0.1 inch on the 4 inch diameter plugs which was generally as predicted from the approximations in Figure 14.

The corrections developed in this work were based on a knowledge of the flow patterns established on gridded billets in the previous section but there are obvious limitations to the general application of these results. The use of a narrow angle on the die was shown in Section 3.1 to promote relatively less shear across the billet and hence a different interface shape in the extruded section than achieved with shear or wide angled dies; thus the plug corrections given above were only valid for 140° dies. Experiments with the same plug shapes on 2-inch billets at the same reduction ratios did confirm, however, that the results can be extrapolated to other billet sizes, provided lubrication conditions were similar.

Previous work by Nowak, Wegner, and Rapperport (1957, 1958) showed that the interface shape will also vary if the yield stress of the materials on each side of the interface varies. Evidence from this work on the relative yield stress of beryllium and mild steel suggests that only minor differences exist and if this is correct, the characteristics of the interface established in this work may have wider significance in relation to the general problem of metal flow in homogeneous billets.

4. SUMMARY

1. The extrusion pressures for beryllium were determined at temperatures between 750°C and 1050°C and extrusion ratios between 4 : 1 and 72 : 1 using graphite lubricants; these values were also determined for mild steel (0.15% carbon) using both graphite and glass lubricants.

2. The friction coefficient between the mild steel sheathed billets and extrusion tools with graphite lubricants was determined as 0.03 – 0.035.

3. Experiments with gridded steel billets using graphite lubricants showed that extrusion proceeds through 140° included angle dies by slip over the die face without significant retardation in "dead metal" zones. Similar effects were noted with 90° and 70° included angle dies.

4. The deformation of an original plane interface normal to the extrusion direction was determined for 140° included angle dies. The extent of deformation (and hence the intrusion of a flat mild steel "plug" following the beryllium) increased with increasing extrusion ratio but the shape of the interface remained approximately parabolic. The extent of intrusion may be reduced, and hence the yield of product increased, by shaping the back "plug" to compensate for unequal strain across the section.

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TABLE 1

EXTRUSION CONSTANT K (p.s.i.)

Temperature °C	Graphite Lubrication 4-inch/sec ram speed		Loewenstein et al. (1955)
	2-inch diameter billets	4-inch diameter billets	
750	not determined	52,000	54,000
850	48,000	41,800	50,000
950	38,500	34,600	43,000
1050	35,000	29,000	40,000

TABLE 2

EXTRUSION CONSTANTS FOR MILD STEEL

Extrusion Constant K (p.s.i.)

Temperature °C	Graphite Lubrication 4-inch/sec ram movement	
	2-inch diameter billets	4-inch diameter billets
750	not determined	53,400
850	59,000	44,700
950	not determined	37,000
1050	39,000	30,500

TABLE 3

"FRICTIONLESS" EXTRUSION CONSTANTS

(4-inch diameter billets)

Extrusion Constant p.s.i.

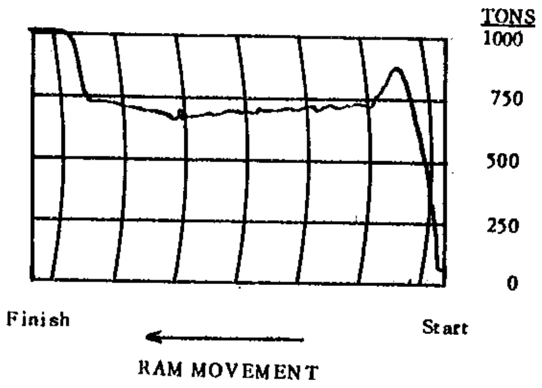
Temperature °C	Beryllium	Mild Steel
750	39,500	40,500
850	32,000	34,000
950	26,000	28,000
1050	22,000	23,000

TABLE 4

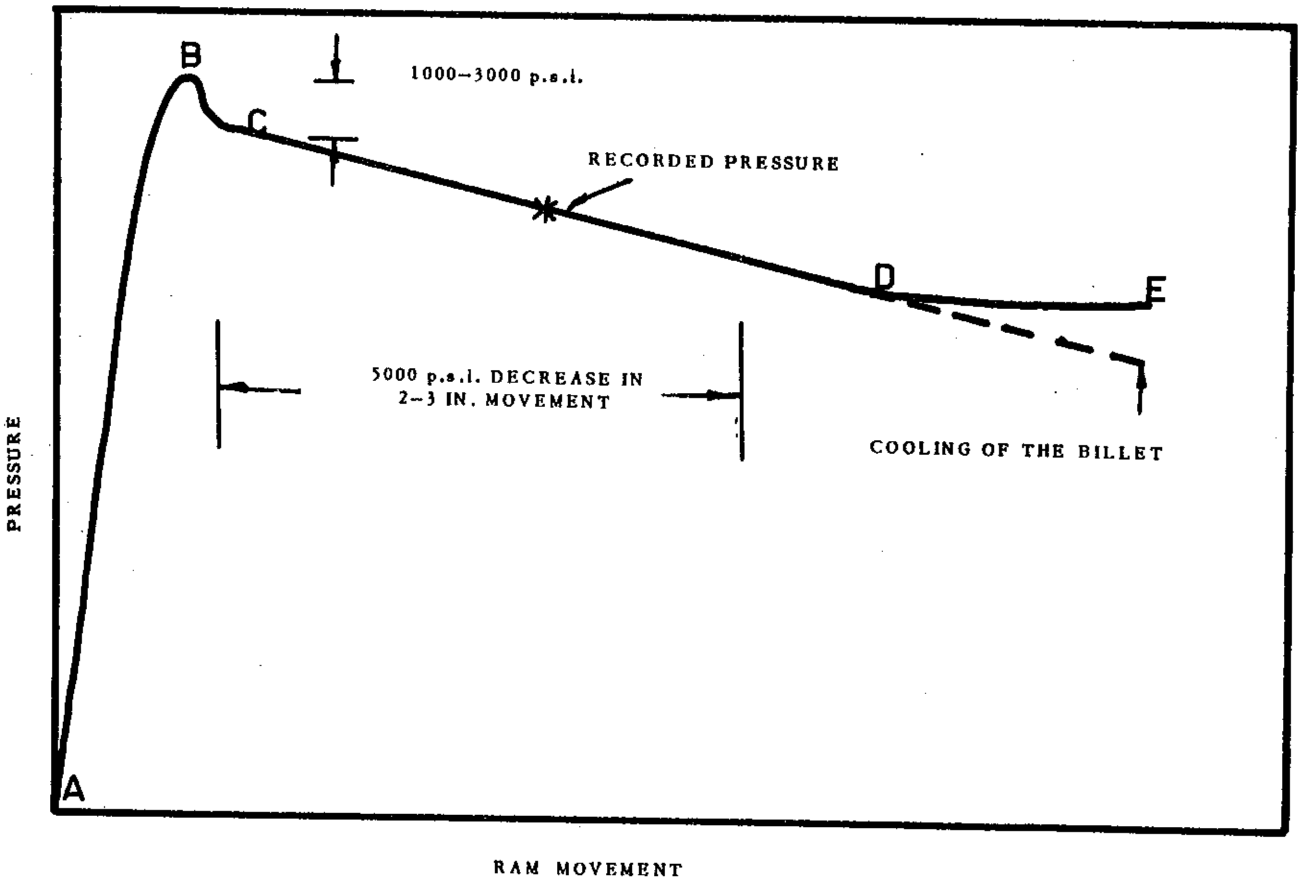
MEASUREMENTS OF INTRUSION LENGTH AS A FUNCTION OF EXTRUSION RATIO

Extrusion Ratio (R)	Maximum Intrusion (I) inches	I/R	No. of Diameters Intrusion (N)	N/R
4	5	1.25	2.5	0.62
11	15	1.35	12.5	1.13
21	30	1.43	35	1.67
31	45	1.45	63	2.04
69	(100)*	(1.45)*	(207)*	(3.0)*

* Figures in brackets are from measurements subject to errors arising from poor definition of the interfaces in the radiography.



(a) ACTUAL RECORD



(b) IDEALISED RECORD

FIGURE 1. ACTUAL AND IDEALISED AUTOGRAPHIC RECORDS IN EXTRUSION OF 4-INCH BILLETS

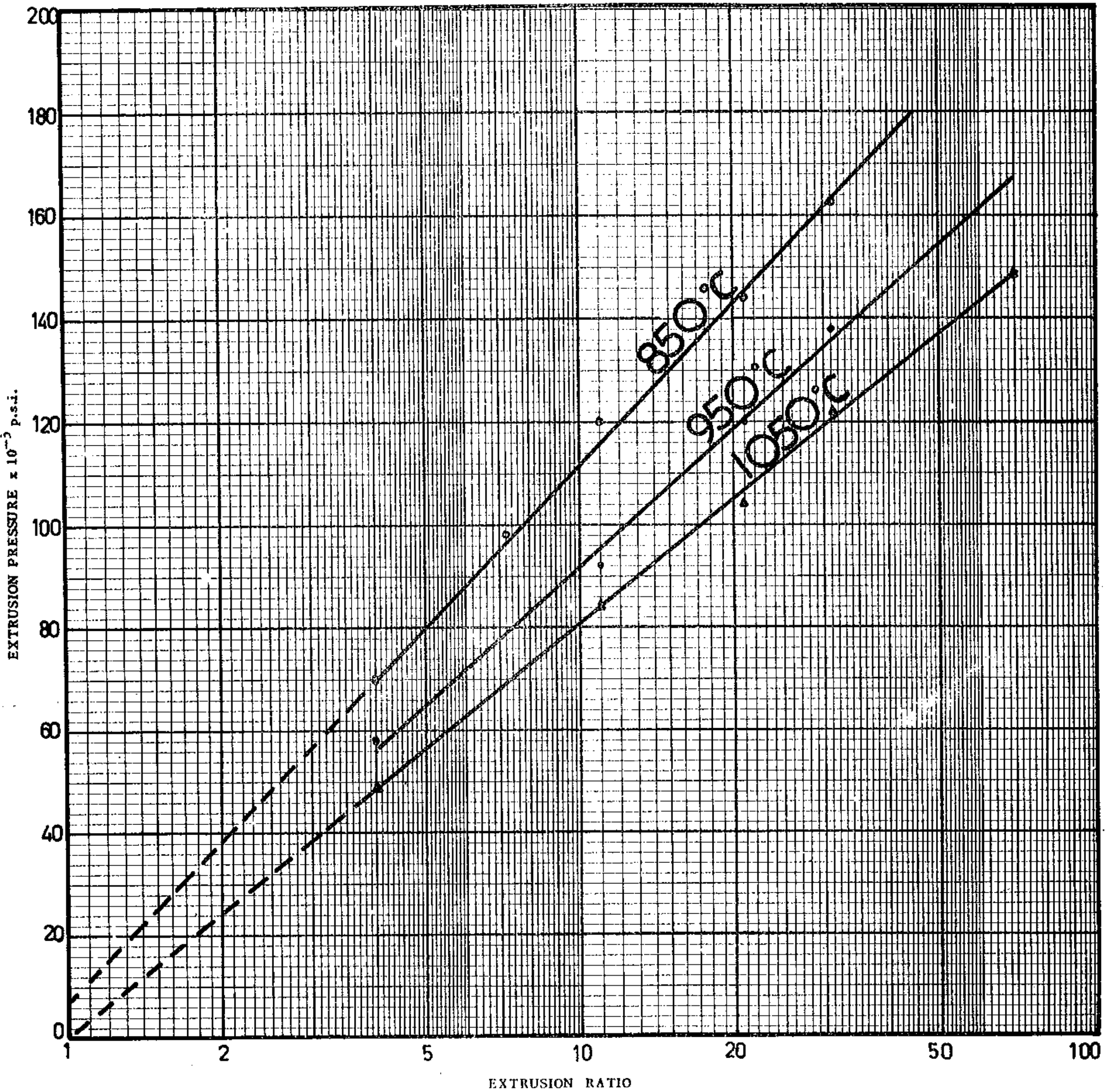


FIGURE 2. EXTRUSION PRESSURES ON 2-INCH BERYLLIUM BILLETS

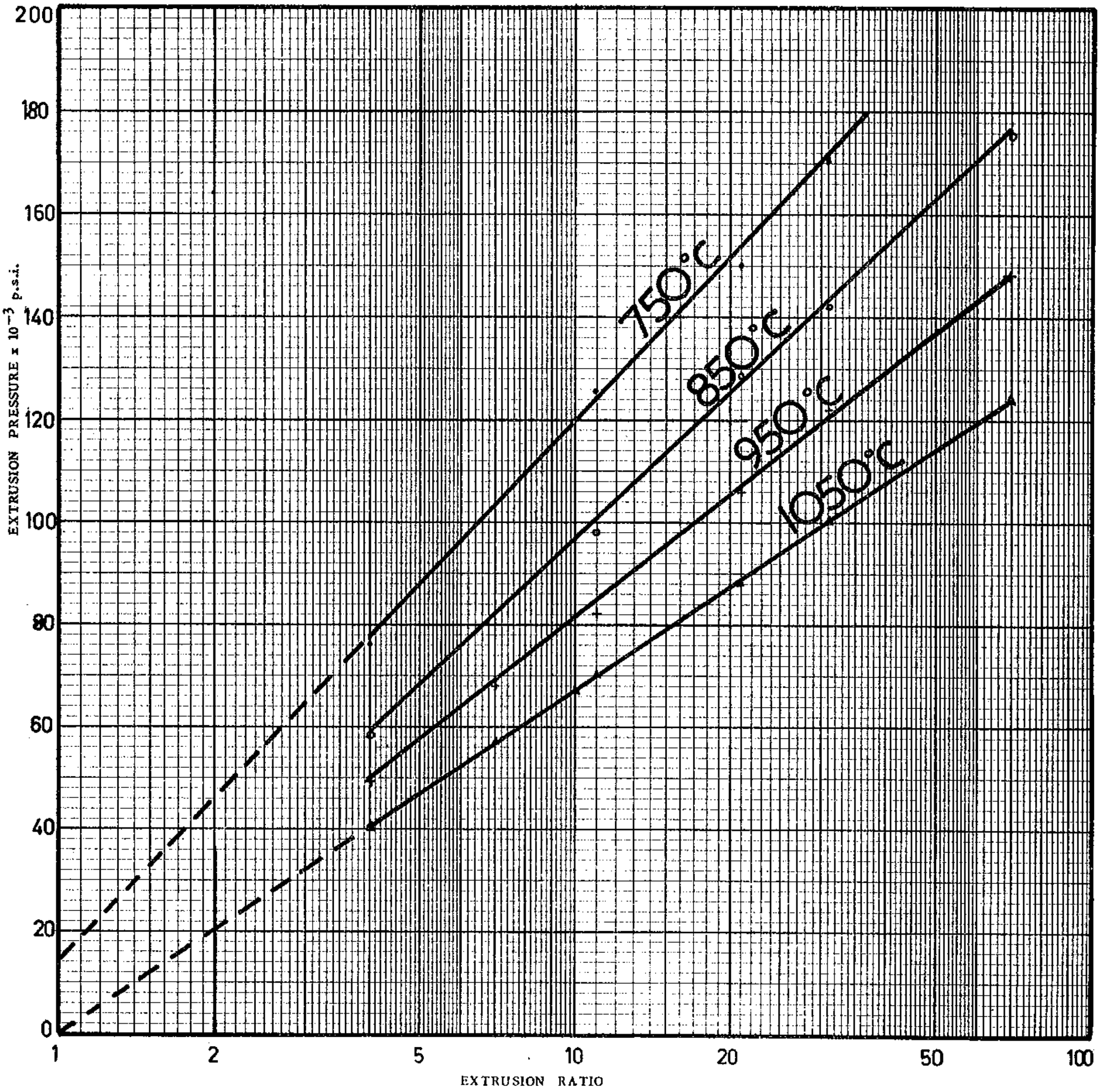


FIGURE 3. EXTRUSION PRESSURES ON 4-INCH BERYLLIUM BILLETS

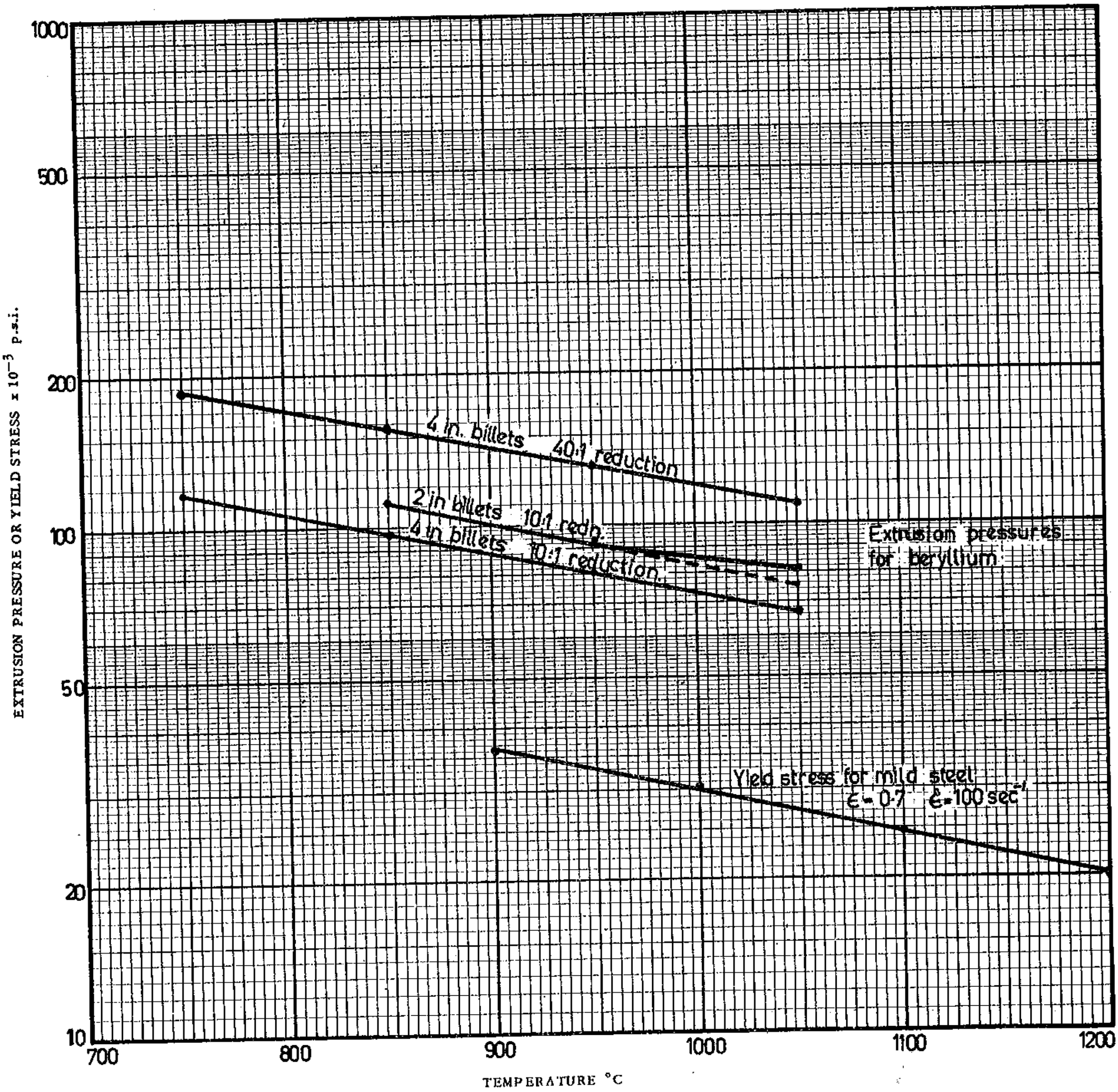


FIGURE 4. VARIATION IN YIELD STRESS OR EXTRUSION PRESSURE WITH TEMPERATURE

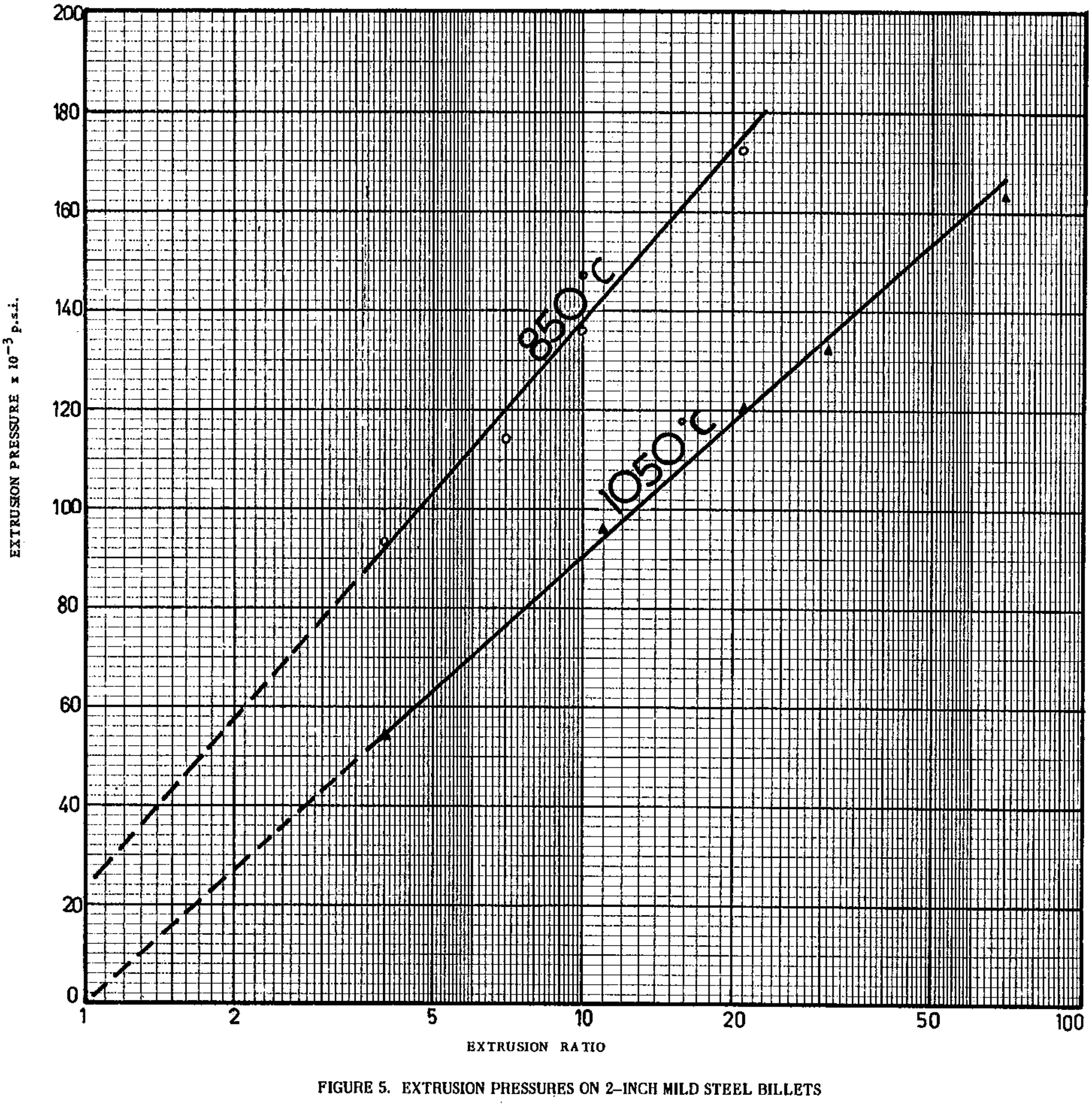


FIGURE 5. EXTRUSION PRESSURES ON 2-INCH MILD STEEL BILLETS

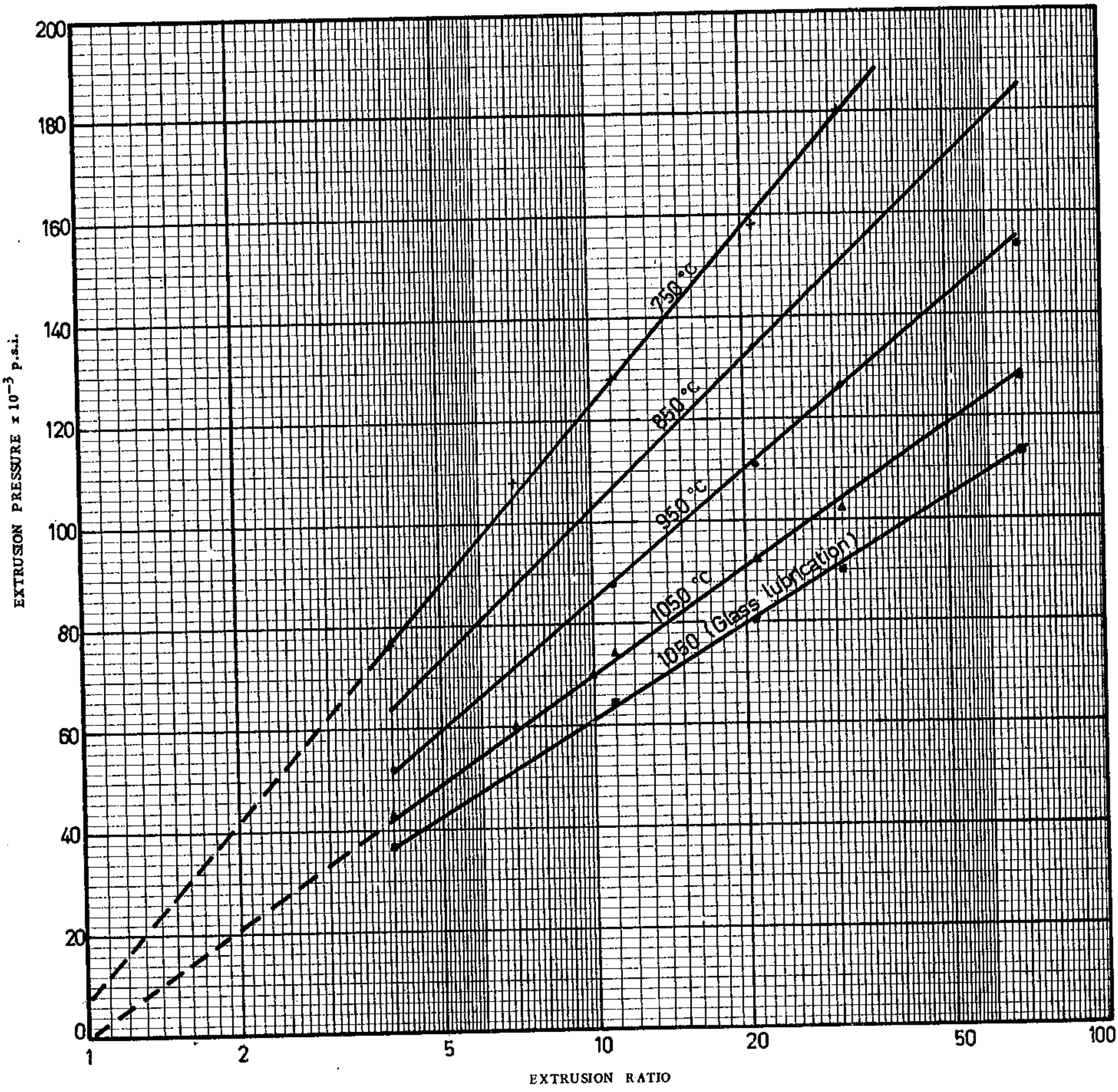
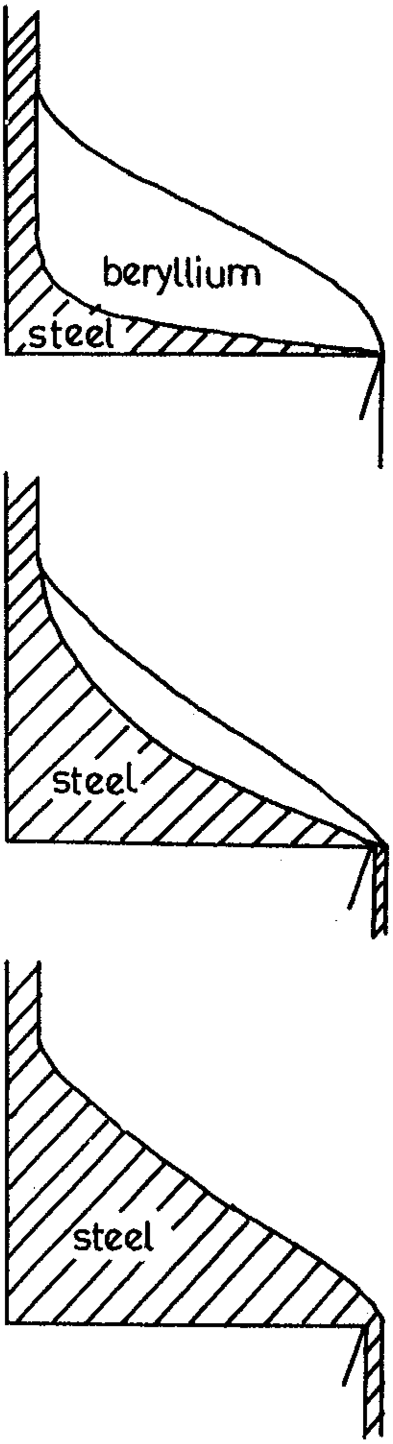


FIGURE 6. EXTRUSION PRESSURES ON 4–INCH MILD STEEL BILLETS

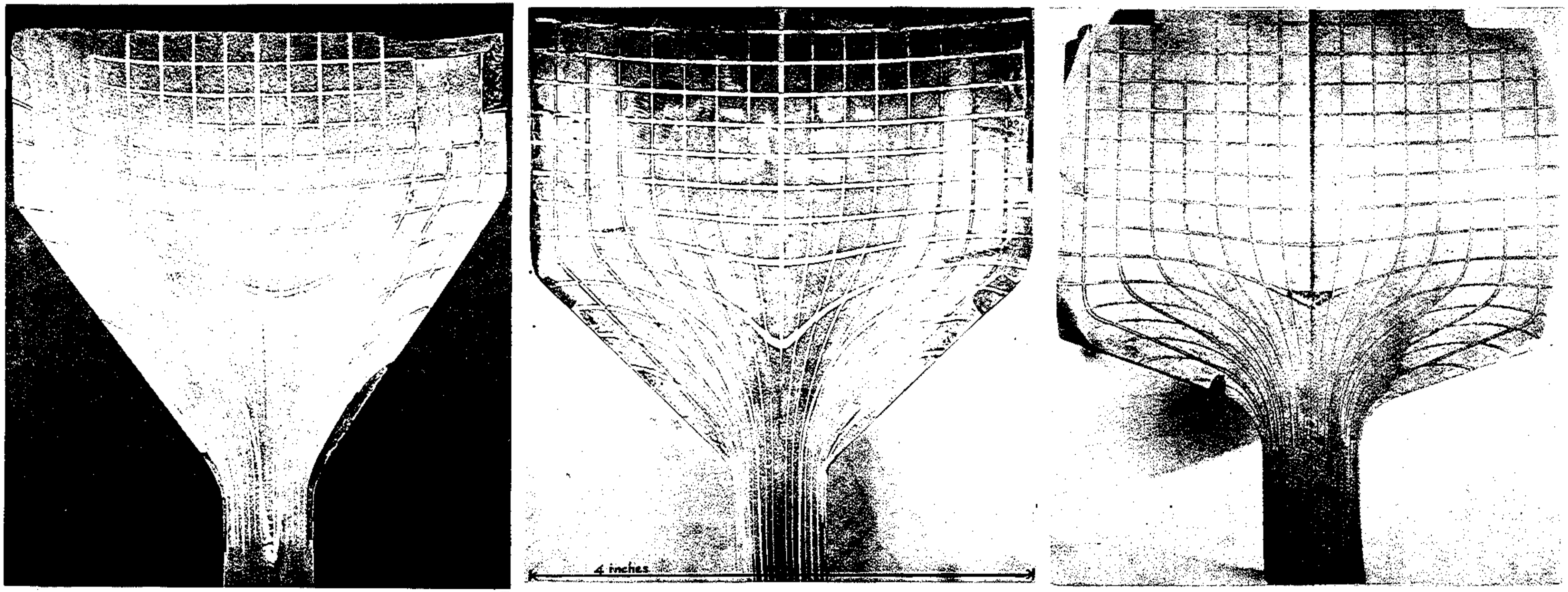


(a) ORIGINAL DEAD METAL ZONE CONTAINS STEEL AND BERYLLIUM

(b) PROPORTIONS OF STEEL AND BERYLLIUM IN THE DEAD ZONE MODIFIED

(c) EQUILIBRIUM CONDITIONS

FIGURE 7. SCHEMATIC ILLUSTRATION OF CHANGES IN THE DEAD METAL ZONE DURING CO-EXTRUSION



(a) 70 DEGREE ANGLE DIE

(b) 90 DEGREE ANGLE DIE

(c) 140 DEGREE ANGLE DIE

FIGURE 8. PHOTOGRAPHS OF DISTORTED GRIDS

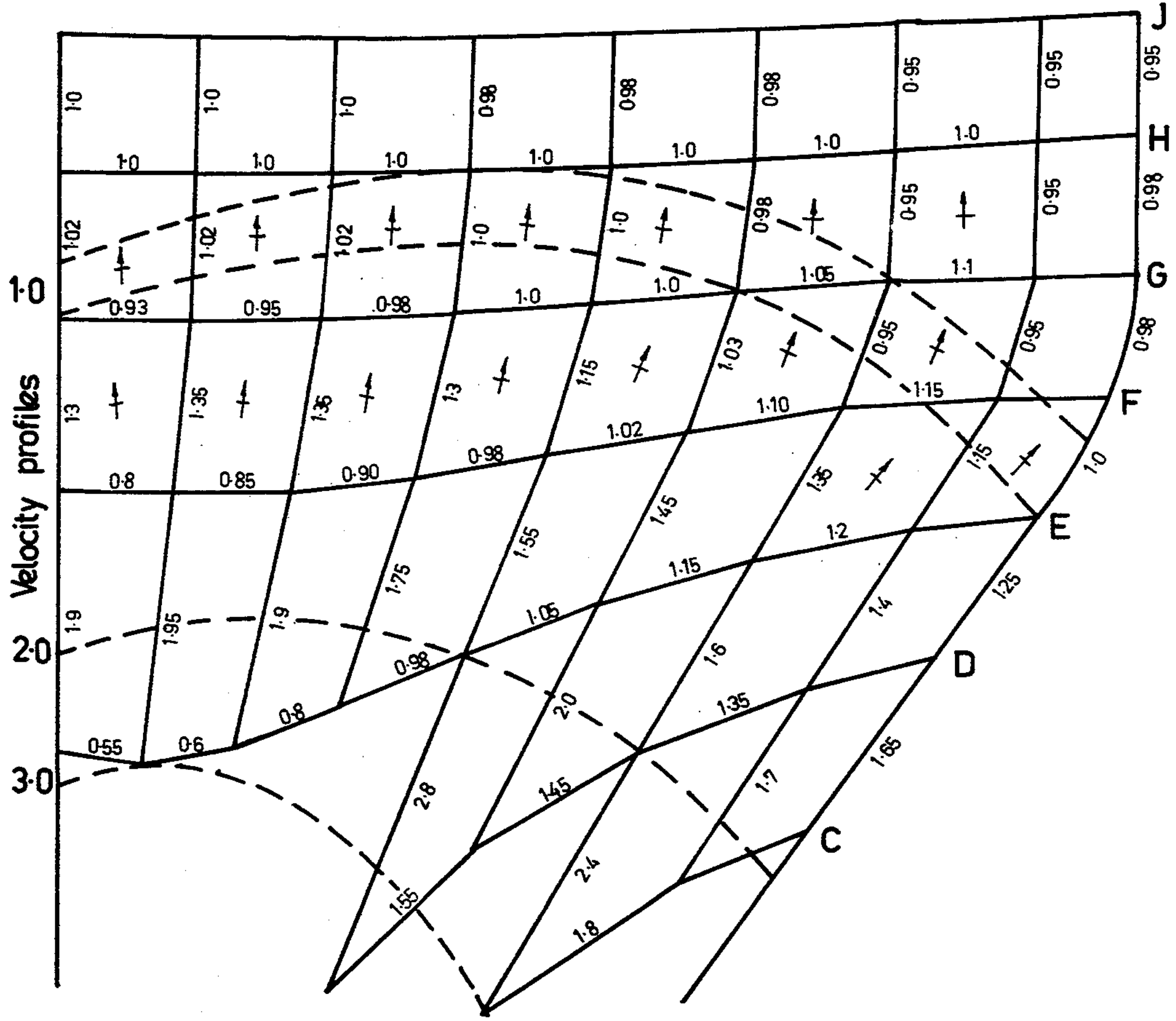


FIGURE 9. DISTORTION OF GRID AND VELOCITY PROFILES WITH 70° INCLUDED ANGLE DIE

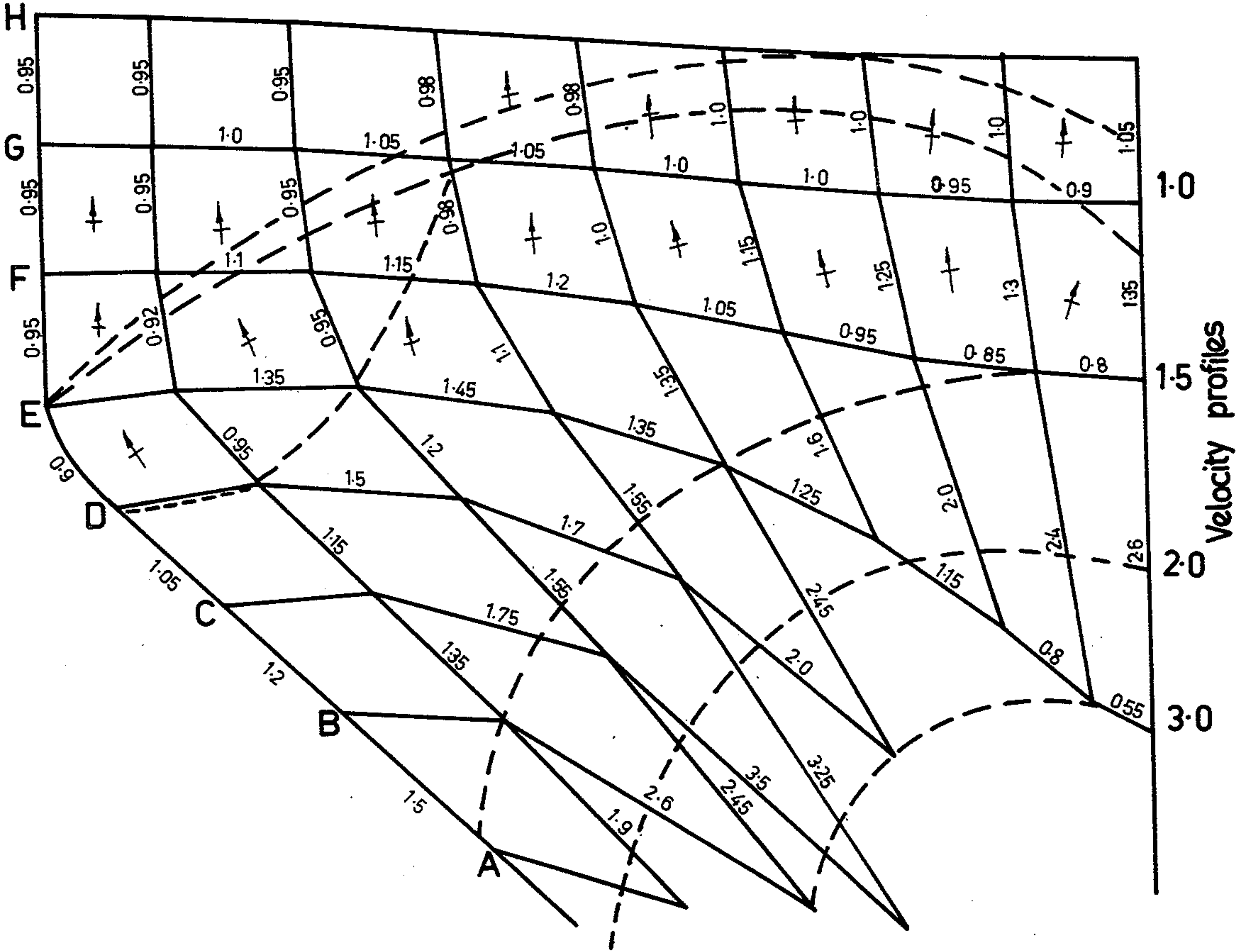


FIGURE 10. DISTORTION OF GRID AND VELOCITY PROFILES WITH 90° INCLUDED ANGLE DIE

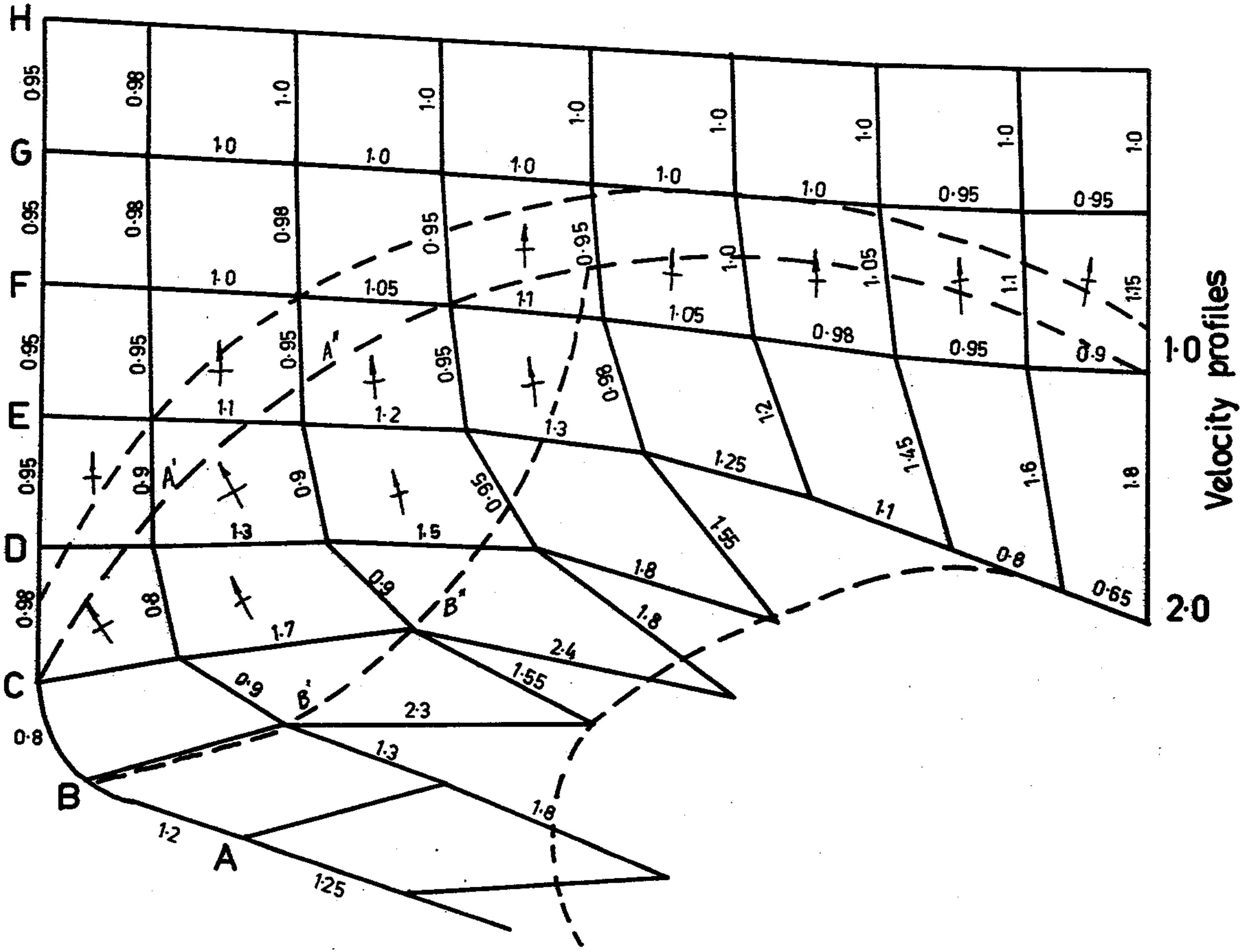


FIGURE 11. DISTORTION OF GRID AND VELOCITY PROFILES WITH 140° INCLUDED ANGLE DIE

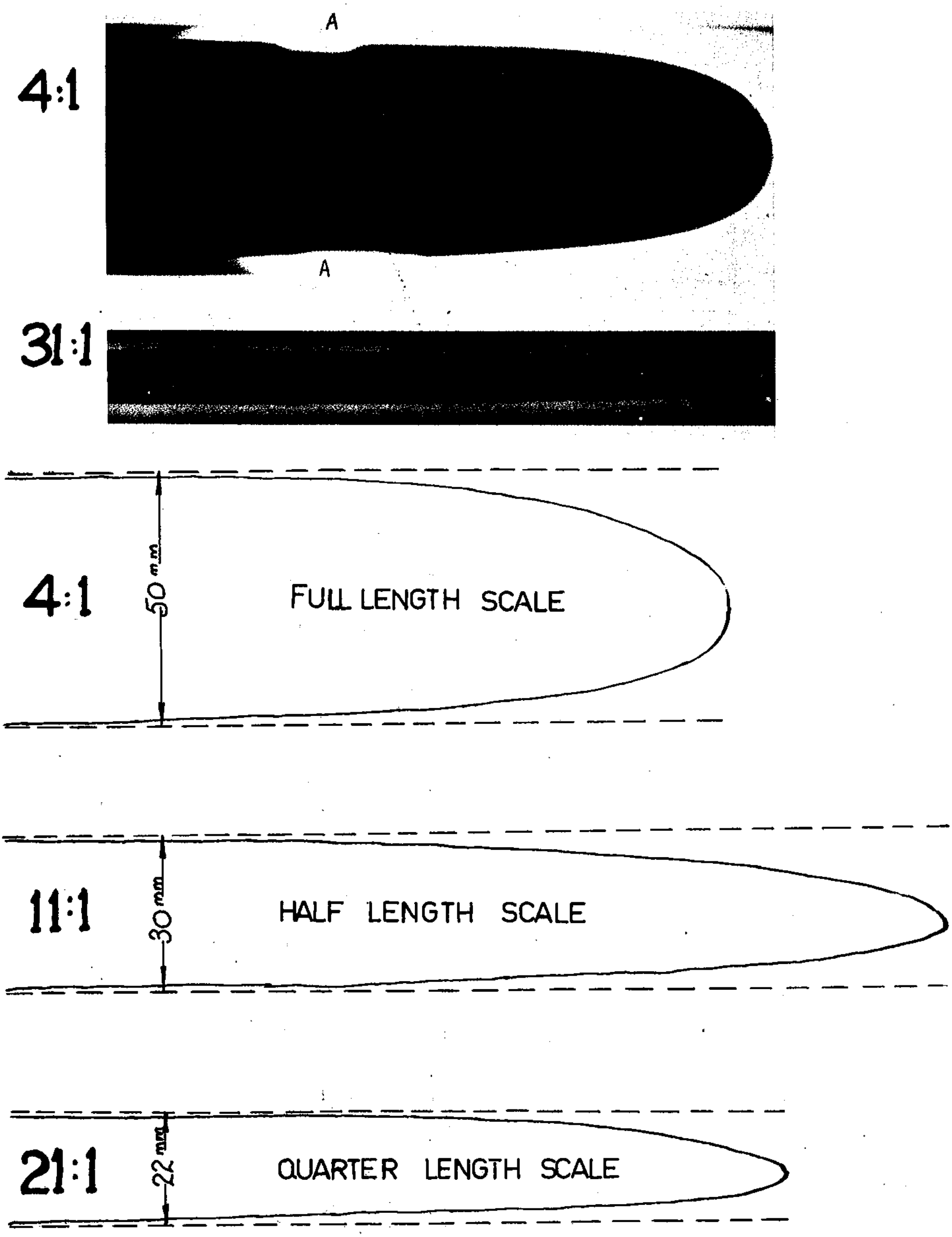


FIGURE 12. SHAPES OF UNCORRECTED BILLET INTERFACES

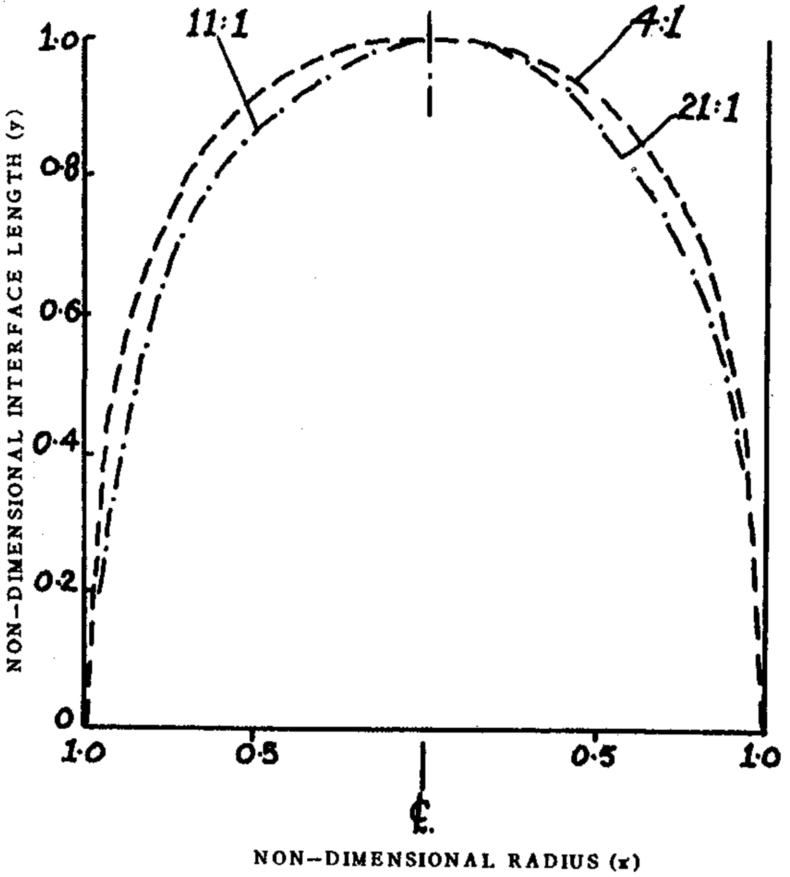


FIGURE 13. NON–DIMENSIONAL PLOT OF INTERFACE SHAPE

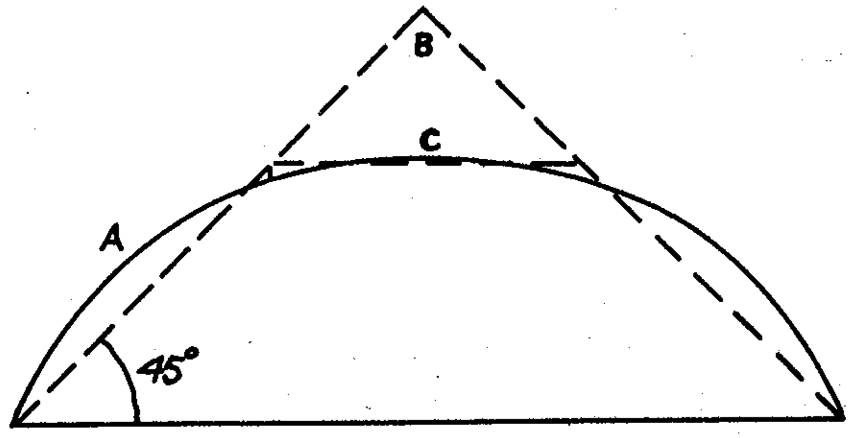


FIGURE 14. IDEAL CORRECTION TO PLUG FACE TO PRODUCE PLANE EXTRUDED INTERFACE (Parabola A), COMPROMISE CONE (B), AND TRUNCATED CONE (C)

FIGURE 15. RADIOGRAPH SHOWING OVER-CORRECTED INTERFACE RESULTING FROM USE OF FULL CONE ON THE PLUG FACE

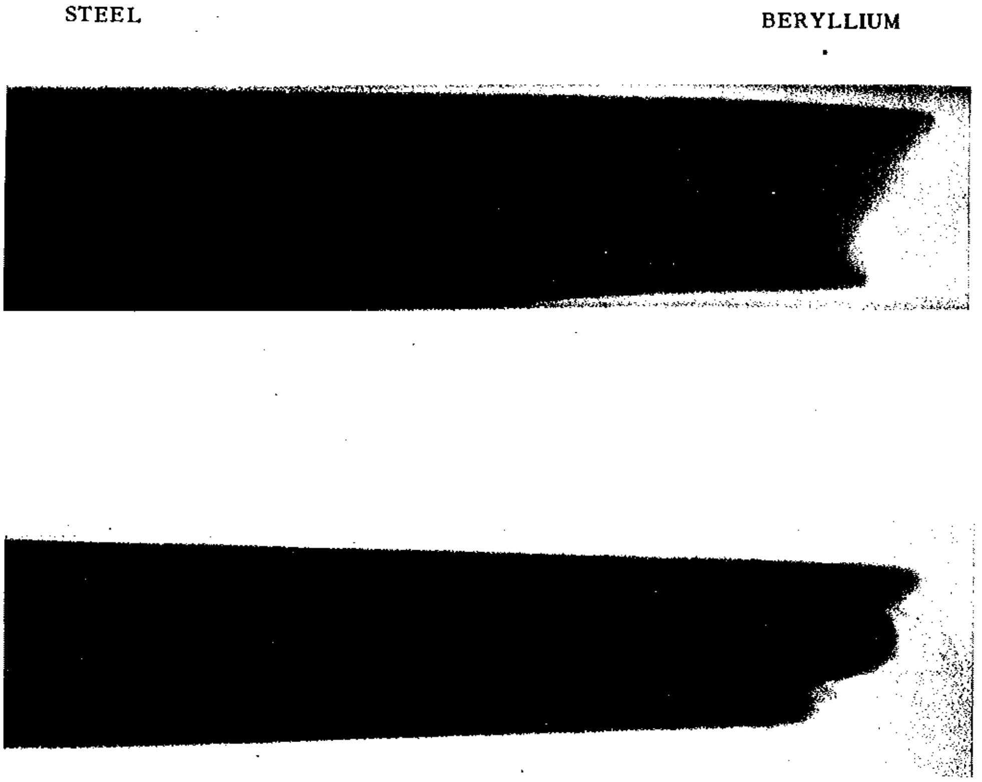


FIGURE 16. NEAR-OPTIMUM CORRECTION TO INTERFACE RESULTING FROM USE OF A TRUNCATED CONE ON THE PLUG FACE