



(22) Date de dépôt/Filing Date: 2007/04/05

(41) Mise à la disp. pub./Open to Public Insp.: 2007/11/09

(45) Date de délivrance/Issue Date: 2009/10/13

(30) Priorité/Priority: 2006/05/09 (US60/746,813)

(51) Cl.Int./Int.Cl. *E21B 29/00* (2006.01),
B21D 39/08 (2006.01)

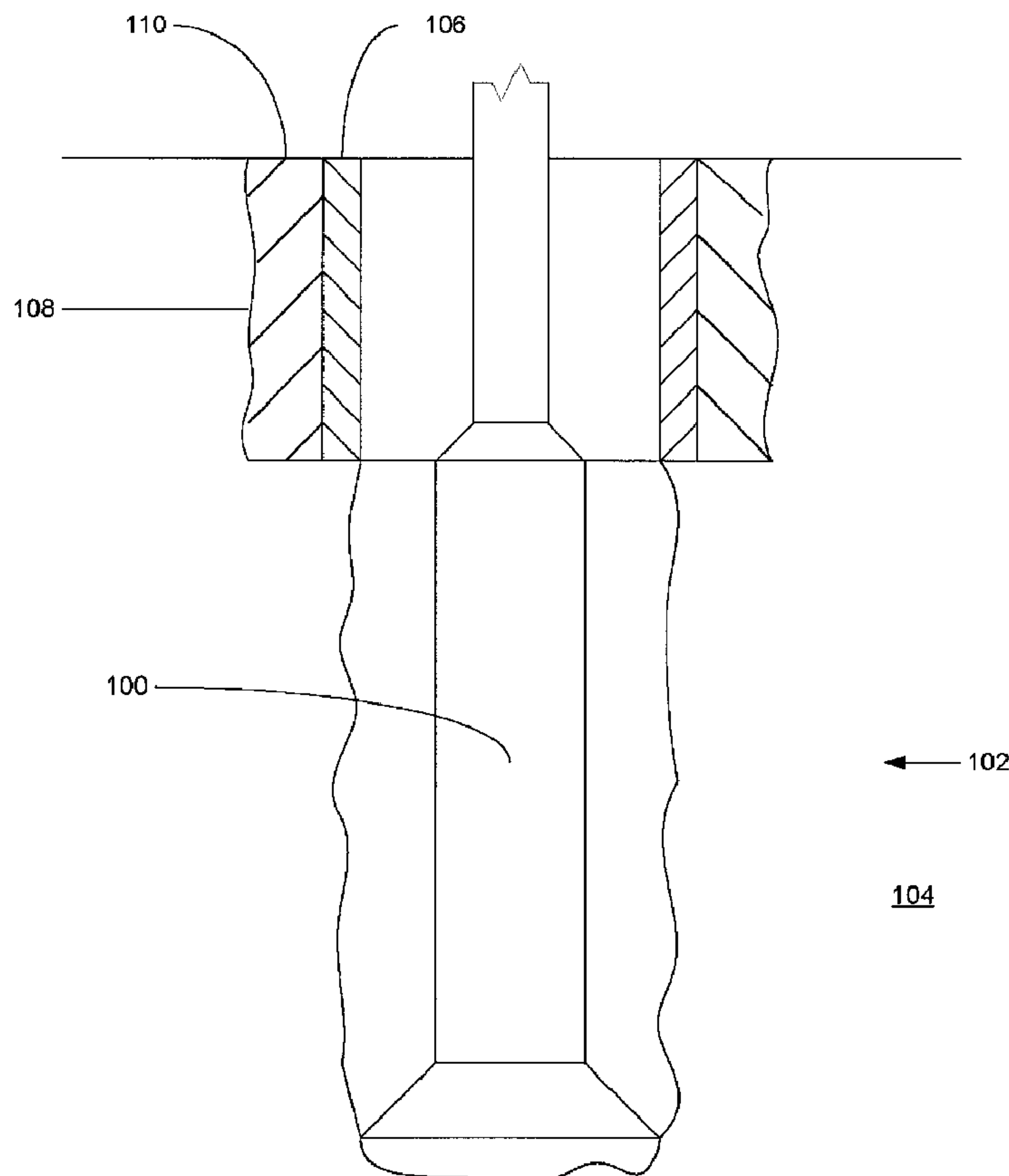
(72) Inventeurs/Inventors:
SHUSTER, MARK, NL;
PETLYUK, ALLA, US;
PALANISWAMY, HARIHARASUDHAN, US;
GRAY, MALCOLM, US;
COSTA, SCOTT, US;
NGAILE, GRACIOUS, US;
GRINBERG, GRIGORIY, US;
...

(73) Propriétaire/Owner:
ENVENTURE GLOBAL TECHNOLOGY, US

(74) Agent: KIRBY EADES GALE BAKER

(54) Titre : CONE ET SYSTEME D'EXPANSION

(54) Title: EXPANSION CONE AND SYSTEM



(57) Abrégé/Abstract:

An apparatus for the radial expansion and plastic deformation of a tubular member.

(72) **Inventeurs(suite)/Inventors(continued)**: WENNING, PATRICK, US; ALTAN, TAYLAN, US; SHADE, MATTHEW M., US;
OLIOSI, CLAUDIO, IT

25791.259

ABSTRACT OF THE DISCLOSURE

[00163]

member.

An apparatus for the radial expansion and plastic deformation of a tubular

D-1520200_1.DOC

EXPANSION CONE AND SYSTEM

BACKGROUND OF THE INVENTION

[0005] The present disclosure relates generally to wellbore casings and/or pipelines, and in particular to wellbore casings and/or pipelines that are formed using expandable tubing.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] Figure 1 is an illustration of a conventional method for drilling a borehole in a subterranean formation.

[0007] Figure 2 is an illustration of a device for coupling an expandable tubular member to an existing tubular member.

[0008] Figure 3 is an illustration of a hardenable fluidic sealing material being pumped down the device of Figure 2.

[0009] Figure 4 is an illustration of the expansion of an expandable tubular member using the expansion device of Figure 2.

- [0010]** Figure 5 is an illustration of the completion of the radial expansion and plastic deformation of an expandable tubular member.
- [0011]** Figure 6 is a side view of an exemplary embodiment of an expansion device of Figure 2.
- [0012]** Figures 7 and 7a are cross sections of the exemplary embodiment of the expansion device of Figure 6.
- [0013]** Figure 8 is a side view of another exemplary embodiment of an expansion device of Figure 2.
- [0014]** Figures 9 and 9a are cross sections of the exemplary embodiment of the expansion device of figure 8.
- [0015]** Figure 10 is a longitudinal cross section of a seamless expandable tubular member.
- [0016]** Figure 11 is a radial cross section of the seamless expandable tubular member of Figure 10.
- [0017]** Figure 12 is an illustration of the expansion of the seamless expandable tubular member of Figure 10 using the expansion device of Figure 6.
- [0018]** Figure 13 and 13a are top views of the expansion of the seamless expandable tubular member as shown in Figure 12.
- [0019]** Figures 14 and 14a are the top views of another embodiment of the expansion of the seamless expandable tubular member of Figure 10 using an expansion device.
- [0020]** Figure 15a is a side view of another embodiment of an expansion device.
- [0021]** Figures 15b and 15c are cross sectional views of the expansion device of Figure 15a.
- [0022]** Figure 16a is a side view of another embodiment of an expansion device.
- [0023]** Figures 16b and 16c are cross sectional views of the expansion device of Figure 16a.
- [0024]** Figures 17a and 17b are illustrations of a computer model of a tapered expansion device and an expandable tubular member.
- [0025]** Figure 17c is an illustration of experimental data for the length of the tapered expansion device surface versus the taper angle of the expansion device for the computer model of Figs. 17a and 17b.

[0026] Figure 17d is an illustration of the true stress-strain curve for the expandable tubular member in the computer model of Figs. 17a and 17b.

[0027] Figure 18 is an illustration of the total axial expansion force versus the friction shear factor for the computer model of Figs. 17a and 17b.

[0028] Figure 19 is an illustration of the influence of the taper angle of an expansion device on the ideal work, frictional work, and redundant work, during the expansion of the expandable tubular member of the computer model of Figs. 17a and 17b.

[0029] Figure 20 is an illustration of the total axial expansion force versus the taper angle of an expansion device, during the expansion of the expandable tubular member of the computer model of Figs. 17a and 17b.

[0030] Figure 21 is an illustration of a free body diagram of various forces acting on the tapered expansion device of the computer model of Figs. 17a and 17b.

[0031] Figure 22 is an illustration of the influence of the taper angle on the radial force acting on the expansion device of the computer model of Figs. 17a and 17b.

[0032] Figure 23 is an illustration of the effective strain in the expandable tubular member versus the taper angle of an expansion device one of the computer model of Figs. 17a and 17b.

[0033] Figures 24a and 24b are illustrations of a computer model of a polynomial curvature expansion device and expandable tubular member.

[0034] Figure 25 is an illustration of experimental data for the location of an inflection point in the expansion surface of the polynomial curvature expansion device of the computer model of Figs. 24a and 24b.

[0035] Figure 26 is an illustration of polynomial curvature expansion device surface shapes with different ratios of L_f/L of the computer model of Figs. 24a and 24b.

[0036] Figure 27 is an illustration of the axial expansion force required for the polynomial curvature expansion device with different L_f/L ratios and a constant length of the polynomial curvature expansion surface (L) and for a shear friction factor of $m=0.05$ of the computer model of Figs. 24a and 24b.

[0037] Figure 28 is a comparison of the axial expansion force for the polynomial curvature expansion device for different L_f/L ratios at various shear friction factors for a given length of the expansion surface of the computer model of Figs. 24a and 24b.

[0038] Figure 29 is a comparison of the axial expansion force for the polynomial curvature expansion device for different lengths of the expansion surface at various shear friction factors for the optimum L/L ratio of 0.6 of the computer model of Figs. 24a and 24b.

[0039] Figure 30 is a comparison of the axial expansion force between the optimum tapered angle expansion device of the computer model of Figs. 17a and 17b and the optimum polynomial curvature expansion device of the computer model of Figs. 24a and 24b for a friction shear factor of $m=0.10$.

[0040] Figure 31 is a comparison of the axial expansion force between the optimum tapered angle expansion device of the computer model of Figs. 17a and 17b and the optimum polynomial curvature expansion device of the computer model of Figs. 24a and 24b for a friction shear factor of $m=0.05$.

[0041] Figure 32 is a comparison of the steady state radial force between the optimum tapered angle expansion device of the computer model of Figs. 17a and 17b and the optimum polynomial curvature expansion device of the computer model of Figs. 24a and 24b for a friction shear factor of $m=0.10$.

[0042] Figure 33 is a comparison of the steady state radial force between the optimum tapered angle expansion device of the computer model of Figs. 17a and 17b and the optimum polynomial curvature expansion device of the computer model of Figs. 24a and 24b for a friction shear factor of $m=0.05$.

[0043] Figure 34 is an illustration of the total axial expansion force versus expansion device displacement for the optimum tapered expansion device of the computer model of Figs. 17a and 17b and a friction shear factor of $m=0.10$.

[0044] Figure 35 is an illustration of the total axial expansion force versus expansion device displacement for the optimum polynomial expansion device of the computer model of Figs. 24a and 24b and a friction shear factor of $m=0.10$.

[0045] Figure 36 is an illustration of the total axial expansion force versus expansion device displacement for the optimum tapered expansion device of the computer model of Figs. 17a and 17b and a friction shear factor of $m=0.05$.

[0046] Figure 37 is an illustration of the total axial expansion force versus expansion device displacement for the optimum polynomial curvature expansion device of the computer model of Figs. 24a and 24b and a friction shear factor of $m=0.05$.

[0047] Figure 38 is a comparison of the maximum effective strain between the optimum tapered angle expansion device of the computer model of Figs. 17a and 17b and the

optimum polynomial curvature expansion device of the computer model of Figs. 24a and 24b for a friction shear factor of $m=0.10$.

[0048] Figure 39 is a comparison of the maximum effective strain between the optimum tapered angle expansion device of the computer model of Figs. 17a and 17b and the optimum polynomial curvature expansion device of the computer model of Figs. 24a and 24b for a friction shear factor of $m=0.05$.

DETAILED DESCRIPTION

[0049] Referring initially to Figure 1, a conventional device 100 for drilling a borehole 102 in a subterranean formation 104 is shown. The borehole 102 may be lined with a casing 106 at the top portion of its length. An annulus 108 formed between the casing 106 and the formation 104 may be filled with a sealing material 110, such as, for example, cement. In an exemplary embodiment, the device 100 may be operated in a conventional manner to extend the length of the borehole 102 beyond the casing 106.

[0050] Referring now to Figure 2, a device 200 for coupling an expandable tubular member 202 to an existing tubular member, such as, for example, the existing casing 106, is shown. The device 200 includes a shoe 206 that defines a centrally positioned valveable passage 206a adapted to receive, for example, a ball, plug or other similar device for closing the passage. An end of the shoe 206b is coupled to a lower tubular end 208a of a tubular launcher assembly 208 that includes the lower tubular end, an upper tubular end 208b, and a tapered tubular transition member 208c. The lower tubular end 208a of the tubular launcher assembly 208 has a greater inside diameter than the inside diameter of the upper tubular end 208b. The tapered tubular transition member 208c connects the lower tubular end 208a and the upper tubular end 208b. The upper tubular end 208b of the tubular launcher assembly 208 is coupled to an end of the expandable tubular member 202. One or more seals 210 are coupled to the outside surface of the other end of the expandable tubular member 202.

[0051] An expansion device 212 is centrally positioned within and mates with the tubular launcher assembly 208. The expansion device 212 defines a centrally positioned fluid pathway 212a, and includes a lower section 212b, a middle section 212c, and an upper section 212d. The lower section 212b of the expansion device 212 includes an inclined expansion surface 212ba that supports the tubular launcher assembly 208 by mating with the tapered tubular transition member 208c of the tubular launcher assembly. The upper section 212d of the expansion device 212 is coupled to an end of a tubular member 218 that defines a fluid pathway 218a. The fluid pathway 218a of the tubular member 218 is fluidically coupled to the fluid pathway 212a defined by the expansion device 212. One or more spaced apart cup seals

220 and 222 are coupled to the outside surface of the tubular member 218 for sealing against the interior surface of the expandable tubular member 202. In an exemplary embodiment, cup seal 222 is positioned near a top end of the expandable tubular member 202. A top fluid valve 224 is coupled to the tubular member 218 above the cup seal 222 and defines a fluid pathway 226 that is fluidically coupled to the fluid pathway 218a.

[0052] During operation of the device 200, as illustrated in Figure 2, the device 200 is initially lowered into the borehole 102. In an exemplary embodiment, during the lowering of the device 200 into the borehole 102, a fluid 228 within the borehole 102 passes upwardly through the device 200 through the valveable passage 206a into the fluid pathway 212a and 218a and out of the device 200 through the fluid pathway 226 defined by the top fluid valve 224.

[0053] Referring now to Figure 3, in an exemplary embodiment, a hardenable fluidic sealing material 300, such as, for example, cement, is then pumped down the fluid pathway 218a and 212a and out through the valveable passage 206a into the borehole 102 with the top fluid valve 224 in a closed position. The hardenable fluidic sealing material 300 thereby fills an annular space 302 between the borehole 102 and the outside diameter of the expandable tubular member 202.

[0054] Referring now to Figure 4, a plug 402 is then injected with a fluidic material 404. The plug thereby fits into and closes the valveable passage 206a to further fluidic flow. Continued injection of the fluidic material 404 then pressurizes a chamber 406 defined by the shoe 206, the bottom of the expansion device 212, and the walls of the launcher assembly 208 and the expandable tubular member 202. Continued pressurization of the chamber 406 then displaces the expansion device 212 in an upward direction 408 relative to the expandable tubular member 202 thereby causing radial expansion and plastic deformation of the launcher assembly 208 and the expandable tubular member.

[0055] Referring now to Figure 5, the radial expansion and plastic deformation of the expandable tubular member 202 is then completed and the expandable tubular member is coupled to the existing casing 106. The hardenable fluidic sealing material 300, such as, for example, cement fills the annulus 302 between the expandable tubular member 202 and the borehole 102. The device 200 has been withdrawn from the borehole and a conventional device 100 for drilling the borehole 102 may then be utilized to drill out the shoe 206 and continue drilling the borehole 102, if desired.

[0056] Referring now to Figures 6, 7 and 7a, an expansion cone 600 includes an upper cone 602, a middle cone 604, and a lower tubular end 606. The upper cone 602 has a

leading surface 608 and an outer inclined surface 610 that defines an angle α_1 . The middle cone 604 has an outer inclined surface 612 that defines an angle α_2 . In an exemplary embodiment, the angle α_1 is greater than the angle α_2 . The outer inclined surfaces 610 and 612 together form the expansion surfaces 614 that upon displacement of the expansion cone 600 relative to the expandable tubular member 202 radially expand and plastically deform the expandable tubular member. In an exemplary embodiment, the expansion cone 600 defines one or more outer inclined expansion faceted surfaces 616. In an exemplary embodiment, one or more contact points 618 are formed at the intersection of the one or more outer inclined expansion faceted surfaces 616.

[0057] Referring now to Figures 8, 9 and 9a, an exemplary embodiment of an expansion cone 800 with an outside expansion surface 802 defining a parabolic equation, is shown. The expansion cone 800 has an upper expansion section 804 and a lower tubular end 806. The upper expansion section 804 has a leading surface 808 and the outside expansion surface 802 is defined by a parabolic equation. In an exemplary embodiment, the expansion cone 800 defines one or more outer inclined expansion faceted surfaces 810. In an exemplary embodiment, one or more contact points 812 are formed at the intersection of the outer inclined expansion faceted surfaces 810.

[0058] In an exemplary embodiment, the expansion device 212 consists of one or more of the expansion devices 600 and 800.

[0059] Referring now to Figures 10 and 11, an exemplary embodiment of a seamless expandable tubular member 1000 is shown. The seamless expandable tubular member 1000 includes a wall thickness t_1 and t_2 where t_1 is not equal to t_2 . In an exemplary embodiment, the seamless expandable tubular member 1000 has a non-uniform wall thickness.

[0060] In an exemplary embodiment, the expandable tubular member 202 consists of one or more of the seamless expandable tubular members 1000.

[0061] Referring now to Figures 12, 13 and 13a, in an exemplary embodiment the expansion cone 600 is displaced by a conventional expansion device, such as, for example, the expansion devices commercially available from Baker Hughes Inc., Enventure Global Technology, or Weatherford International, in an upward direction 1200 relative to the seamless expandable tubular member 1000 thereby causing radial expansion and plastic deformation of the seamless expandable tubular member. In an exemplary embodiment, stress concentrations 1300 are formed within the seamless expandable tubular member 1000 where the contact point 618 of the expansion cone 600 is displaced into the seamless expandable tubular member.

[0062] The use of seamless expandable tubular members, such as, for example the seamless expandable tubular member 100, with a variable wall thickness may require higher expansion forces when the expansion device encounters areas of increased wall thickness. An expansion device may take the path of least resistance when the expansion device encounters an area of increased wall thickness t_1 and over-expand the corresponding area of thin wall thickness t_2 of the seamless expandable tubular member in comparison to the thicker wall section t_1 . The use of a faceted expansion cone, such as, for example, the expansion cone 600 creates areas of stress concentrations in the seamless expandable tubular member, which may assist in maintaining a proportional wall thickness during the radial expansion and plastic deformation process. In addition, the use of a faceted expansion cone, such as, for example, the expansion cone 600 creates areas of stress concentrations in the seamless expandable tubular member, which may result in reduced expansion and initiation forces.

[0063] Referring to Figures 14 and 14a, in an exemplary embodiment, an expansion cone 1400 includes a plurality of outer inclined expansion faceted surfaces 1402, having corresponding widths (V), that intersect to form contact points 1404. Several factors may be considered when determining the appropriate number of outer inclined expansion faceted surfaces 1402, such as, for example, the coefficient of friction between the expansion cone and the expandable tubular member 1000, pipe quality, and data from lubrication tests. In an exemplary embodiment, for an expandable tubular member with uniform thickness, the number of circumferential spaced apart contact points may be infinity. In an exemplary experimental embodiment, the dimensions of the final design of an expansion cone may ultimately be refined by performing an empirical study.

[0064] In an exemplary embodiment, the following equations may be used to make a preliminary calculation of the optimum number of outer inclined expansion faceted surfaces 1402 on an expansion cone 1400 for expanding an expandable tubular member 1000:

$$R = (D_1 + D_{\text{exp}}) / 2; \quad (1)$$

$$\sin(\alpha/2) = 1 - (H/R); \text{ and} \quad (2)$$

$$N = 360^\circ / \alpha; \quad (3)$$

where,

D_1 = Original tubular member inside diameter;

D_{exp} = Expanded tubular member inside diameter;

H = Gap between gap surface and tubular member inside diameter;

R = Radius of polygon at midpoint of expansion cone;

α = Angle between circumferential spaced apart contact points of polygon; and

N= Number of polygon flat surfaces.

In an exemplary embodiment, expandable tubular member 1000 has an original inside diameter of 4.77" that is expanded to an inside diameter of 5.68" utilizing an expansion cone 1400. In an exemplary embodiment, there is a lubricant gap depth of .06". The optimum number of outer inclined expansion faceted surfaces 1402 is determined as follows:

$$R=(D_1+D_{\text{exp}})/2= (4.77-5.68)/2= .42;$$

$$\sin (\alpha/2) = 1-(H/R) = 1-(.06/.42);$$

$$\alpha/2= 12.3^\circ;$$

$$\alpha= 24.6^\circ;$$

$$N = 360^\circ/\alpha= 360^\circ/24.6^\circ= 15;$$

Accordingly, the theoretical number (N) of outer inclined expansion faceted surfaces 1402, on an expansion cone 1400 having a tapered faceted polygonal outer expansion surface is 15, but the actual number that may result from an empirical analysis may depend on tubular member quality, coefficient of friction, and data from lubrication tests. In an exemplary embodiment, a range for the actual number (N) of outer inclined expansion faceted surfaces 1402 necessary to expand an expandable tubular member having an original inside diameter of 4.77" to an inside diameter of 5.68" may range from 12 to 15.

[0065] Referring to Figures 15a, 15b and 15c, in an exemplary embodiment, expansion cone 1500 includes tapered faceted polygonal outer expansion surfaces 1510, a front end 1500a, a rear end 1500b, recesses 1512, internal passage 1530 for drilling fluid, internal passages 1514 for lubricating fluids, and radial passageways 1516. The width 1520 of tapered faceted polygonal outer expansion surfaces 1510 of expansion cone 1500 may be constant for the length of the cone, resulting in trapezoidal shaped lubricant gap 1522 between each contact surface 1510. The following equations may be used for calculating the width (W) 1520 of the contact surface:

$$W = [2R \sin(\alpha/2)] / K; \quad (4)$$

$$R = (D1+D2)/4; \quad (5)$$

$$\alpha = 360 \text{ degrees} / N; \quad (6)$$

where:

W = Width of contact point;

D1 = initial tubular member diameter;

D2 = expanded diameter;

N= Number of polygon flat surfaces; and

K= System friction coefficient that must be determined.

In an exemplary embodiment, K is between 3 to 5 for an expandable tubular member having an original inside diameter of 4.77" and an expanded inside diameter of 5.68". N may range from 12 to 15. In an exemplary embodiment, K is 4.2.

[0066] Referring now to Figures 16a, 16b and 16c, in an exemplary embodiment, expansion cone 1600 has a tapered faceted polygonal outer expansion surface 1610, a front end 1600a, a rear end 1600b, recesses 1612, internal passage 1630 for drilling fluid, internal passages 1614 for lubricating fluids, and radial passageways 1616. The width 1620 of tapered faceted polygonal outer expansion surfaces 1610 of expansion cone 1600 may vary the length of the cone. In an exemplary embodiment, width 1620 of tapered faceted polygonal outer expansion surfaces 1610 may be larger at the front end W1 and become smaller toward the rear end W2.

[0067] In several exemplary embodiments, the tapered faceted polygonal outer expansion surface of an expansion cone may be implemented in any expansion cone, including one or more of expansion cones 600, 800, 1404, 1500, and 1600. Furthermore, it may be implemented in any expansion device including one or more expansion surfaces.

[0068] The optimum taper angle θ of the tapered portion of each expansion cone, including the tapered portions in expansion cones 600, 800, 1400, 1500, and 1600, may be dependant on the amount of friction between the tapered portion of the expansion cone and the inside diameter of the tubular member. In an exemplary experimental embodiment, a cone angle of 8.5° to 12.5° was shown to be sufficient to expand an expandable tubular member having an original inside diameter of 4.77" to an inside diameter of 5.68". The optimum taper angle θ may be determined after testing the lubricant system to determine the exact coefficient of friction. A cone angle greater than 10° may be required to minimize the effect of thinning the tubular member wall during expansion and may potentially reduce failures related to collapsing.

[0069] Referring to Figures 17a and 17b, in an exemplary experimental embodiment 1700, using finite element analysis ("FEA"), the radial expansion and plastic deformation of an expandable tubular member 1702 by a tapered expansion device 1704 displaced in direction 1706 relative to the expandable tubular member, was modeled using commercially available FEA software DEFORM-2D in order to predict the actual performance of a corresponding actual tapered expansion device during the radial expansion and plastic deformation of an actual expandable tubular member. The FEA optimized the taper angle θ of the tapered expansion device 1704 for minimum expansion forces. The tapered expansion device surface 1708 of the tapered expansion device 1704 has a length L. The tapered expansion device 1704 has an

initial diameter D_0 and a final diameter D_1 . Since the initial diameter D_0 and the final diameter D_1 are fixed in the tapered expansion device 1704, any increase in the taper angle θ would result in an increase in the length L of the expansion surface 1708.

[0070] Referring to Figure 17c, in the exemplary experimental embodiment 1700 using FEA, the length L of the expansion surface 1708 versus the taper angle θ is shown. The length L of the expansion surface 1708 increases as the taper angle θ decreases.

[0071] Referring to Figure 17d, in the exemplary experimental embodiment 1700 using FEA, a true stress-strain curve 1710 for the expandable tubular member 1702 with a modulus of elasticity of $E=30 \times 10^6$ psi and a Poisson's ratio of 0.3, is provided. In the FEA, the expansion device 1704 was modeled as rigid body while the expandable tubular member 1702 was modeled as an elastic-plastic object.

[0072] In an exemplary embodiment, friction conditions at the interface 1712 between the expansion device 1704 and the expandable tubular member 1702 influence metal flow and stresses acting on the expansion device. Interface friction conditions may be expressed quantitatively in terms of a factor or coefficient. The friction shear stress, f_s , may be expressed using Coulomb or shear friction. If Coulomb friction is assumed, the friction shear stress takes the following form

$$f_s = \mu p \quad (7)$$

p being a compressive normal stress at the interface and μ being the coefficient of friction. However, if shear friction is assumed, the friction shear stress takes the form of

$$f_s = mk = \frac{m}{\sqrt{3}} \bar{\sigma} \quad (8)$$

k being the instantaneous shear strength of the material and m being the friction shear factor, $0 \leq m \leq 1$. The instantaneous shear strength can be expressed as a function of instantaneous yield strength, $\bar{\sigma}$, assuming the material obeys a von Mises yield criterion.

[0073] When contact pressures at the interface 1712 become large, the shear stress predicted by Coulomb friction can exceed the shear strength of the material. Therefore, shear friction should be used to model the interface friction conditions for operations that produce high contact stresses. Since there is potential for large contact stress in the radial expansion and plastic deformation of the expandable tubular member 1702 by the expansion device 1704, the shear friction model was used in all experimental embodiments.

[0074] Referring to Figure 18, in the exemplary experimental embodiment 1700 using FEA, a total axial expansion force curve 1800 shows axial expansion force as a function of the friction shear factor (m) for a given tapered expansion device surface 1708 angle of 10° . The total axial expansion force curve 1800 increases with increasing friction shear factor (m). In an exemplary embodiment, in cold forming of steels with lubrication, the friction shear factor (m) falls in the range $0.05 \leq m \leq 0.15$.

[0075] In an exemplary embodiment, the actual work w_a required to cause radial expansion and plastic deformation of the expandable tubular member 1702 is comprised of three components, a) ideal work w_i , b) frictional work w_f and c) redundant work w_r . The actual work w_a required to cause deformation is the sum of the three components, $w_a = w_i + w_f + w_r$. Ideal work w_i is the work required for homogeneous deformation, which exists only when plane sections remain plane during the deformation. Frictional work w_f is consumed at the interface between the deforming metal and the tool faces that constrain the metal. Redundant work w_r is due to internal shearing and bending that causes distortion of plane sections as they pass through the deformation zone, which increases the strain in the deforming metal.

[0076] Referring to Figure 19, in the exemplary experimental embodiment 1700 using FEA, the influence of the taper angle θ of the tapered expansion device surface 1708 on the actual work w_a , ideal work w_i , frictional work w_f , and redundant work w_r is shown. The actual work w_a is the sum of the frictional work w_f , the redundant work w_r , and the ideal work w_i . The ideal work w_i remains constant and does not depend on the taper angle θ of the tapered expansion device surface 1708. However, the frictional work w_f and redundant work w_r largely depend on the taper angle θ of the tapered expansion device surface 1708. The frictional work w_f increases with decreasing taper angle θ of the tapered expansion device surface 1708, while the redundant work w_r increases with increasing taper angle θ of the tapered expansion device surface. The actual work w_a is minimized, thereby minimizing the required total axial expansion force, at the low point $\theta-1$ on the actual work w_a curve. The low point $\theta-1$ on the actual work w_a curve thereby determines the optimum taper angle θ of the tapered expansion device surface 1708.

[0077] Referring to Figure 20, in the exemplary experimental embodiment 1700 using FEA, total axial expansion force curves 2002, 2004, and 2006 are shown as a function of taper angle θ for three different friction shear factors (m), is shown. Axial expansion force curve 2002 has a friction shear factor of $m=0.10$ and a minimum axial expansion force at a taper angle of 8° . Axial expansion force curve 2004 has a friction shear factor of $m=0.05$ and a minimum axial

expansion force at a taper angle of 7°. Axial expansion force curve 2006 has a friction shear factor of $m=0.0$ and a minimum axial expansion force at a taper angle of 5°.

[0078] Referring to Figure 21, in the exemplary experimental embodiment 1700 using FEA, a free-body diagram 2100 illustrates the forces acting on the tapered expansion device 1704 including the force required to deform the expandable tubular member 1702 F_N , the axial force component F_z , the radial force component F_r , and the friction force F_f . The following equations explain the forces acting on the tapered expansion device 1704:

$$F_r = F_N \cos(\theta) - F_f \sin(\theta) \text{ and} \quad (9)$$

$$F_z = F_N \sin(\theta) + F_f \cos(\theta); \quad (10)$$

where

F_N = Normal force during deformation

F_f = Frictional Force

F_r = Radial force acting on the tapered expansion device 1704

F_z = Axial force acting on the tapered expansion device 1704

The axial force component F_z increases with increase in the taper angle θ of the tapered expansion device surface 1708, while the contribution from friction force F_f to the axial force component decreases with increase in the taper angle θ of the tapered expansion device surface 1708. This is because, with increase in taper angle θ , the $\cos(\theta)$ term decreases while the $\sin(\theta)$ term increase. In an exemplary embodiment, however, the initial increase in the axial force for small taper angles in the presence of friction is due to the contribution from the friction force because for smaller angles the $\cos(\theta)$ is approximately one, while the $\sin(\theta)$ term is negligible.

[0079] Referring to Figure 22, in the exemplary experimental embodiment 1700 using FEA, radial reaction force curve 2202 shows the radial reaction force F_r on the expansion device 1704 as a function of taper angle θ and friction shear factor (m). In an exemplary embodiment, the radial reaction force F_r decreases with increase in the taper angle θ , and the radial reaction force F_r was independent of the friction shear factor (m). The radial reaction force curve 2202 was approximately linear for taper angles of 15 degrees or greater, and non-linear for taper angles less than 15 degrees.

[0080] Referring to Figure 23, in the exemplary experimental embodiment 1700 using FEA, effective strain curve 2302 in the expandable tubular member 1702 as a function of taper angle θ for three different friction shear factors (m), is shown. In an exemplary embodiment, the maximum effective strain in the expandable tubular member 1702 increased with increasing taper angle θ , and was independent of friction shear factor (m). In an exemplary embodiment,

the increase in the maximum effective strain with increasing taper angle θ is due to increased redundant deformation w_r in the expandable tubular member 1702 for large taper angles. In an exemplary embodiment, taper angles of approximately 15 degrees or greater were more effective at straining the expandable tubular member 1702.

[0081] Referring to Figures 24a and 24b, in an exemplary experimental embodiment 2400 using finite element analysis ("FEA"), the radial expansion and plastic deformation of an expandable tubular member 1702 by a polynomial curvature expansion device 2402 displaced in direction 1706 relative to the expandable tubular member, was modeled using commercially available FEA software DEFORM-2D in order to predict the actual performance of a corresponding actual polynomial curvature expansion device during the radial expansion and plastic deformation of an actual expandable tubular member. In an exemplary embodiment, the FEA optimized the shape and length L of the polynomial curvature expansion device 2402 for minimum expansion forces. Polynomial curvature expansion device surface 2404 has a length L . In an exemplary embodiment, the polynomial curvature expansion device 2402 has an initial diameter D_0 at one end and a final diameter D_1 at another end.

[0082] Referring to Figure 25, in the exemplary experimental embodiment 2400 using FEA, the shape of a polynomial curvature expansion device surface 2502 is illustrated. The polynomial curvature expansion surface 2502 has a length L and an inflection point L_f . In an exemplary embodiment, the ratio of L_f/L determines the shape of the polynomial curvature expansion surface 2502.

[0083] In the exemplary experimental embodiment 2400 using FEA, the polynomial curvature is expressed as:

$$r(z) = a_0 + a_1z + a_2z^2 + a_3z^3 + a_4z^4 \quad (11)$$

$$a_0 = R_1 \quad (12)$$

$$a_1 = 0 \quad (13)$$

$$a_2 = \text{input} \quad (14)$$

$$a_3 = \frac{2}{L} \left[a_2 + \frac{2(R_1 - R_0)}{L^2} \right] \quad (15)$$

$$a_4 = \frac{1}{L^2} \left[a_2 + \frac{3(R_1 - R_0)}{L^2} \right] \quad (16)$$

where

$r(z)$ = radial distance from the centerline of the expansion cone; and

z = longitudinal distance along the polynomial curvature expansion surface

In an exemplary embodiment, the optimum polynomial curvature expansion surface for minimum axial expansion forces for a friction shear factor $m=0.10$ was $r(z) = 2.020 - 0.150z^2 - 0.043z^3 + 0.055z^4$. In an exemplary embodiment, the optimum polynomial curvature expansion surface for minimum axial expansion forces for a friction shear factor $m=0.05$ was $r(z) = 2.020 - 0.095z^2 - 0.023z^3 + 0.023z^4$.

[0084] Referring to Figure 26, in the exemplary experimental embodiment 2400 using FEA, five different polynomial curvature expansion device surfaces 2602, 2604, 2606, 2608, and 2610, are shown. Polynomial curvature expansion device surface 2602 has a $L_f/L = 0.67$. Polynomial curvature expansion device surface 2604 has a $L_f/L = 0.60$. Polynomial curvature expansion device surface 2606 has a $L_f/L = 0.50$. Polynomial curvature expansion device surface 2608 has a $L_f/L = 0.40$. Polynomial curvature expansion device surface 2610 has a $L_f/L = 0.32$.

[0085] Referring to Figure 27, in the exemplary experimental embodiment 2400 using FEA, axial expansion force curves 2702, 2704, 2706, and 2708 are shown for increasing ratios of L_f/L for four different polynomial curvature expansion device surface lengths at a constant friction shear factor of $m=0.05$. In an exemplary embodiment, the axial expansion force curve 2702 has a polynomial curvature expansion device surface length of 0.75 inches and the minimum axial expansion force was found at a L_f/L ratio of 0.6. In an exemplary embodiment, the axial expansion force curve 2704 has a polynomial curvature expansion device surface length of 1.1626 inches and the minimum axial expansion force was found at a L_f/L ratio of 0.6. In an exemplary embodiment, the axial expansion force curve 2706 has a polynomial curvature expansion device surface length of 2.0 inches and the minimum axial expansion force was found at a L_f/L ratio of 0.6. In an exemplary embodiment, the axial expansion force curve 2708 has a polynomial curvature expansion device surface length of 2.25 inches and the minimum axial expansion force was found at a L_f/L ratio of 0.6. In an exemplary embodiment, the minimum axial expansion force for the four axial expansion force curves 2702, 2704, 2706, and 2708, was found to be at the L_f/L ratio of about 0.6, thus, the ratio L_f/L at which the minimum axial expansion force occurs was found to be independent of the length of the polynomial curvature expansion surface for a given shear friction factor (m).

[0086] Referring to Figure 28, in the exemplary experimental embodiment 2400 using FEA, axial expansion force curves 2802, 2804, and 2806 are shown for increasing L_f/L ratios at three different friction shear factors (m) and a constant polynomial curvature expansion surface length of 1.1626 inches. Axial expansion force curve 2802 has a friction shear factor of $m=0.1$ and a minimum axial expansion force at a L_f/L ratio of 0.6. Axial expansion force curve 2804

has a friction shear factor of $m=0.05$ and a minimum axial expansion force at a L_f/L ratio of 0.6. Axial expansion force curve 2806 has a friction shear factor of $m=0.0$ and a minimum axial expansion force at a L_f/L ratio of 0.6. For the three axial expansion force curves 2802, 2804, and 2806, the minimum axial expansion force was found to be at the L_f/L ratio of 0.6, thus, the ratio L_f/L at which the minimum axial expansion force occurs was found to be independent of the shear friction factor (m) for a given length of the polynomial curvature expansion surface.

[0087] Referring to Figure 29, in the exemplary experimental embodiment 2400 using FEA, axial expansion force curves 2902, 2904, and 2906 are shown for increasing lengths of the polynomial curvature expansion device surface 2404 with the optimum L_f/L ratio of 0.6 for three different shear friction factors (m). Axial expansion force curve 2902 has a friction shear factor of $m=0.1$, the optimum length of the polynomial curvature expansion device surface 2404 was found to be 1.625 inches for a expansion cone that is to achieve a 0.25" increase in diameter. Axial expansion force curve 2904 has a friction shear factor of $m=0.05$, the optimum length of the polynomial curvature expansion device surface 2404 was found to be 1.875 inches for a expansion cone that is to achieve a 0.25" increase in diameter. Axial expansion force curve 2906 has a friction shear factor of $m=0.0$, the optimum length of the polynomial curvature expansion device surface 2404 was found to be 2.5 inches for a expansion cone that is to achieve a 0.25" increase in diameter.

[0088] Referring to Figure 30, in the exemplary experimental embodiments 1700 and 2400 using FEA, axial expansion force 3002 corresponding to an optimum taper angle of 8 degrees for the tapered expansion device surface 1708 is compared to the axial expansion force 3004 corresponding to an optimum polynomial curvature expansion device surface 2404 with an optimum L_f/L ratio of 0.6 and a length of 1.625 inches, for a friction shear factor of $m=0.10$. The optimum tapered expansion device surface 1708 and the optimum polynomial curvature expansion device surface 2404 required approximately the same axial expansion force, for a friction shear factor of $m=0.10$.

[0089] Referring to Figure 31, in the exemplary experimental embodiments 1700 and 2400 using FEA, axial expansion force 3102 corresponding to an optimum taper angle of 7 degrees for the tapered expansion device surface 1708 is compared to the axial expansion force 3104 corresponding to an optimum polynomial curvature expansion device surface 2404 with an optimum L_f/L ratio of 0.6 and a length of 1.875 inches, for a friction shear factor of $m=0.05$. The optimum tapered expansion surface 1708 and the optimum polynomial curvature expansion surface 2404 required approximately the same axial expansion force, for a friction shear factor of $m=0.05$.

[0090] Referring to Figure 32, in the exemplary experimental embodiments 1700 and 2400 using FEA, radial expansion force 3202 required for the optimum taper angle of 8 degrees for the tapered expansion surface 1708 is compared to the axial expansion force 3204 required for the optimum polynomial curvature expansion surface 2404 with the optimum L_r/L ratio of 0.6 and a length of 1.625 inches, for a friction shear factor of $m=0.10$. The radial reaction force produced by the polynomial curvature expansion surface 2404 was 16.4% lower than that of the tapered expansion surface 1708, for a friction shear factor of $m=0.10$.

[0091] Referring to Figure 33, in the exemplary experimental embodiments 1700 and 2400 using FEA, radial expansion force 3302 required for the optimum taper angle of 7 degrees for the tapered expansion surface 1708 is compared to the axial expansion force 3304 required for the optimum polynomial curvature expansion surface 2404 with the optimum L_r/L ratio of 0.6 and a length of 1.875 inches, for a friction shear factor of $m=0.05$. The radial reaction force produced by the polynomial curvature expansion surface 2404 was 5% lower than that of the tapered expansion surface 1708, for a friction shear factor of $m=0.05$.

[0092] Referring to Figure 34, in an exemplary experimental embodiment 1700 using FEA, total axial expansion force curve 3402 shows the total axial expansion force versus the displacement of the tapered expansion device 1704 with an optimum taper angle of 8 degrees for a friction shear factor of $m=0.10$. The total axial expansion force curve 3402 has transient force spike 3404 at the beginning of the displacement of the tapered expansion device 1704 and transient force spike 3406 at the end of the displacement of the tapered expansion device.

[0093] Referring to Figure 35, in an exemplary experimental embodiment 2400 using FEA, total axial expansion force curve 3502 shows the total axial expansion force versus the displacement of the polynomial curvature expansion device 2402 with the optimum polynomial curvature expansion surface 2404 with the optimum L_r/L ratio of 0.6 and a length of 1.625 inches for a friction shear factor of $m=0.10$. There are no transient force spikes at the beginning or at the end of the displacement of the polynomial curvature expansion device 2402 for a friction shear factor of $m=0.10$. The lack of transient force spikes may result in longer equipment life in comparison to the corresponding tapered expansion device 1704.

[0094] Referring to Figure 36, in an exemplary experimental embodiment 1700 using FEA, total axial expansion force curve 3602 shows the total axial expansion force versus the displacement of the tapered expansion device 1704 with an optimum taper angle of 7 degrees for a friction shear factor of $m=0.05$. The total axial expansion force curve 3602 has transient

force spike 3604 at the beginning of the displacement of the tapered expansion device 1704 and transient force spike 3606 at the end of the displacement of the tapered expansion device.

[0095] Referring to Figure 37, in an exemplary experimental embodiment 2400 using FEA, total axial expansion force curve 3702 shows the total axial expansion force versus the displacement of the polynomial curvature expansion device 2402 with the optimum polynomial curvature expansion surface 2404 with the optimum L_r/L ratio of 0.6 and a length of 1.875 inches for a friction shear factor of $m=0.05$. There are no transient force spikes at the beginning or at the end of the displacement of the expansion device 2402 for a friction shear factor of $m=0.05$. The lack of transient force spikes may result in longer equipment life in comparison to the corresponding tapered expansion device 1704.

[0096] Referring to Figure 38, in an exemplary experimental embodiment using FEA, the maximum effective strain 3802 corresponding to an optimum taper angle of 7 degrees for the tapered expansion surface 1708 is compared to the maximum effective strain 3804 corresponding to an optimum polynomial curvature expansion surface 2404 with an optimum L_r/L ratio of 0.6 and a length of 1.625 inches, for a friction shear factor of $m=0.10$. The maximum effective strain 3802 produced by the optimum tapered expansion surface 1708 was approximately the same as the maximum effective strain 3804 produced by the optimum polynomial curvature expansion surface 2404, for a friction shear factor of $m=0.10$.

[0097] Referring to Figure 39, in an exemplary experimental embodiment using FEA, the maximum effective strain 3902 corresponding to an optimum taper angle of 7 degrees for the tapered expansion surface 1708 is compared to the maximum effective strain 3904 corresponding to an optimum polynomial curvature expansion surface 2404 with an optimum L_r/L ratio of 0.6 and a length of 1.875 inches, for a friction shear factor of $m=0.05$. The maximum effective strain 3902 produced by the optimum tapered expansion surface 1708 was approximately the same as the maximum effective strain 3904 produced by the optimum polynomial curvature expansion surface 2404, for a friction shear factor of $m=0.05$.

[0098] An expansion device for radially expanding a tubular member has been described that includes a first tapered outer surface.

[0099] An expansion device for radially expanding a tubular member has been described that includes: a first tapered outer surface defined by a polynomial equation.

[00100] An expansion device for radially expanding a tubular member has been described that includes: a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L_r/L ratio ranging from about 0.32 to 0.67.

[00101] An expansion device for radially expanding a tubular member has been described that includes: a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L_r/L ratio ranging from about 0.32 to 0.67; wherein the length of the first tapered outer surface ranges from 0.5 inches to 2.5 inches.

[00102] An expansion device for radially expanding a tubular member has been described that includes: a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L_r/L ratio ranging from about 0.32 to 0.67; wherein the length of the first tapered outer surface ranges from 1.6 inches to 1.9 inches.

[00103] An expansion device for radially expanding a tubular member has been described that includes: a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L_r/L ratio ranging from about 0.32 to 0.67; and wherein the first tapered outer surface comprises one or more facets in cross section.

[00104] An expansion device for radially expanding a tubular member has been described that includes: a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L_r/L ratio ranging from about 0.32 to 0.67; wherein the first tapered outer surface comprises one or more facets in cross section; wherein the number of facets ranges from about 12 to 16.

[00105] An expansion device for radially expanding a tubular member has been described that includes: a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L_r/L ratio ranging from about 0.32 to 0.67; wherein the first tapered outer surface comprises one or more facets in cross section; wherein the number of facets ranges from about 12 to 16; wherein the faceted surfaces are wider near the front of the expansion device and become narrower toward the rear end of the expansion device.

[00106] An expansion device for radially expanding a tubular member has been described that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees.

[00107] An expansion device for radially expanding a tubular member has been described that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; and wherein the first angle of attack is greater than the second angle of attack.

[00108] An expansion device for radially expanding a tubular member has been described that includes a first tapered outer surface; wherein the first tapered outer surface

comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; wherein the first angle of attack is greater than the second angle of attack; wherein the first angle of attack ranges from about 6 to 20 degrees; and wherein the second angle of attack ranges from about 4 to 15 degrees.

[00109] An expansion device for radially expanding a tubular member has been described that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; wherein the first angle of attack is greater than the second angle of attack; and one or more intermediate tapered outer surfaces coupled between the first and second tapered outer surfaces.

[00110] An expansion device for radially expanding a tubular member has been described that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; wherein the first angle of attack is greater than the second angle of attack; and one or more intermediate tapered outer surfaces coupled between the first and second tapered outer surfaces; wherein the angle of attack of the intermediate tapered outer surfaces continually decreases from the first tapered outer surface to the second tapered outer surface.

[00111] An expansion device for radially expanding a tubular member has been described that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; wherein the first angle of attack is greater than the second angle of attack; and one or more intermediate tapered outer surfaces coupled between the first and second tapered outer surfaces; wherein the angle of attack of the intermediate tapered outer surfaces decreases in steps from the first tapered outer surface to the second tapered outer surface.

[00112] An expansion device for radially expanding a tubular member has been described that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; wherein the first tapered outer surface comprises one or more facets in cross section.

[00113] An expansion device for radially expanding a tubular member has been described that includes a first tapered outer surface; wherein the first tapered outer surface

comprises an angle of attack ranging from about 6 to 10 degrees; wherein the first tapered outer surface comprises one or more facets in cross section; wherein the number of facets ranges from about 12 to 16.

[00114] An expansion device for radially expanding a tubular member has been described that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; wherein the first tapered outer surface comprises one or more facets in cross section; wherein the faceted surfaces are wider near the front of the expansion device and become narrower toward the rear end of the expansion device.

[00115] An expansion device for radially expanding a tubular member has been described that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; and wherein the first angle of attack is greater than the second angle of attack; wherein the first tapered outer surface and the second tapered outer surface comprise one or more facets in cross section.

[00116] An expansion device for radially expanding a tubular member has been described that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; and wherein the first angle of attack is greater than the second angle of attack; wherein the first tapered outer surface and the second tapered outer surface comprise one or more facets in cross section; wherein the number of facets ranges from about 12 to 16.

[00117] An expansion device for radially expanding a tubular member has been described that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; and wherein the first angle of attack is greater than the second angle of attack; wherein the first tapered outer surface and the second tapered outer surface comprise one or more facets in cross section; wherein the faceted surfaces are wider near the front of the expansion device and become narrower toward the rear end of the expansion device.

[00118] An expansion device for radially expanding a tubular member has been described that includes: a first tapered outer surface defined by a polynomial equation; wherein

the polynomial equation has a L_f/L ratio ranging from about 0.32 to 0.67; wherein the length of the tapered outer surface ranges from about 1.6 inches to 1.9 inches; wherein the tapered outer surface comprises one or more facets in cross section; wherein the number of facets ranges from about 12 to 16; wherein the faceted surfaces are wider near the front of the expansion device and become narrower toward the rear end of the expansion device.

[00119] An expansion system for radially expanding a tubular member has been described that includes a first tapered outer surface; and means for displacing the expansion device relative to the expandable tubular member.

[00120] An expansion system for radially expanding a tubular member has been described that includes: an expansion device that includes a first tapered outer surface defined by a polynomial equation; and means for displacing the expansion device relative to the expandable tubular member.

[00121] An expansion system for radially expanding a tubular member has been described that includes: an expansion device that includes a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L_f/L ratio ranging from about 0.32 to 0.67; and means for displacing the expansion device relative to the expandable tubular member; and means for displacing the expansion device relative to the expandable tubular member.

[00122] An expansion system for radially expanding a tubular member has been described that includes: an expansion device that includes a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L_f/L ratio ranging from about 0.32 to 0.67; wherein the length of the first tapered outer surface ranges from 0.5 inches to 2.5 inches; and means for displacing the expansion device relative to the expandable tubular member.

[00123] An expansion system for radially expanding a tubular member has been described that includes: an expansion device that includes a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L_f/L ratio ranging from about 0.32 to 0.67; wherein the length of the first tapered outer surface ranges from 1.6 inches to 1.9 inches; and means for displacing the expansion device relative to the expandable tubular member.

[00124] An expansion system for radially expanding a tubular member has been described that includes: an expansion device that includes a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L_f/L ratio ranging from about

0.32 to 0.67; and wherein the first tapered outer surface comprises one or more facets in cross section; and means for displacing the expansion device relative to the expandable tubular member.

[00125] An expansion system for radially expanding a tubular member has been described that includes: an expansion device that includes a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L/L ratio ranging from about 0.32 to 0.67; wherein the first tapered outer surface comprises one or more facets in cross section; wherein the number of facets ranges from about 12 to 16; and means for displacing the expansion device relative to the expandable tubular member.

[00126] An expansion system for radially expanding a tubular member has been described that includes: an expansion device that includes a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L/L ratio ranging from about 0.32 to 0.67; wherein the first tapered outer surface comprises one or more facets in cross section; wherein the number of facets ranges from about 12 to 16; wherein the faceted surfaces are wider near the front of the expansion device and become narrower toward the rear end of the expansion device; and means for displacing the expansion device relative to the expandable tubular member.

[00127] An expansion system for radially expanding a tubular member has been described that includes an expansion device that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; and means for displacing the expansion device relative to the expandable tubular member.

[00128] An expansion system for radially expanding a tubular member has been described that includes: an expansion device that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; and wherein the first angle of attack is greater than the second angle of attack; and means for displacing the expansion device relative to the expandable tubular member.

[00129] An expansion system for radially expanding a tubular member has been described that includes an expansion device that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; wherein the first angle of attack is greater than the second angle of attack; wherein the first angle of attack ranges from about 6 to 20 degrees; and wherein the second

angle of attack ranges from about 4 to 15 degrees; and means for displacing the expansion device relative to the expandable tubular member.

[00130] An expansion system for radially expanding a tubular member has been described that includes an expansion device that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; wherein the first angle of attack is greater than the second angle of attack; and one or more intermediate tapered outer surfaces coupled between the first and second tapered outer surfaces; and means for displacing the expansion device relative to the expandable tubular member.

[00131] An expansion system for radially expanding a tubular member has been described that includes an expansion device that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; wherein the first angle of attack is greater than the second angle of attack; and one or more intermediate tapered outer surfaces coupled between the first and second tapered outer surfaces; wherein the angle of attack of the intermediate tapered outer surfaces continually decreases from the first tapered outer surface to the second tapered outer surface; and means for displacing the expansion device relative to the expandable tubular member.

[00132] An expansion system for radially expanding a tubular member has been described that includes an expansion device that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; wherein the first angle of attack is greater than the second angle of attack; and one or more intermediate tapered outer surfaces coupled between the first and second tapered outer surfaces; wherein the angle of attack of the intermediate tapered outer surfaces decreases in steps from the first tapered outer surface to the second tapered outer surface; and means for displacing the expansion device relative to the expandable tubular member.

[00133] An expansion system for radially expanding a tubular member has been described that includes an expansion device that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; wherein the first tapered outer surface comprises one or more facets in cross section; and means for displacing the expansion device relative to the expandable tubular member.

[00134] An expansion system for radially expanding a tubular member has been described that includes an expansion device that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; wherein the first tapered outer surface comprises one or more facets in cross section; wherein the number of facets ranges from about 12 to 16; and means for displacing the expansion device relative to the expandable tubular member.

[00135] An expansion system for radially expanding a tubular member has been described that includes an expansion device that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; wherein the first tapered outer surface comprises one or more facets in cross section; wherein the faceted surfaces are wider near the front of the expansion device and become narrower toward the rear end of the expansion device; and means for displacing the expansion device relative to the expandable tubular member.

[00136] An expansion system for radially expanding a tubular member has been described that includes an expansion device that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; and wherein the first angle of attack is greater than the second angle of attack; wherein the first tapered outer surface and the second tapered outer surface comprise one or more facets in cross section; and means for displacing the expansion device relative to the expandable tubular member.

[00137] An expansion system for radially expanding a tubular member has been described that includes an expansion device that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; and wherein the first angle of attack is greater than the second angle of attack; wherein the first tapered outer surface and the second tapered outer surface comprise one or more facets in cross section; wherein the number of facets ranges from about 12 to 16; and means for displacing the expansion device relative to the expandable tubular member.

[00138] An expansion system for radially expanding a tubular member has been described that includes an expansion device that includes a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered

outer surface; and wherein the first angle of attack is greater than the second angle of attack; wherein the first tapered outer surface and the second tapered outer surface comprise one or more facets in cross section; wherein the faceted surfaces are wider near the front of the expansion device and become narrower toward the rear end of the expansion device; and means for displacing the expansion device relative to the expandable tubular member.

[00139] An expansion system for radially expanding a tubular member has been described that includes: an expansion device that includes a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L/L ratio ranging from about 0.32 to 0.67; wherein the length of the tapered outer surface ranges from about 1.6 inches to 1.9 inches; wherein the tapered outer surface comprises one or more facets in cross section; wherein the number of facets ranges from about 12 to 16; wherein the faceted surfaces are wider near the front of the expansion device and become narrower toward the rear end of the expansion device; and means for displacing the expansion device relative to the expandable tubular member.

[00140] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface.

[00141] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface defined by a polynomial equation.

[00142] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L/L ratio ranging from about 0.32 to 0.67.

[00143] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L/L ratio ranging from about 0.32 to 0.67; wherein the length of the first tapered outer surface ranges from 0.5 inches to 2.5 inches.

[00144] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L_f/L ratio ranging from about 0.32 to 0.67; wherein the length of the first tapered outer surface ranges from 1.6 inches to 1.9 inches.

[00145] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L_f/L ratio ranging from about 0.32 to 0.67; and wherein the first tapered outer surface comprises one or more facets in cross section.

[00146] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L_f/L ratio ranging from about 0.32 to 0.67; wherein the first tapered outer surface comprises one or more facets in cross section; wherein the number of facets ranges from about 12 to 16.

[00147] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L_f/L ratio ranging from about 0.32 to 0.67; wherein the first tapered outer surface comprises one or more facets in cross section; wherein the number of facets ranges from about 12 to 16; wherein the faceted surfaces are wider near the front of the expansion device and become narrower toward the rear end of the expansion device.

[00148] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees.

[00149] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; and wherein the first angle of attack is greater than the second angle of attack.

[00150] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; wherein the first angle of attack is greater than the second angle of attack; wherein the first angle of attack ranges from about 6 to 20 degrees; and wherein the second angle of attack ranges from about 4 to 15 degrees.

[00151] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; wherein the first angle of attack is greater than the second angle of attack; and one or more intermediate tapered outer surfaces coupled between the first and second tapered outer surfaces.

[00152] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; wherein the first angle of attack is greater than the second angle of attack; and one or more intermediate tapered outer surfaces coupled between the first and second tapered outer surfaces; wherein the angle of attack of the intermediate tapered outer surfaces continually decreases from the first tapered outer surface to the second tapered outer surface.

[00153] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; wherein the first angle of attack is greater than the second angle of attack; and one or more intermediate tapered outer surfaces coupled between the first and second tapered outer surfaces; wherein the angle of attack of the intermediate tapered outer surfaces decreases in steps from the first tapered outer surface to the second tapered outer surface.

[00154] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; wherein the first tapered outer surface comprises one or more facets in cross section.

[00155] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; wherein the first tapered outer surface comprises one or more facets in cross section; wherein the number of facets ranges from about 12 to 16.

[00156] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; wherein the first tapered outer surface comprises one or more facets in cross section; wherein the faceted surfaces are wider near the front of the expansion device and become narrower toward the rear end of the expansion device.

[00157] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a

portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; and wherein the first angle of attack is greater than the second angle of attack; wherein the first tapered outer surface and the second tapered outer surface comprise one or more facets in cross section.

[00158] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; and wherein the first angle of attack is greater than the second angle of attack; wherein the first tapered outer surface and the second tapered outer surface comprise one or more facets in cross section; wherein the number of facets ranges from about 12 to 16.

[00159] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface; wherein the first tapered outer surface comprises an angle of attack ranging from about 6 to 10 degrees; a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; and wherein the first angle of attack is greater than the second angle of attack; wherein the first tapered outer surface and the second tapered outer surface comprise one or more facets in cross section; wherein the faceted surfaces are wider near the front of the expansion device and become narrower toward the rear end of the expansion device.

[00160] A method of radially expanding a tubular member has been described that includes radially expanding at least a portion of the tubular member by extruding at least a portion of the tubular member off of an expansion device; wherein the expansion device comprises a first tapered outer surface defined by a polynomial equation; wherein the polynomial equation has a L_r/L ratio ranging from about 0.32 to 0.67; wherein the length of the tapered outer surface ranges from about 1.6 inches to 1.9 inches; wherein the tapered outer surface comprises one or more facets in cross section; wherein the number of facets ranges from about 12 to 16; wherein the faceted surfaces are wider near the front of the expansion device and become narrower toward the rear end of the expansion device.

[00161] The teaching of the present disclosure may be applied to the construction and/or repair of wellbore casings, pipelines, and/or structural supports.

[00162] Although illustrative embodiments of the invention have been shown and described, a wide range of modification, changes and substitution is contemplated in the foregoing disclosure. In some instances, some features of the present invention may be employed without a corresponding use of the other features, and some steps of the present invention may be executed without a corresponding execution of other steps. Accordingly, all such modifications, changes and substitutions are intended to be included within the scope of this invention as defined in the following claims, and it is appropriate that the claims be construed broadly and in a manner consistent with the scope of the invention. In the claims, means-plus-function clauses are intended to cover the structures described herein as performing the recited function and not only structural equivalents, but also equivalent structures.

CLAIMS

1. An expansion device for radially expanding and plastically deforming a tubular member, the expansion device comprising:
 - a front end having a first diameter;
 - a rear end having a second diameter, wherein the second diameter is greater than the first diameter; and
 - a first tapered outer surface comprising a curvature defined by a polynomial equation and having a point of inflection.
2. The expansion device of claim 1, wherein the first tapered surface comprises the curvature defined by the polynomial equation; and
 - wherein the polynomial equation has an L_f/L ratio ranging from 0.32 to 0.67, wherein L is the length of the first tapered outer surface measured relative to a longitudinal axis through the expansion device and L_f is the distance between the rear end and the inflection point measured relative to the longitudinal axis.
3. The expansion device of claim 1, wherein the first tapered surface comprises the curvature defined by the polynomial equation; and
 - wherein the length of the first tapered outer surface ranges from 0.5 inches to 2.5 inches.
4. The expansion device of claim 3, wherein the length of the first tapered outer surface ranges from 1.6 inches to 1.9 inches.
5. The expansion device of claim 1, wherein the first tapered outer surface comprises one or more facets in cross section.
6. The expansion device of claim 5, wherein the number of facets ranges from 12 to 16.

7. The expansion device of claim 5, wherein the faceted surfaces are wider near the front end of the expansion device and become narrower toward the rear end of the expansion device.
8. The expansion device of claim 1, wherein the first tapered outer surface further comprises a first angle of attack ranging from 6 degrees to 20 degrees.
9. The expansion device of claim 8, wherein the expansion device further comprises a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; and
wherein the first angle of attack is greater than the second angle of attack.
10. The expansion device of claim 9, wherein the second angle of attack ranges from 4 degrees to 15 degrees.
11. The expansion device of claim 9, further comprising one or more intermediate tapered outer surfaces coupled between the first and second tapered outer surfaces.
12. The expansion device of claim 11, wherein the angle of attack of the one or more intermediate tapered outer surfaces continually decreases from the first tapered outer surface to the second tapered outer surface.
13. The expansion device of claim 11, wherein the angle of attack of the one or more intermediate tapered outer surfaces decreases in steps from the first tapered outer surface to the second tapered outer surface.

14. The expansion device of claim 9, wherein the first tapered outer surface and the second tapered outer surface comprise one or more facets in cross section.
15. The expansion device of claim 14, wherein the number of facets ranges from 12 to 16.
16. The expansion device of claim 14, wherein the faceted surfaces are wider near the front end of the expansion device and become narrower toward the rear end of the expansion device.
17. A method of radially expanding a tubular member comprising:
 - radially expanding at least a portion of the tubular member by displacing an expansion device relative to the tubular member, wherein the expansion device comprises:
 - a front end having a first diameter;
 - a rear end having a second diameter, wherein the second diameter is greater than the first diameter; and
 - a first tapered outer surface, the first tapered outer surface comprising a curvature defined by a polynomial equation and having a point of inflection.
18. The method of claim 17, wherein the first tapered surface comprises the curvature defined by the polynomial equation; and
 - wherein the polynomial equation has an L_f/L ratio ranging from 0.32 to 0.677, wherein L is the length of the first tapered outer surface measured relative to a longitudinal axis through the expansion device and L_f is the distance between the rear end and the inflection point measured relative to the longitudinal axis.

19. The method of claim 17, wherein the first tapered surface comprises the curvature defined by the polynomial equation; and
wherein the length of the first tapered outer surface ranges from 0.5 inches to 2.5 inches.
20. The method of claim 19, wherein the length of the first tapered outer surface ranges from 1.6 inches to 1.9 inches.
21. The method of claim 17, wherein the first tapered outer surface comprises one or more facets in cross section.
22. The method of claim 21, wherein the number of facets ranges from 12 to 16.
23. The method of claim 21, wherein the faceted surfaces are wider near the front end of the expansion device and become narrower toward the rear end of the expansion device.
24. The method of claim 17, wherein the expansion device further comprises a second tapered outer surface comprising a second angle of attack coupled to the first tapered outer surface; and
wherein the first angle of attack is greater than the second angle of attack.
25. The method of claim 24, wherein the second angle of attack ranges from 4 degrees to 15 degrees.
26. The method of claim 24, further comprising one or more intermediate tapered outer surfaces coupled between the first and second tapered outer surfaces.

27. The method of claim 26, wherein the angle of attack of the intermediate tapered outer surfaces continually decreases from the first tapered outer surface to the second tapered outer surface.
28. The method of claim 26, wherein the angle of attack of the intermediate tapered outer surfaces decreases in steps from the first tapered outer surface to the second tapered outer surface.
29. The method of claim 24, wherein the first tapered outer surface and the second tapered outer surface comprise one or more facets in cross section.
30. The method of claim 29, wherein the number of facets ranges from 12 to 16.
31. The method of claim 29, wherein the faceted surfaces are wider near the front end of the expansion device and become narrower toward the rear end of the expansion device.
32. The method of claim 17, wherein the first tapered outer surface further comprises a first angle of attack ranging from 6 degrees to 20 degrees.

25791.259

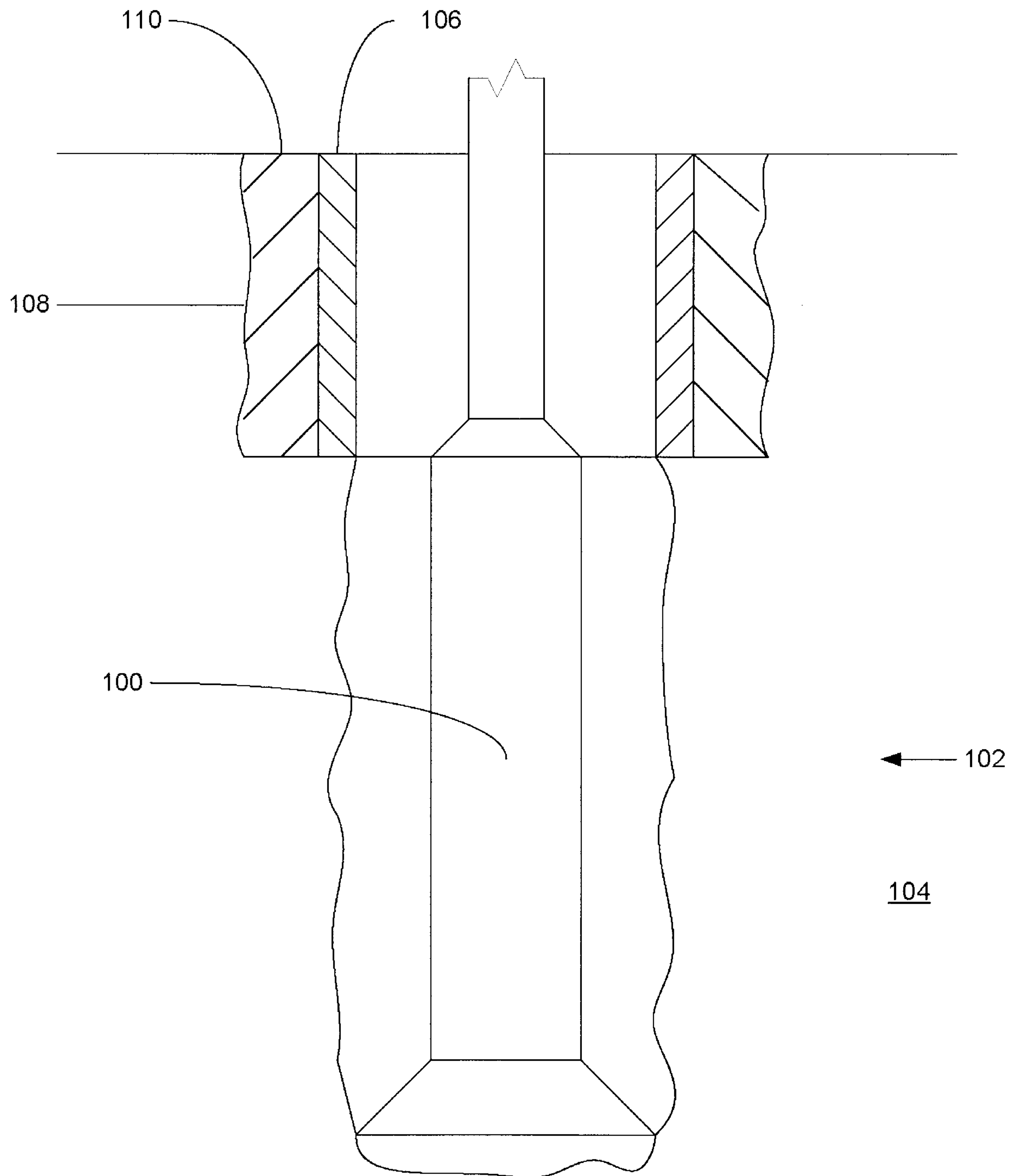


FIGURE 1

25791.259

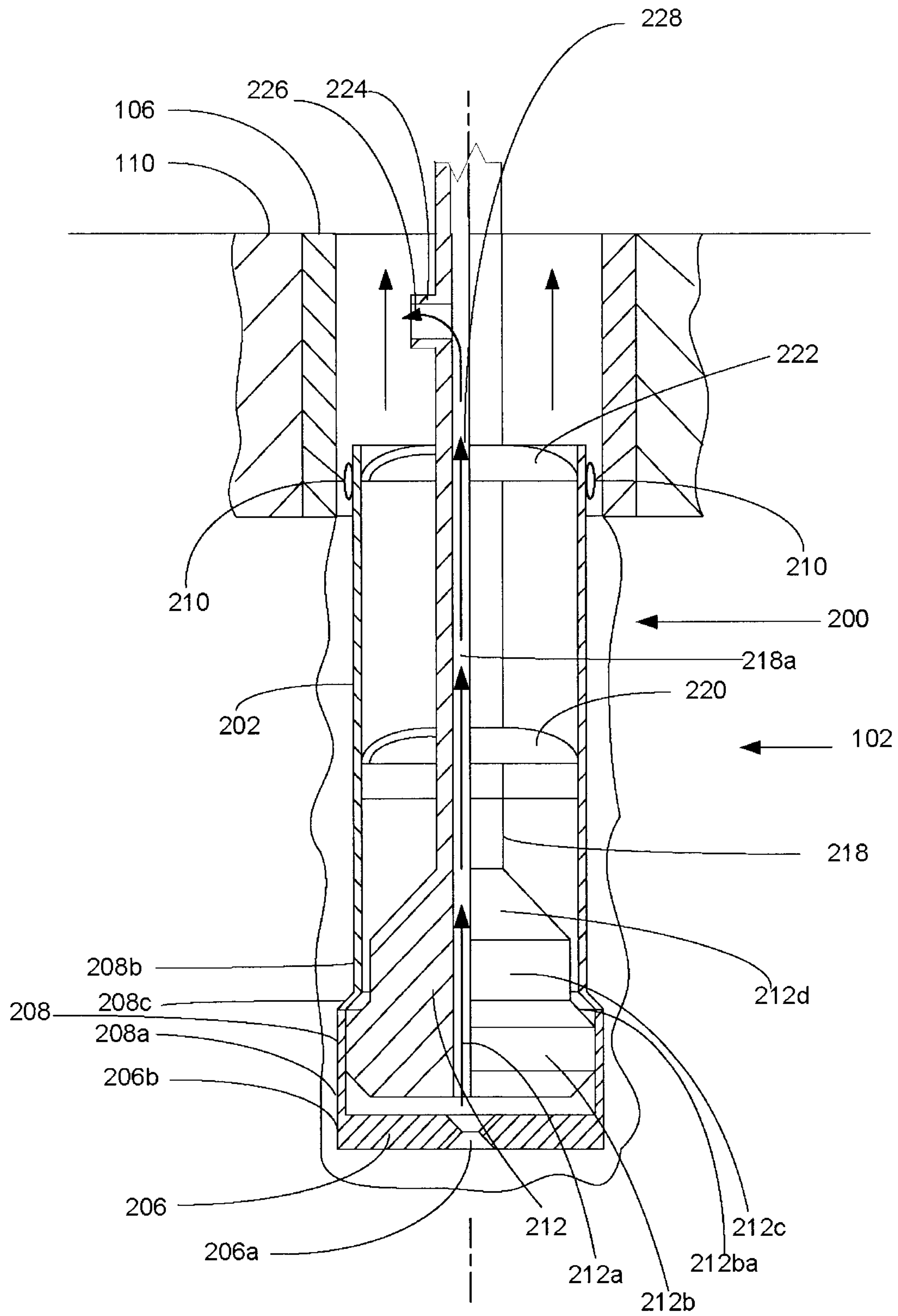
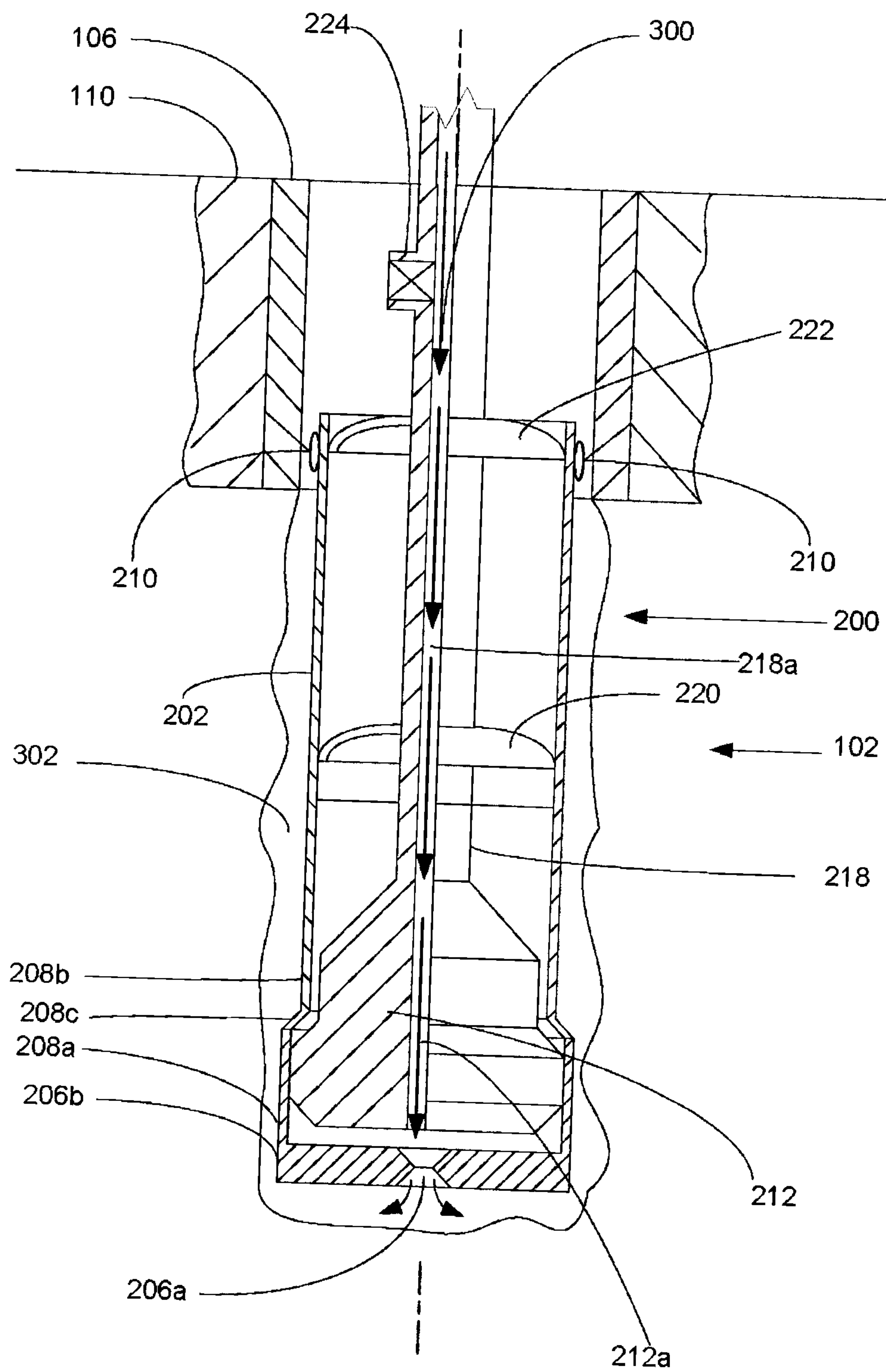


FIGURE 2

25791.259



25791.259

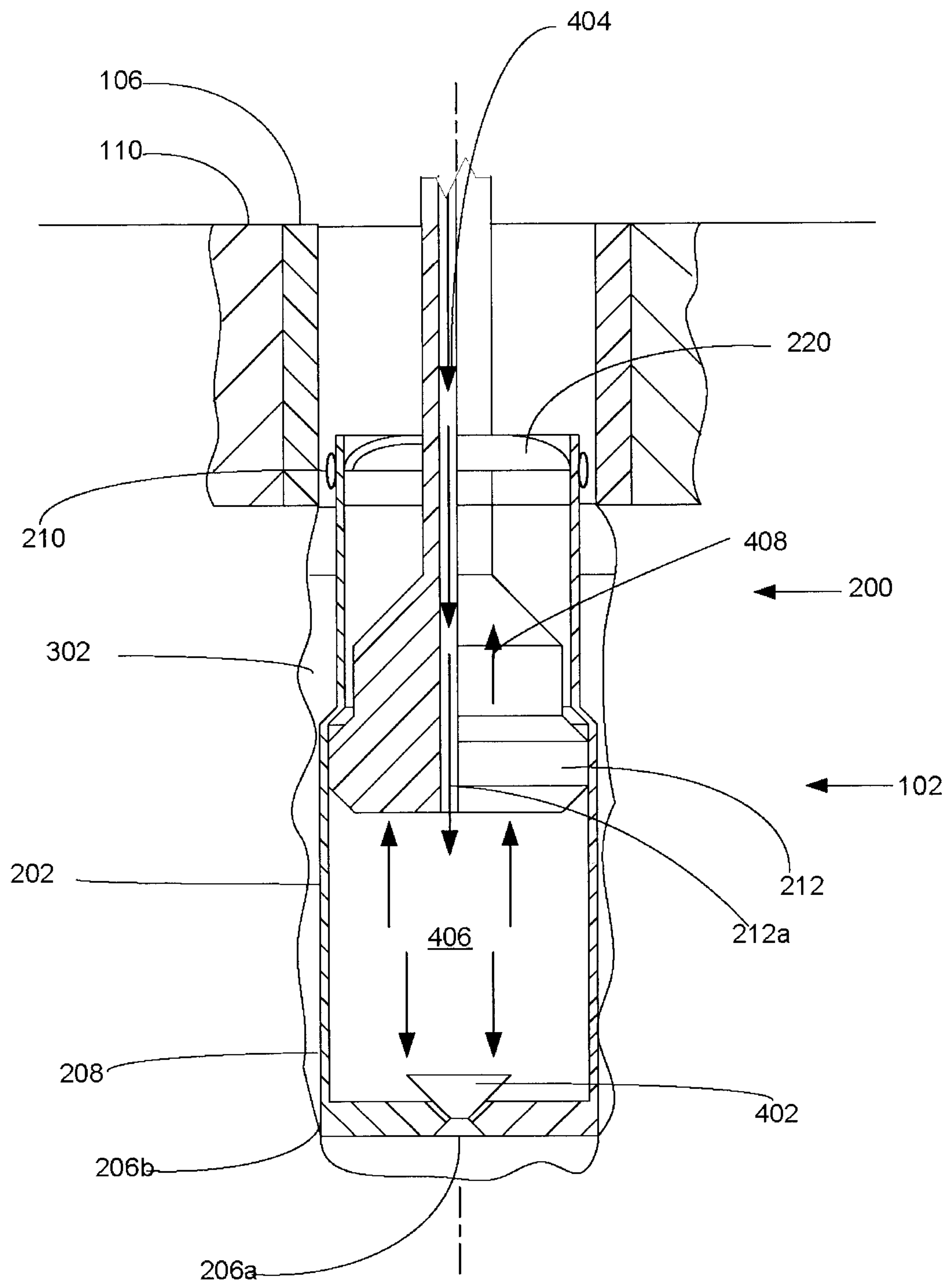


FIGURE 4

25791.259

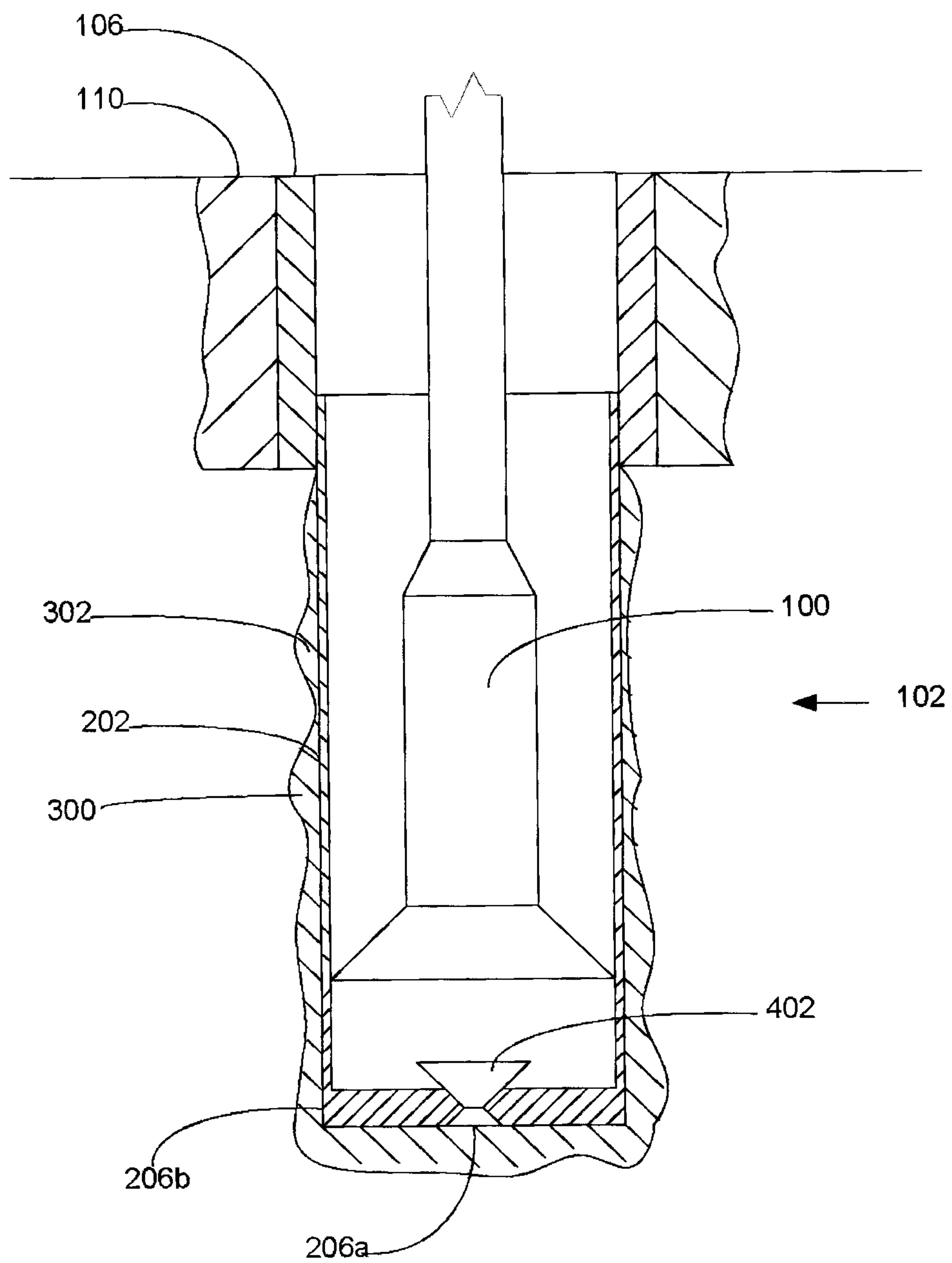


FIGURE 5

25791.259

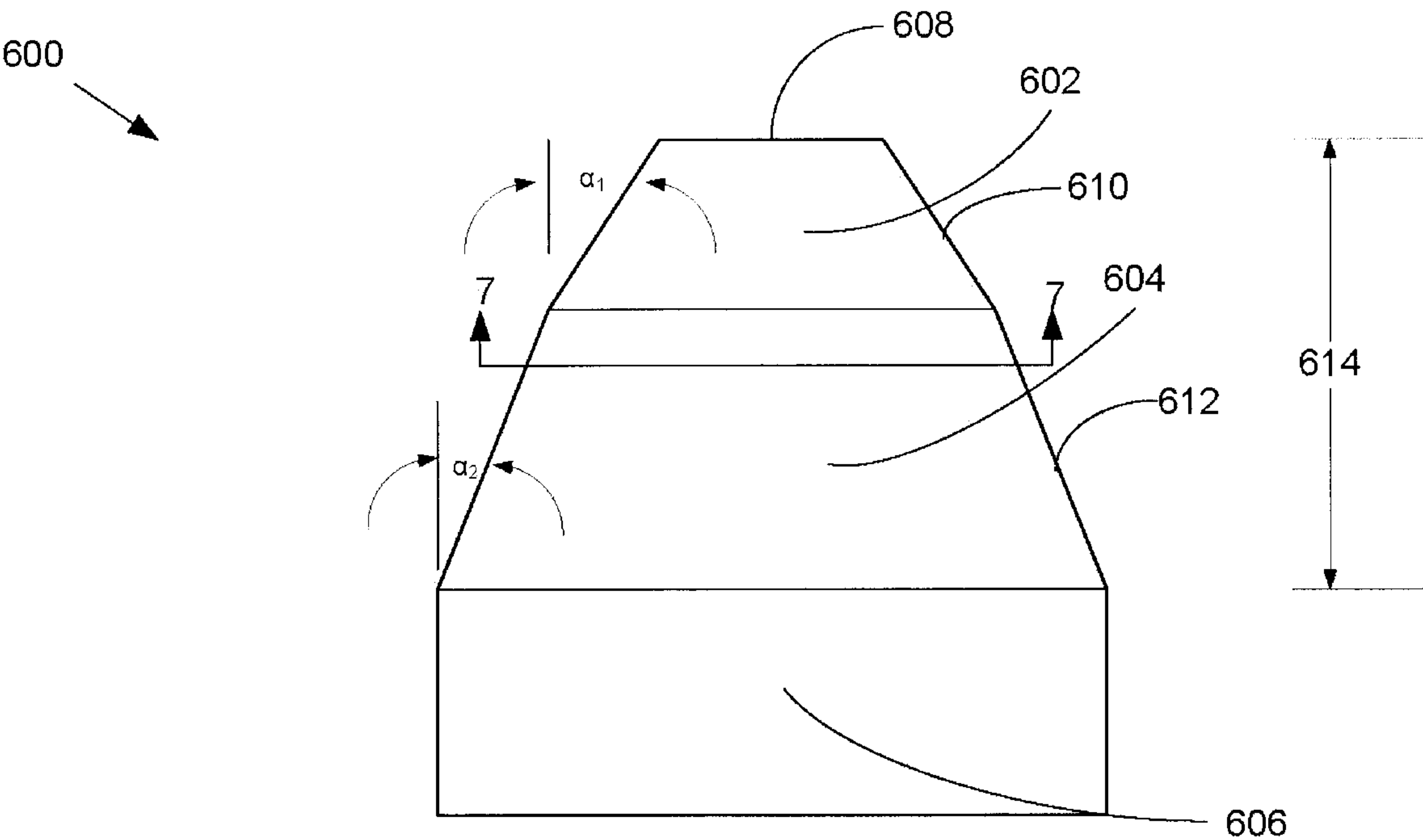


FIGURE 6

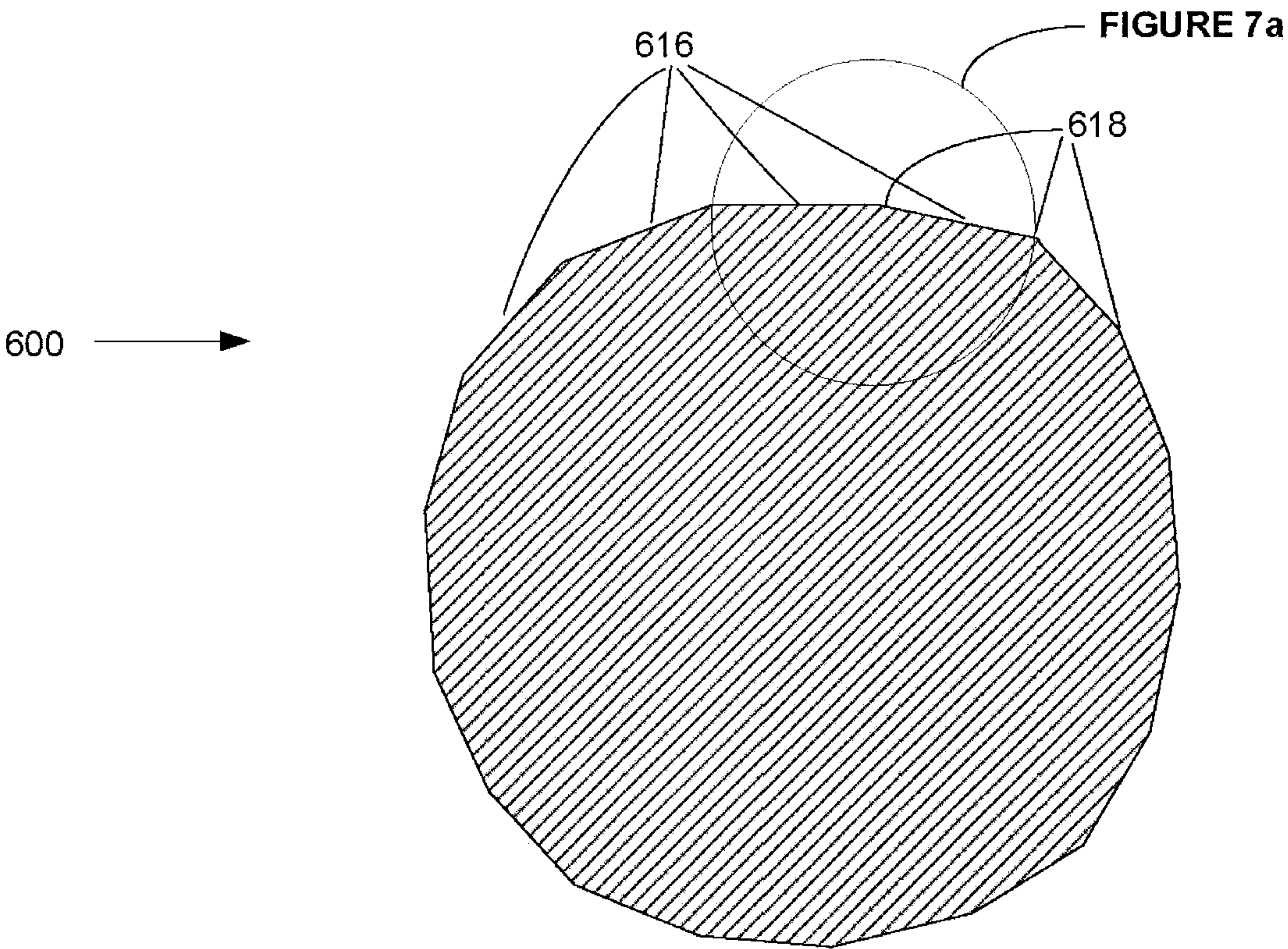


FIGURE 7

25791.259

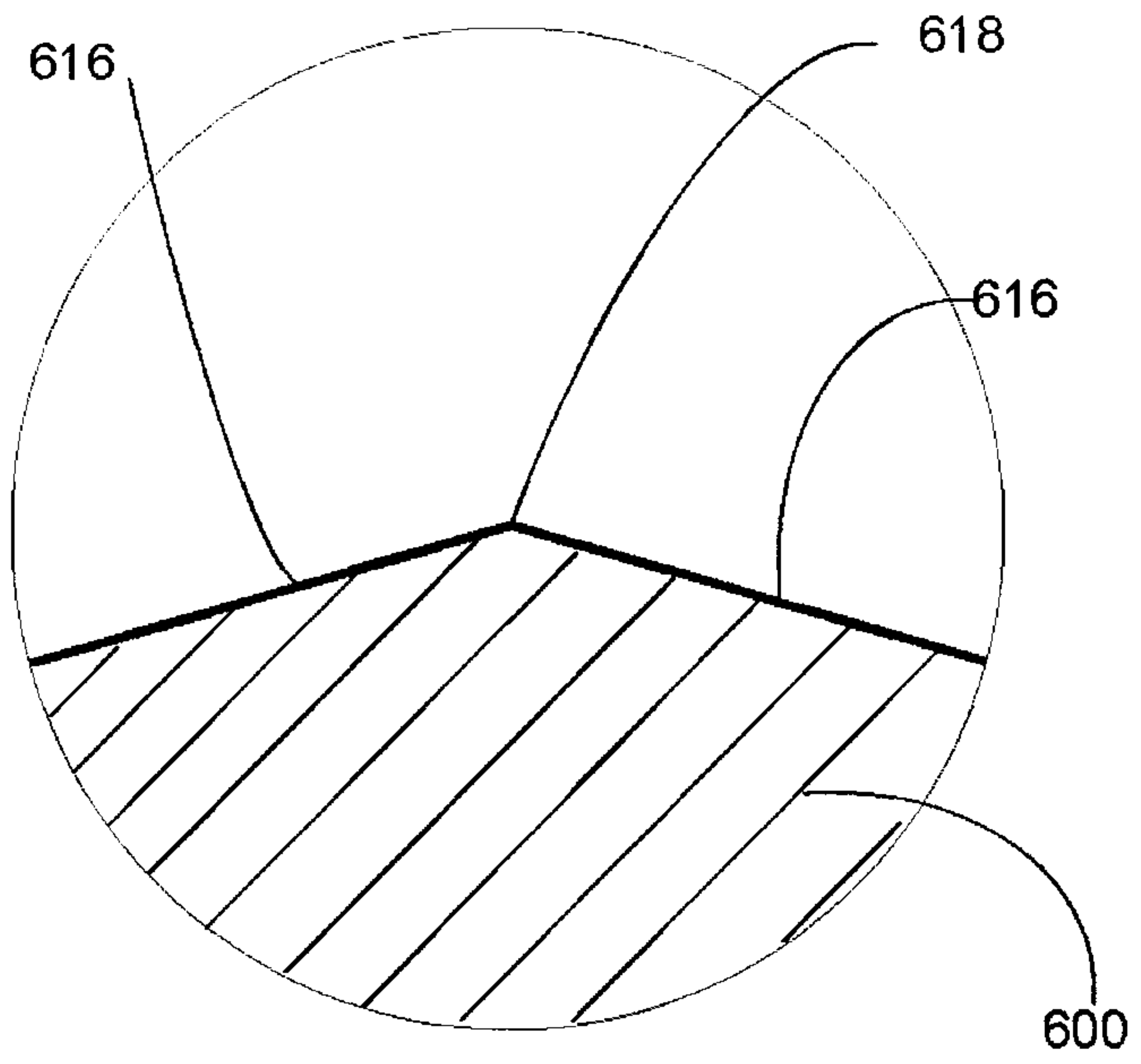


FIGURE 7a

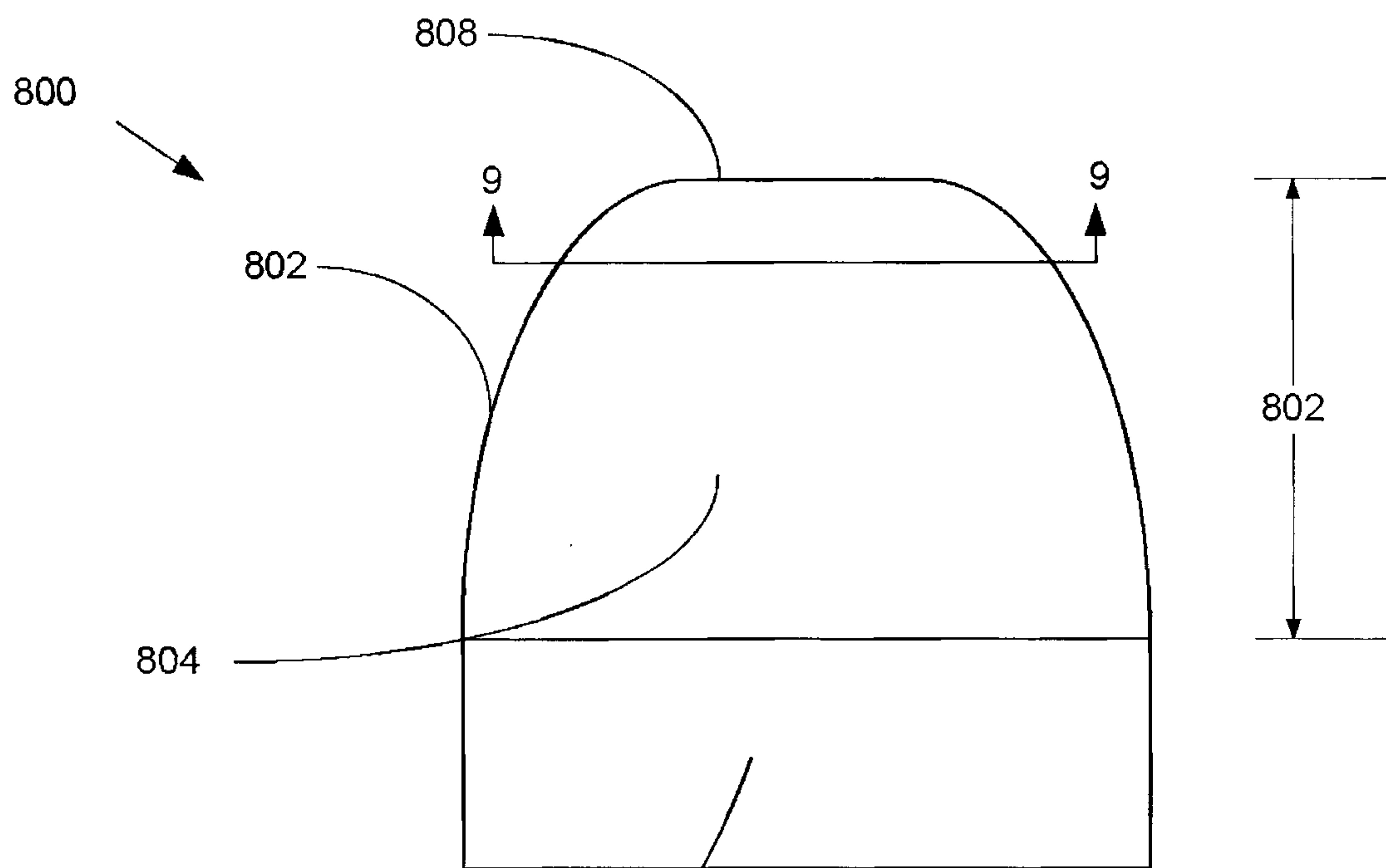


FIGURE 8

806

25791.259

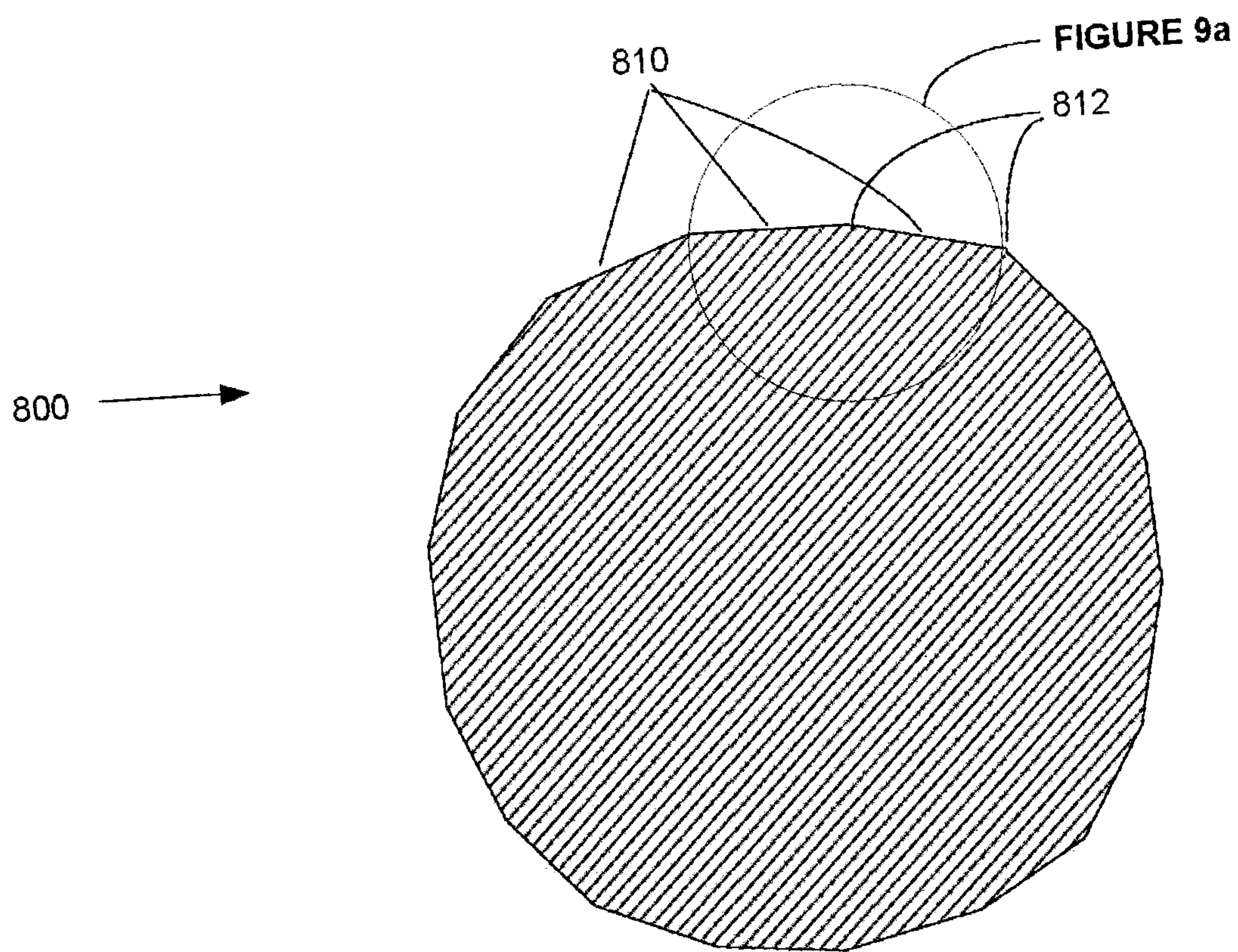


FIGURE 9

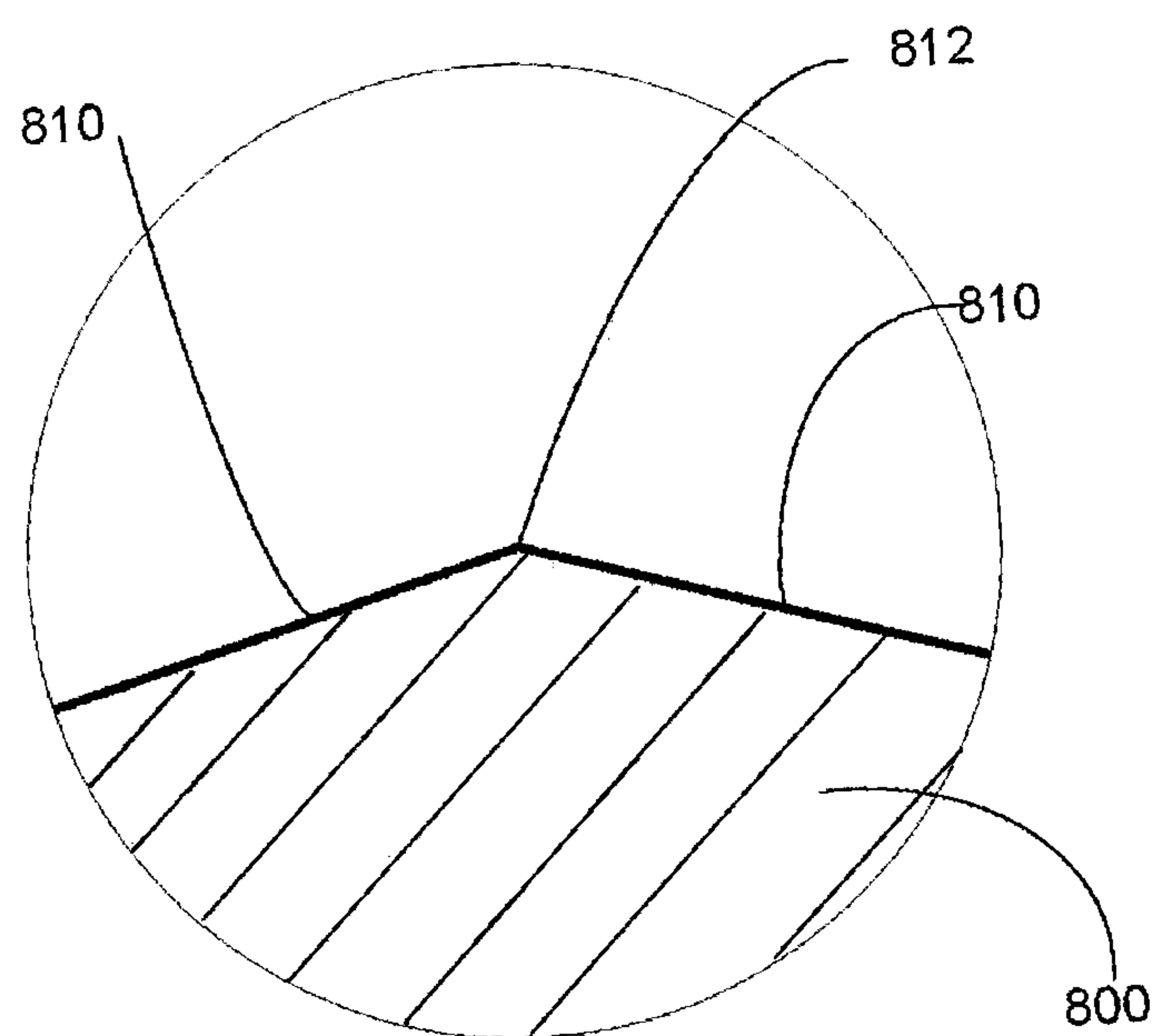


FIGURE 9a

25791.259

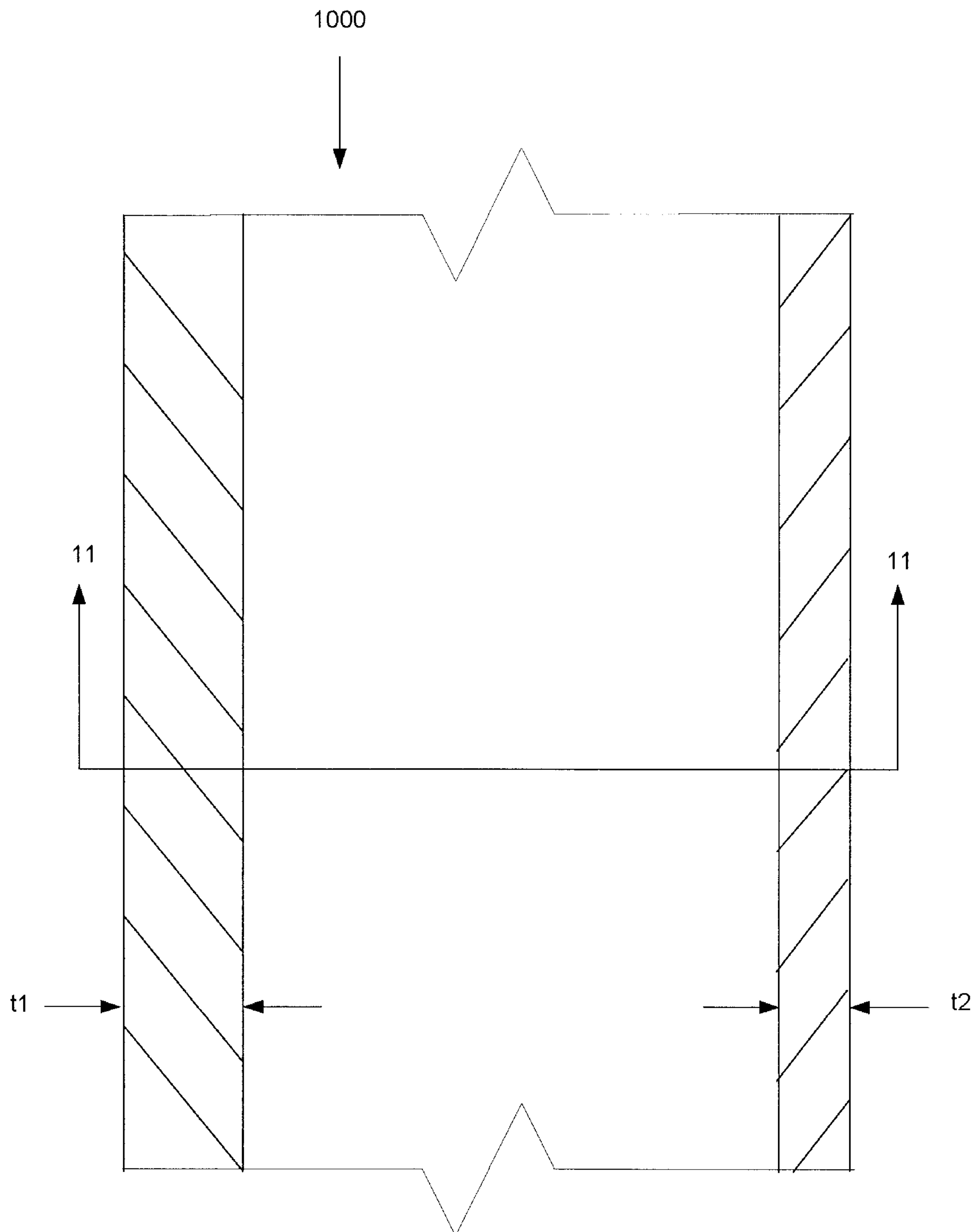


FIGURE 10

25791.259

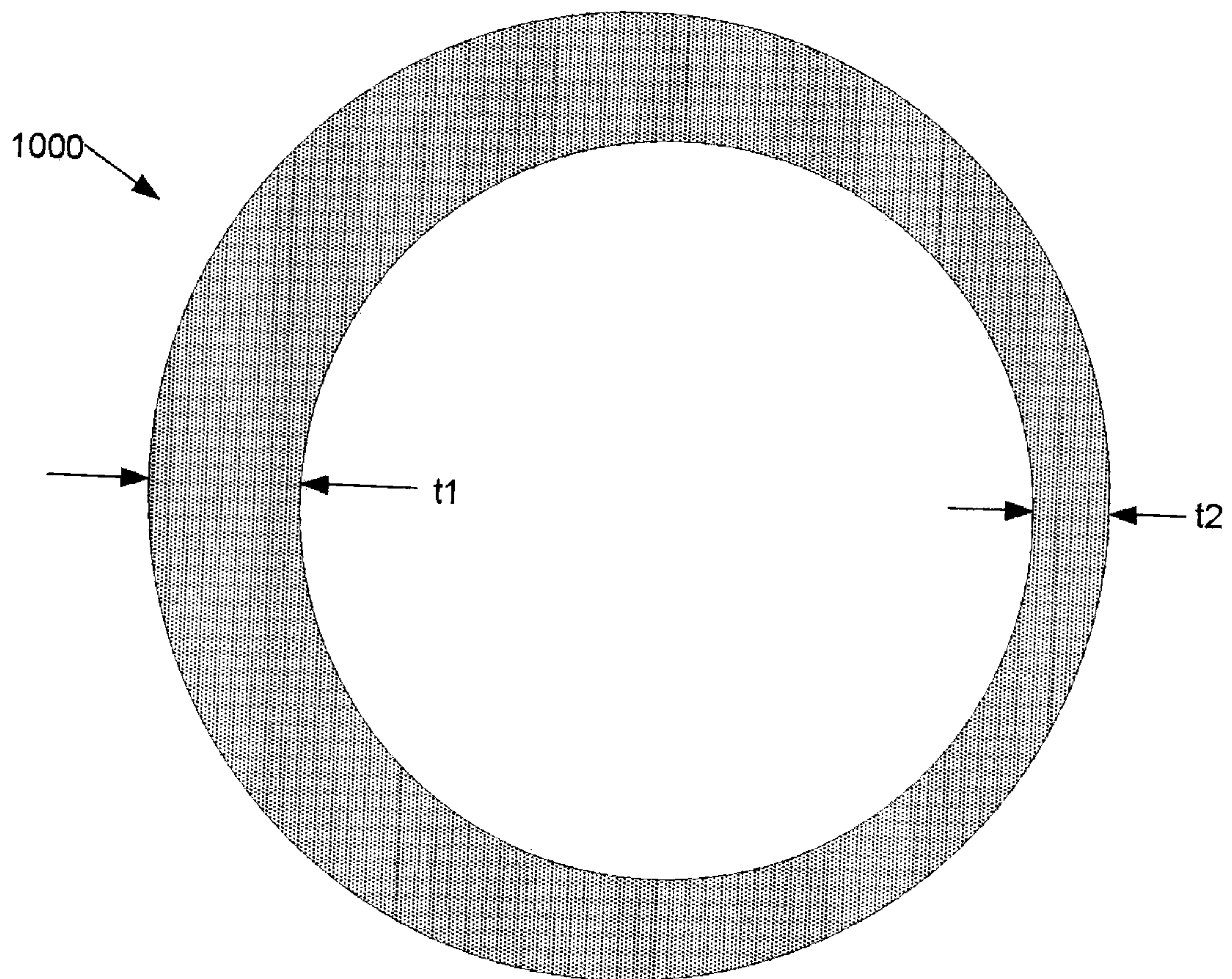


FIGURE 11

25791.259

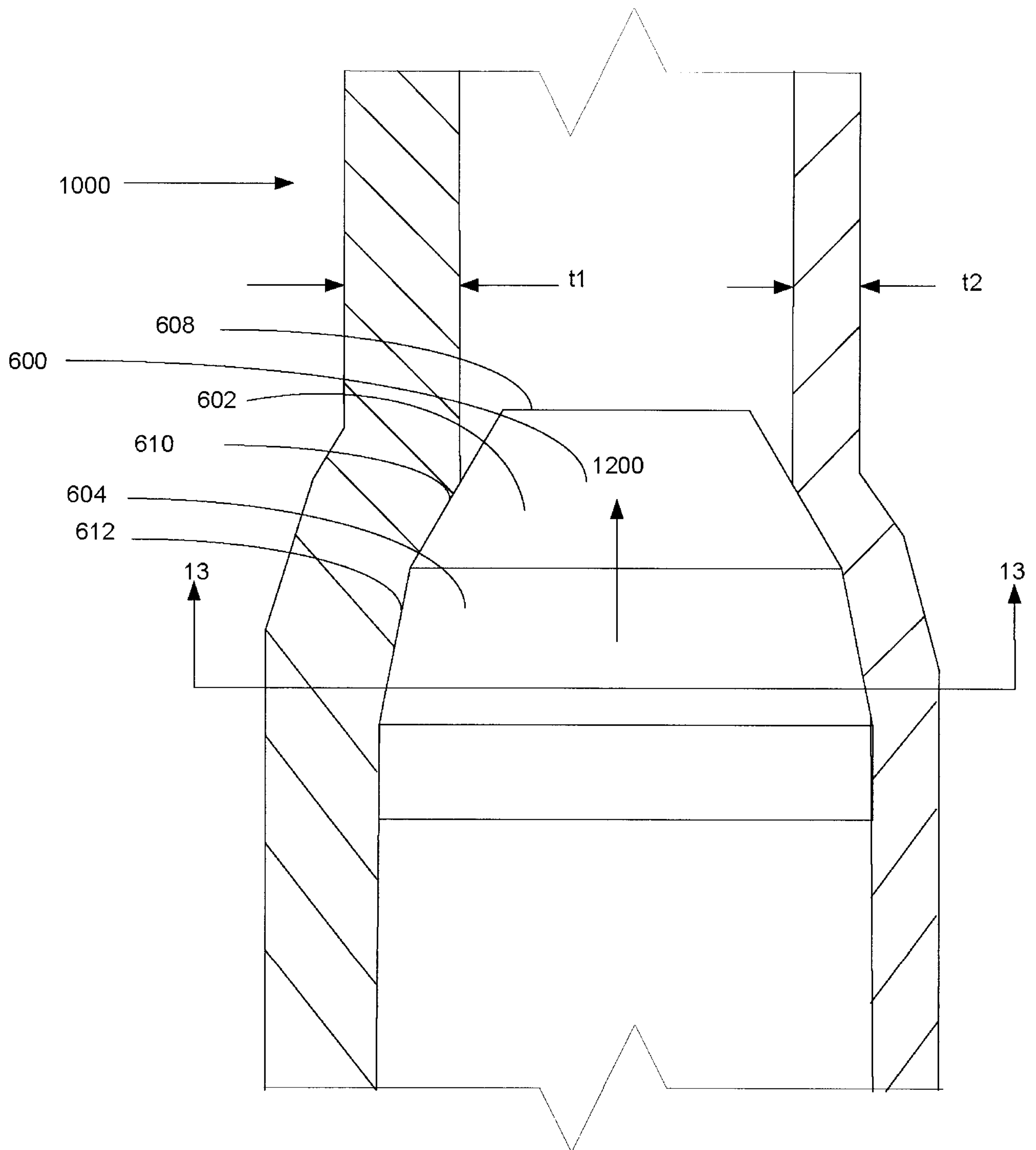
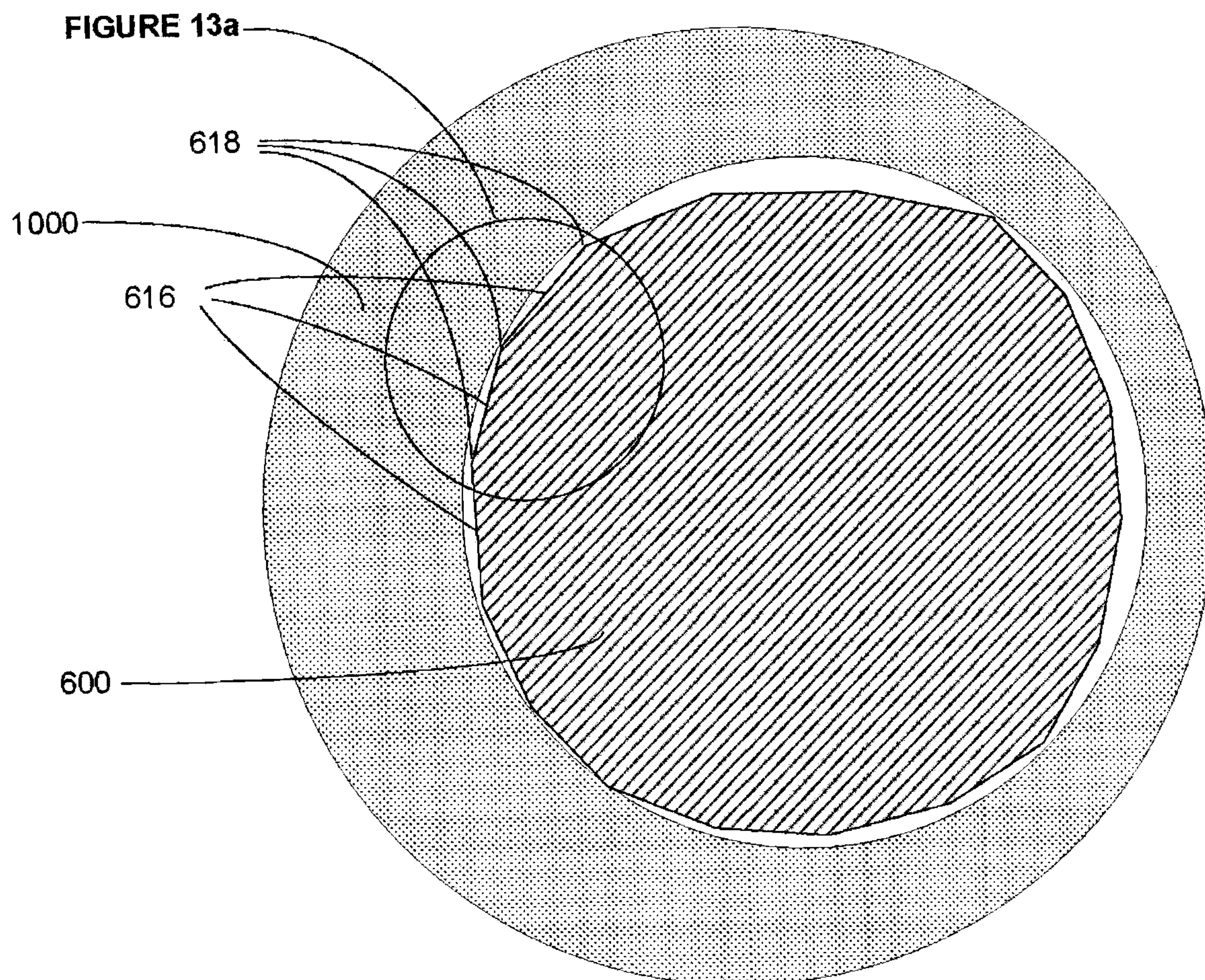


FIGURE 12

25791.259

**FIGURE 13**

25791.259

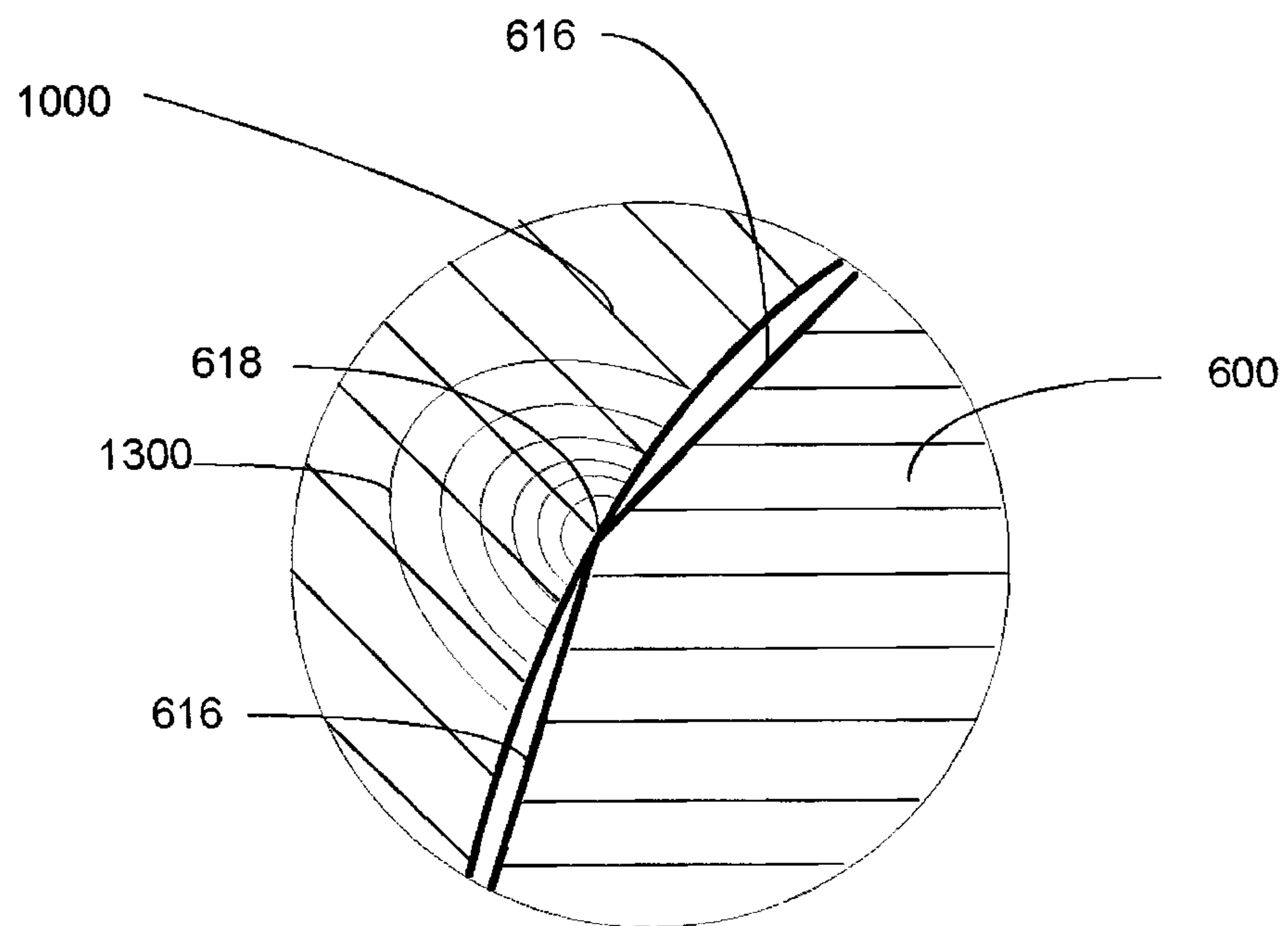
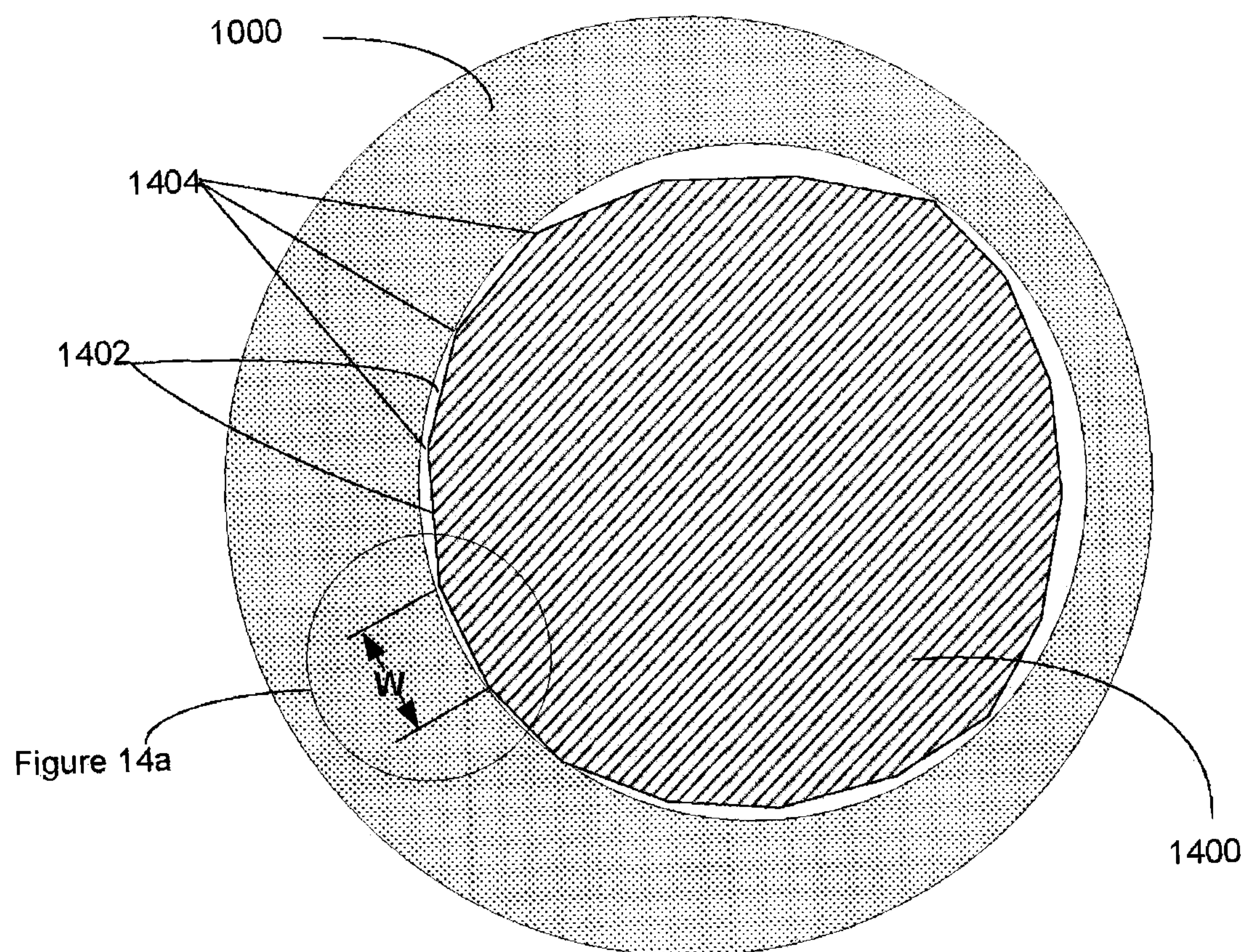
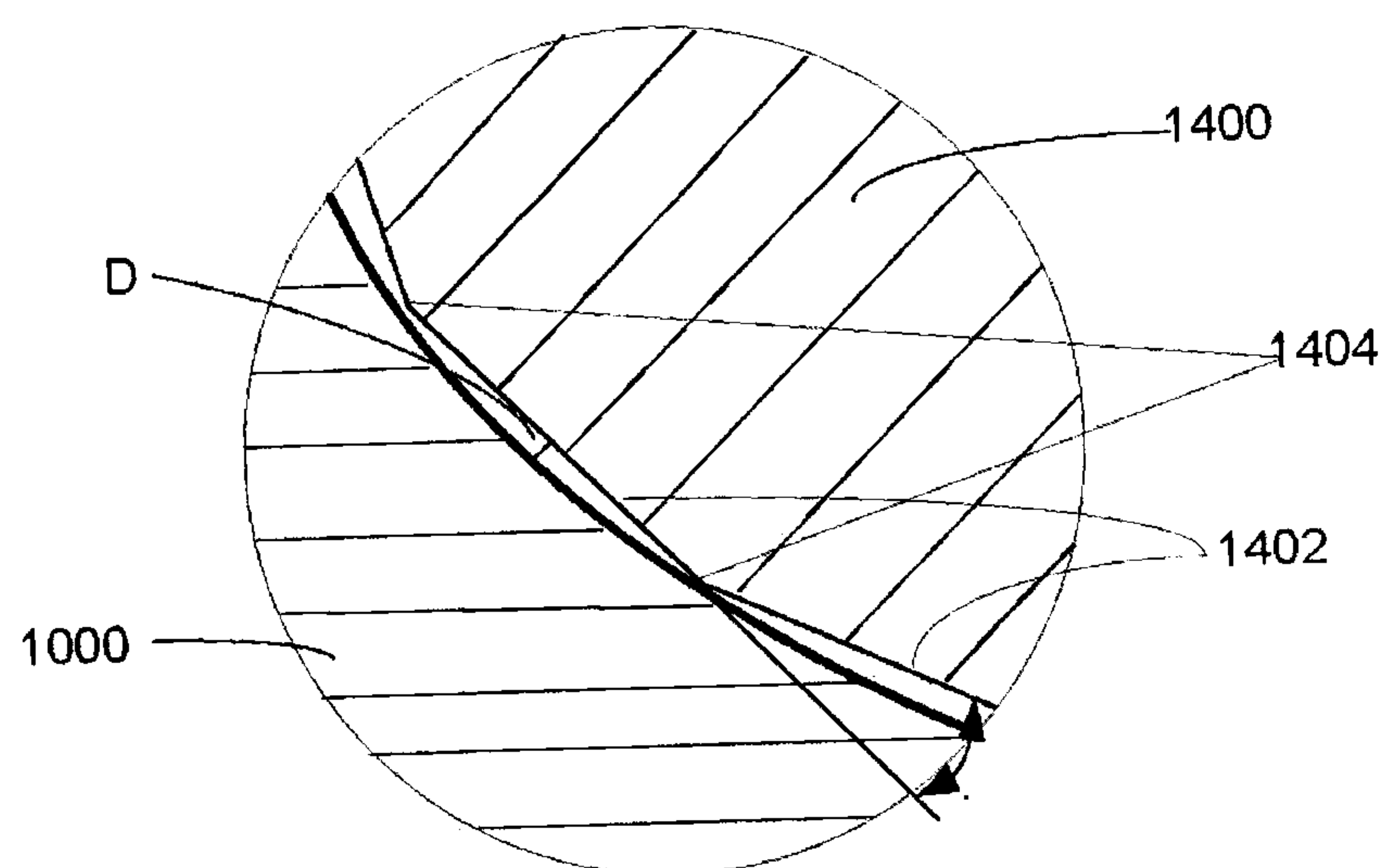


FIGURE 13a

25791.259

**FIGURE 14****FIGURE 14a**

25791.259

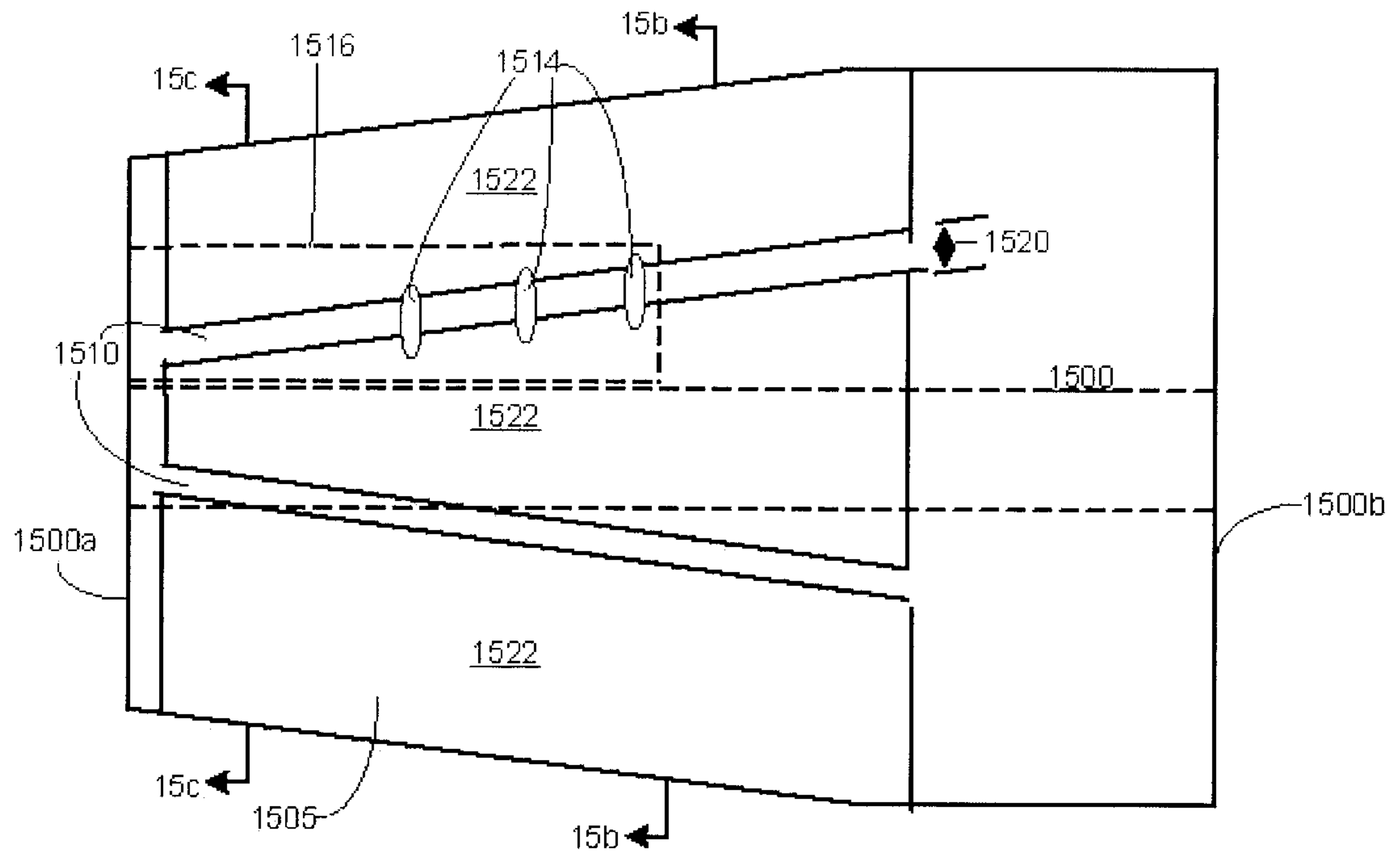


FIGURE 15a

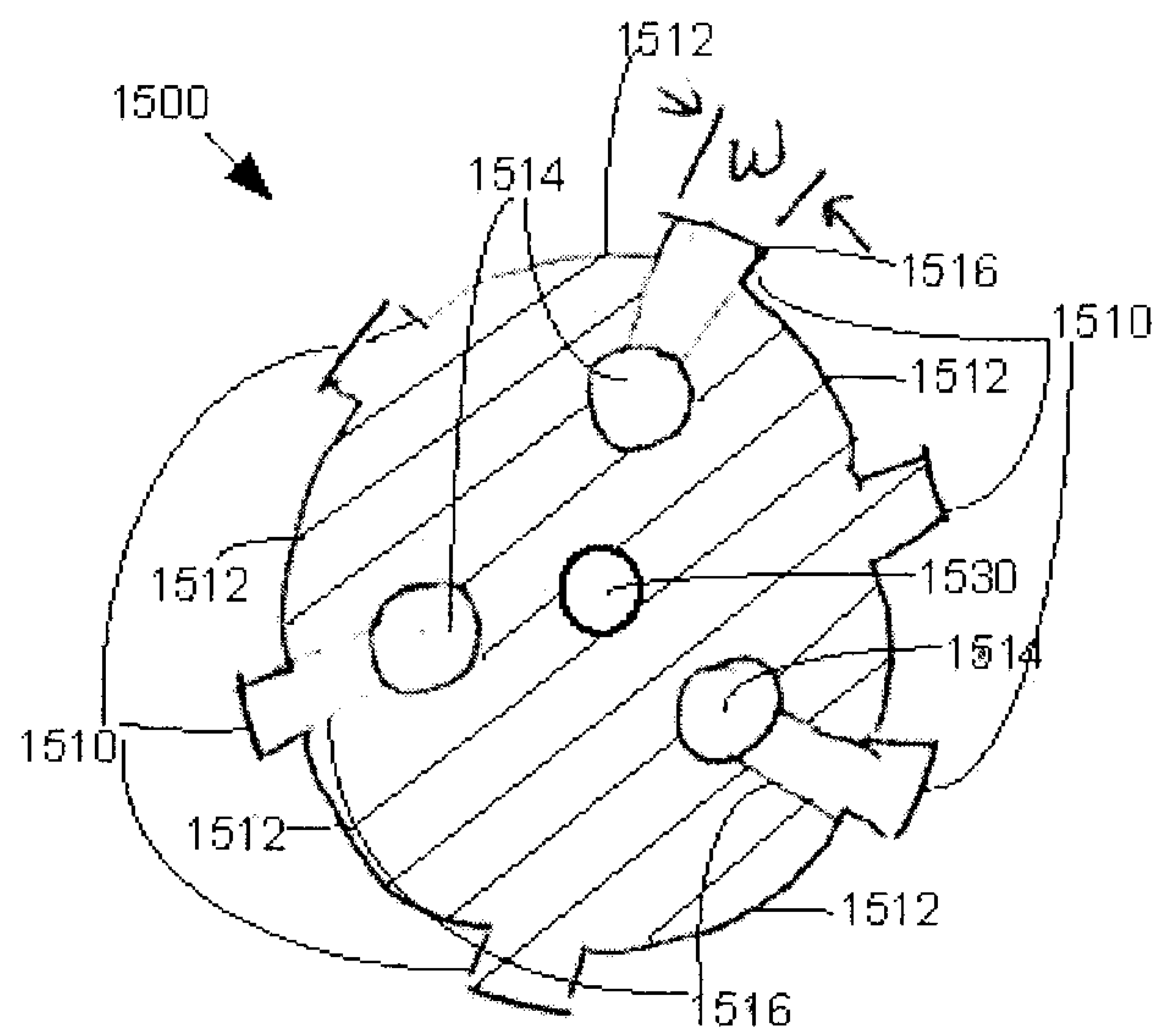


FIGURE 15b

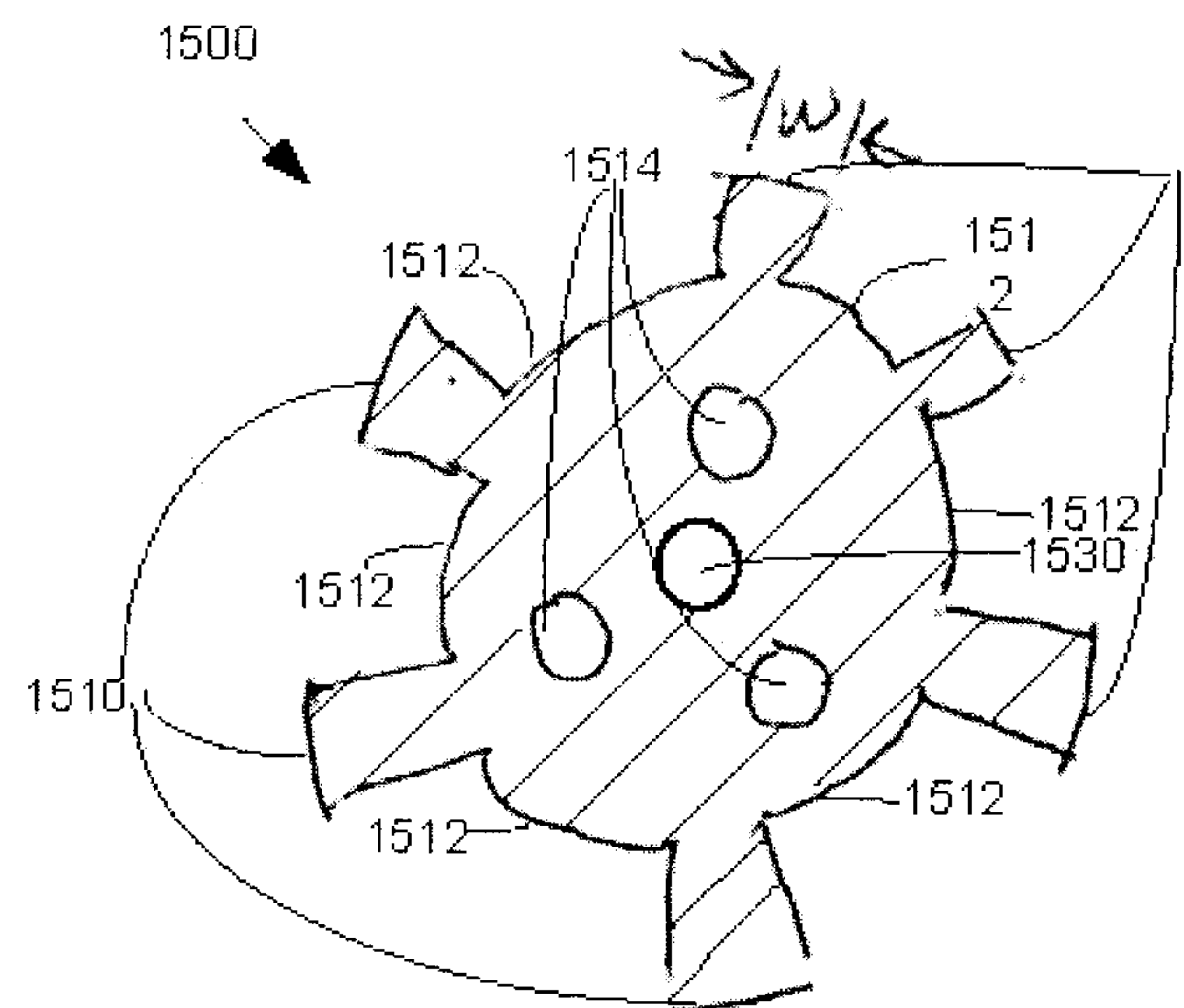
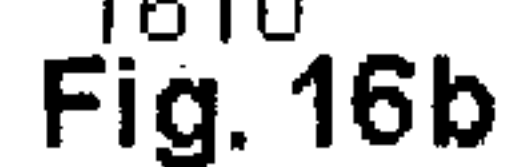


FIGURE 15c



25791.259

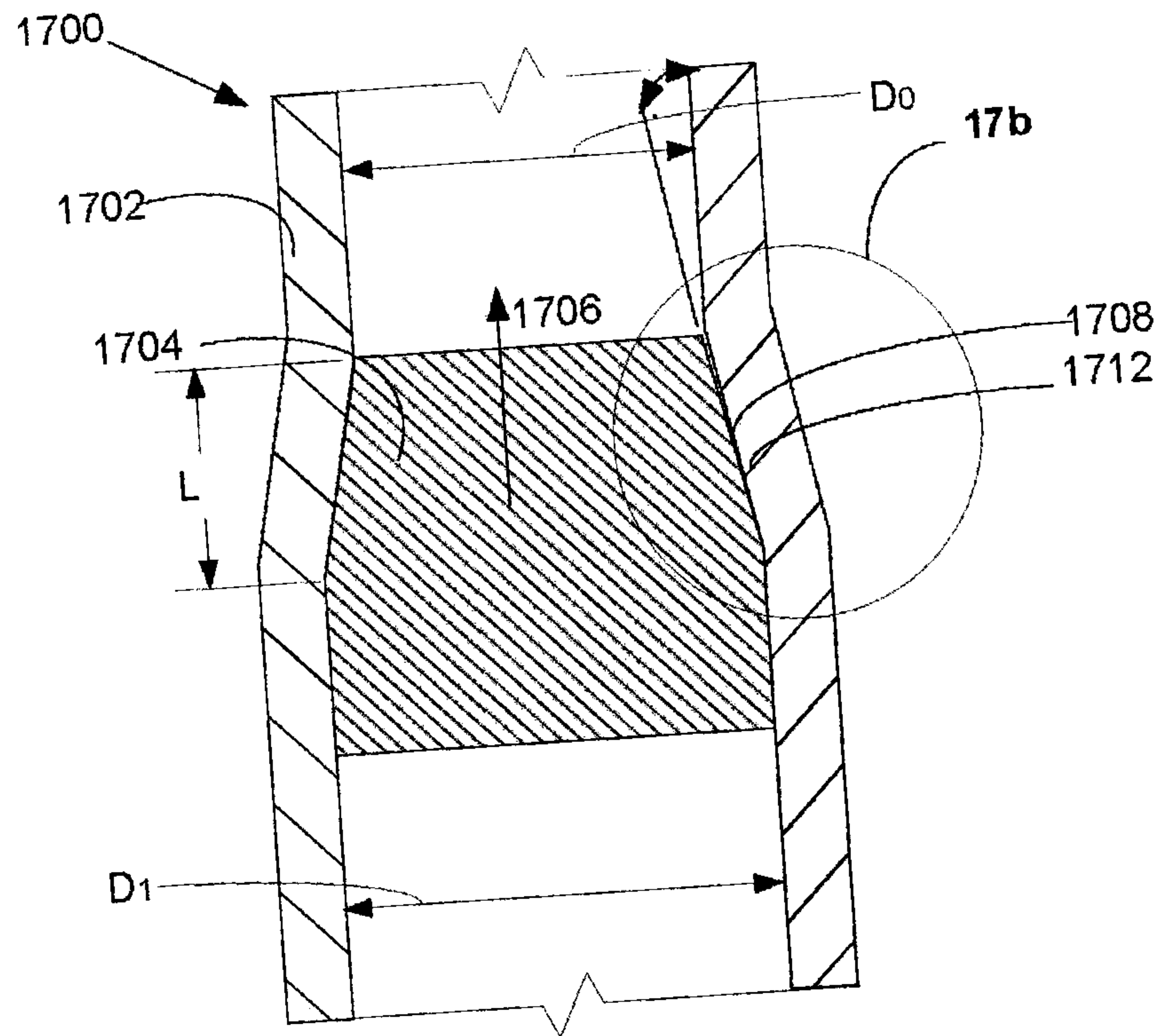


FIGURE 17a

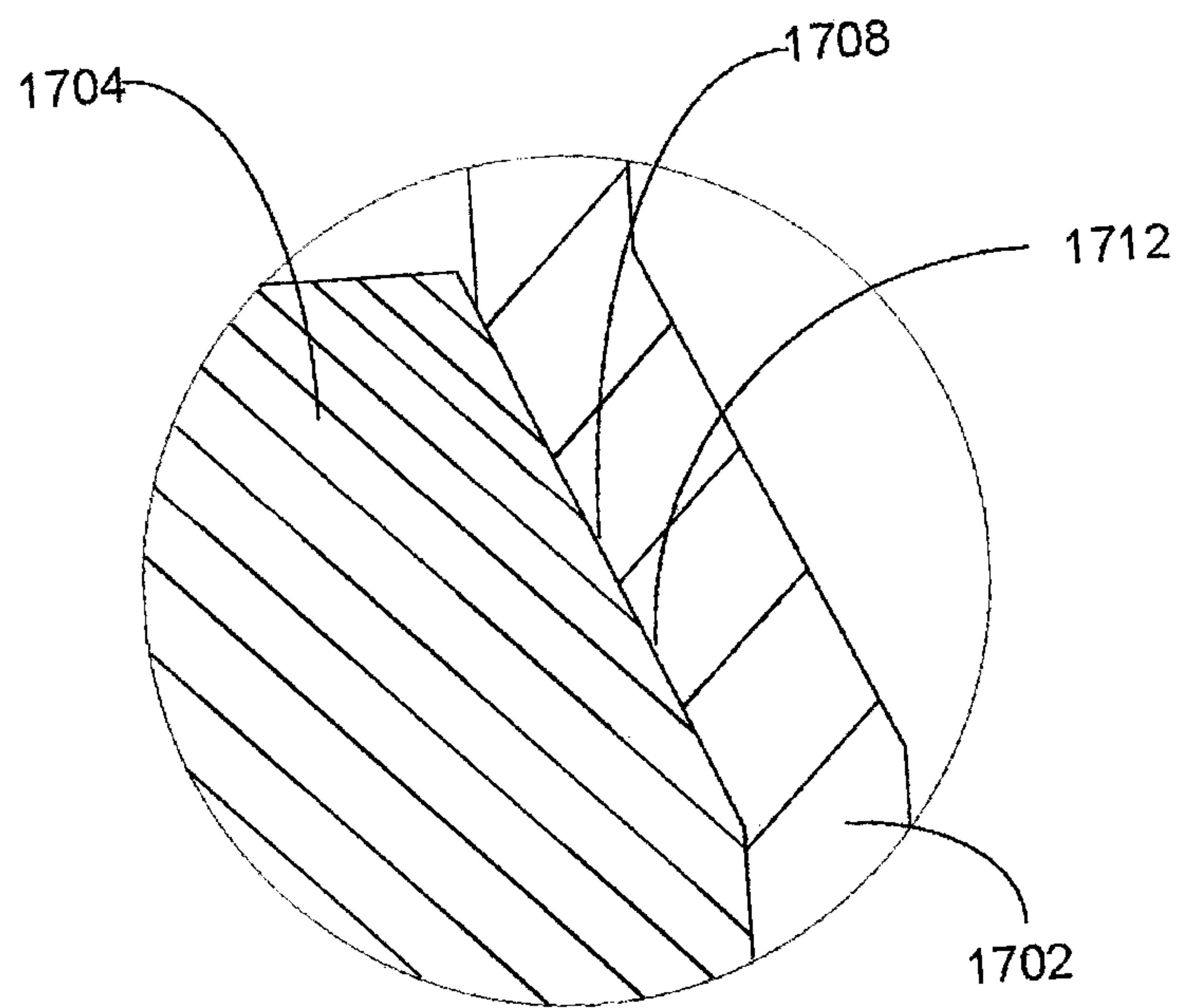


FIGURE 17b

25791.259

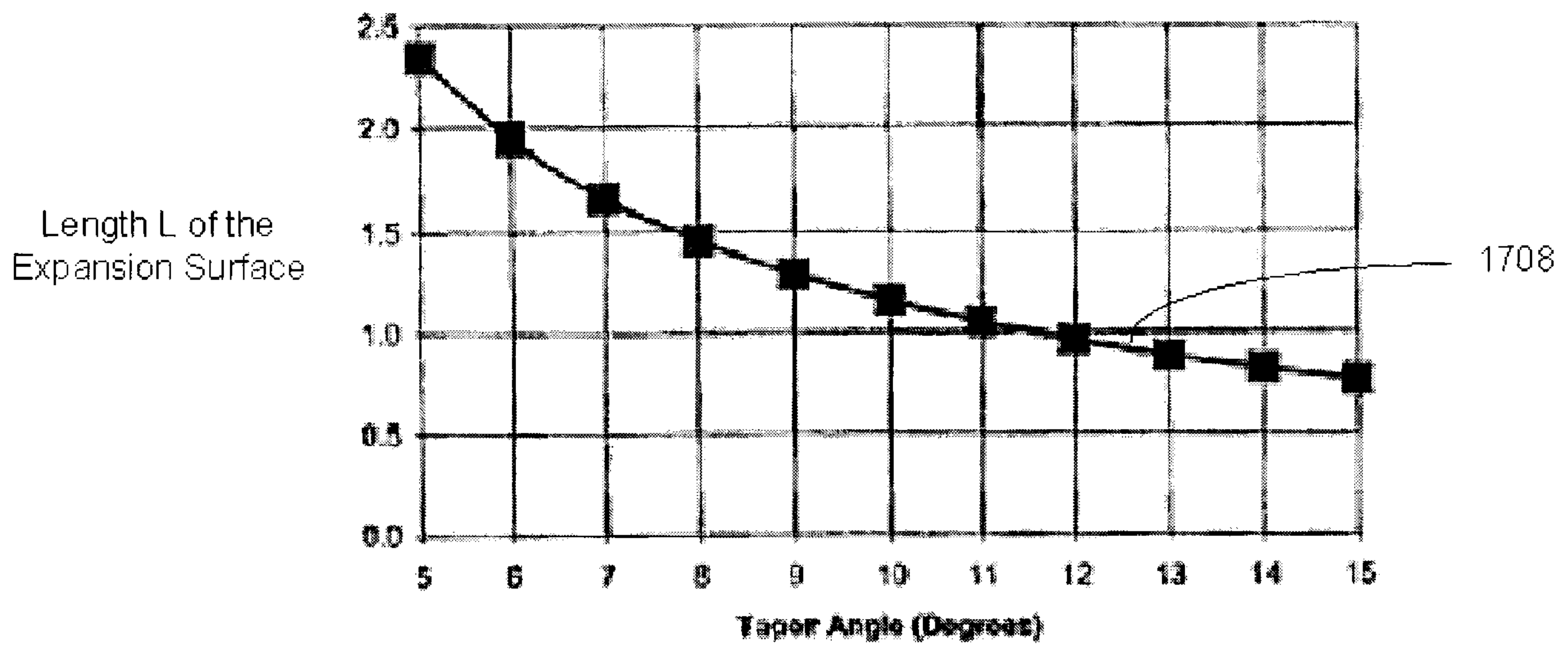
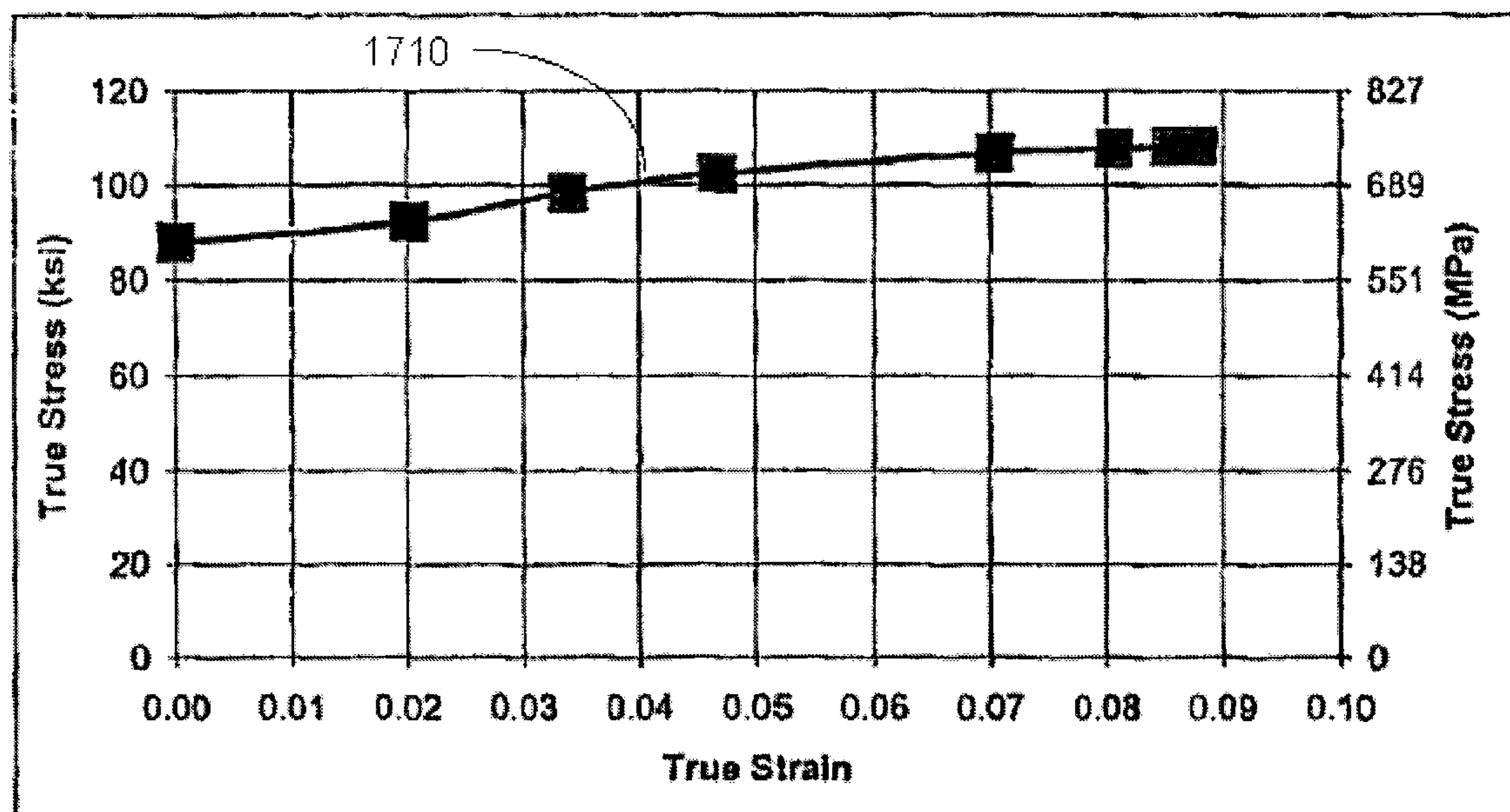


FIGURE 17c



Modulus of Elasticity, $E = 30 \times 10^6$ psi, Poisson's Ratio, $\nu = 0.3$

FIGURE 17d

25791.259

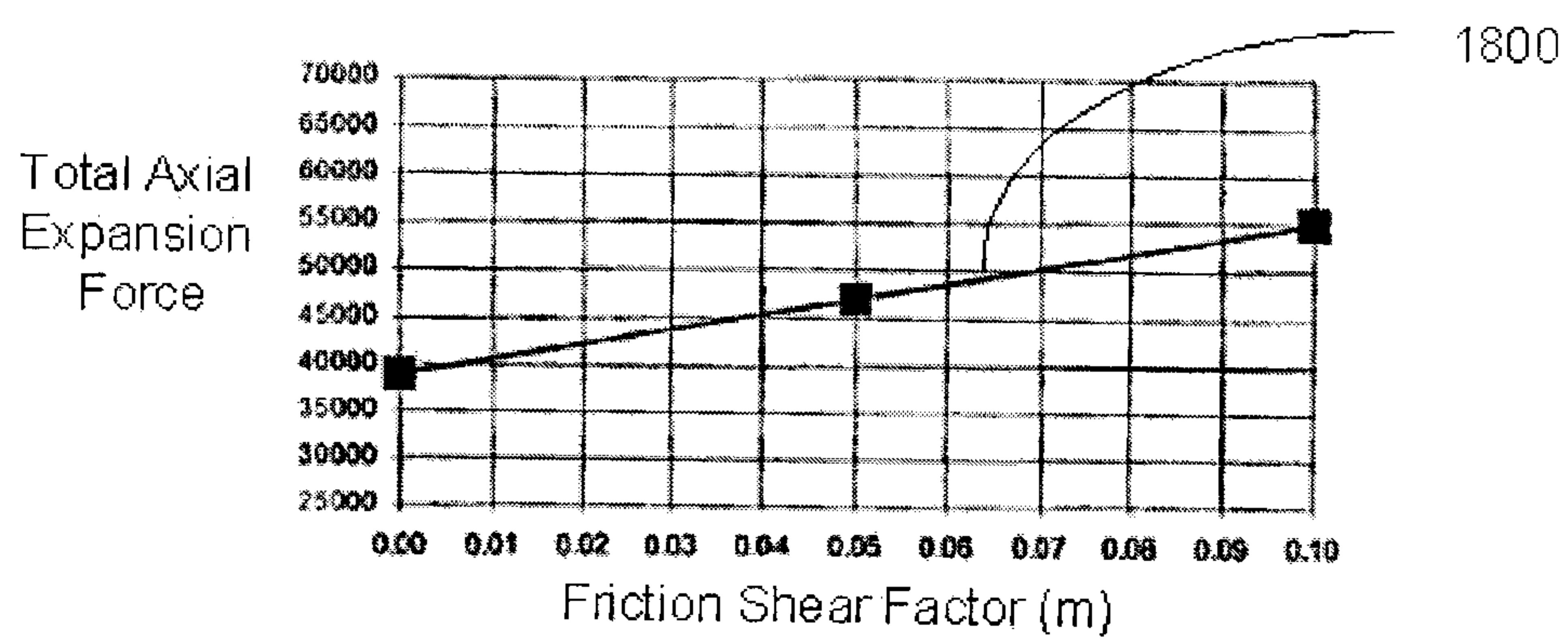


FIGURE 18

25791.259

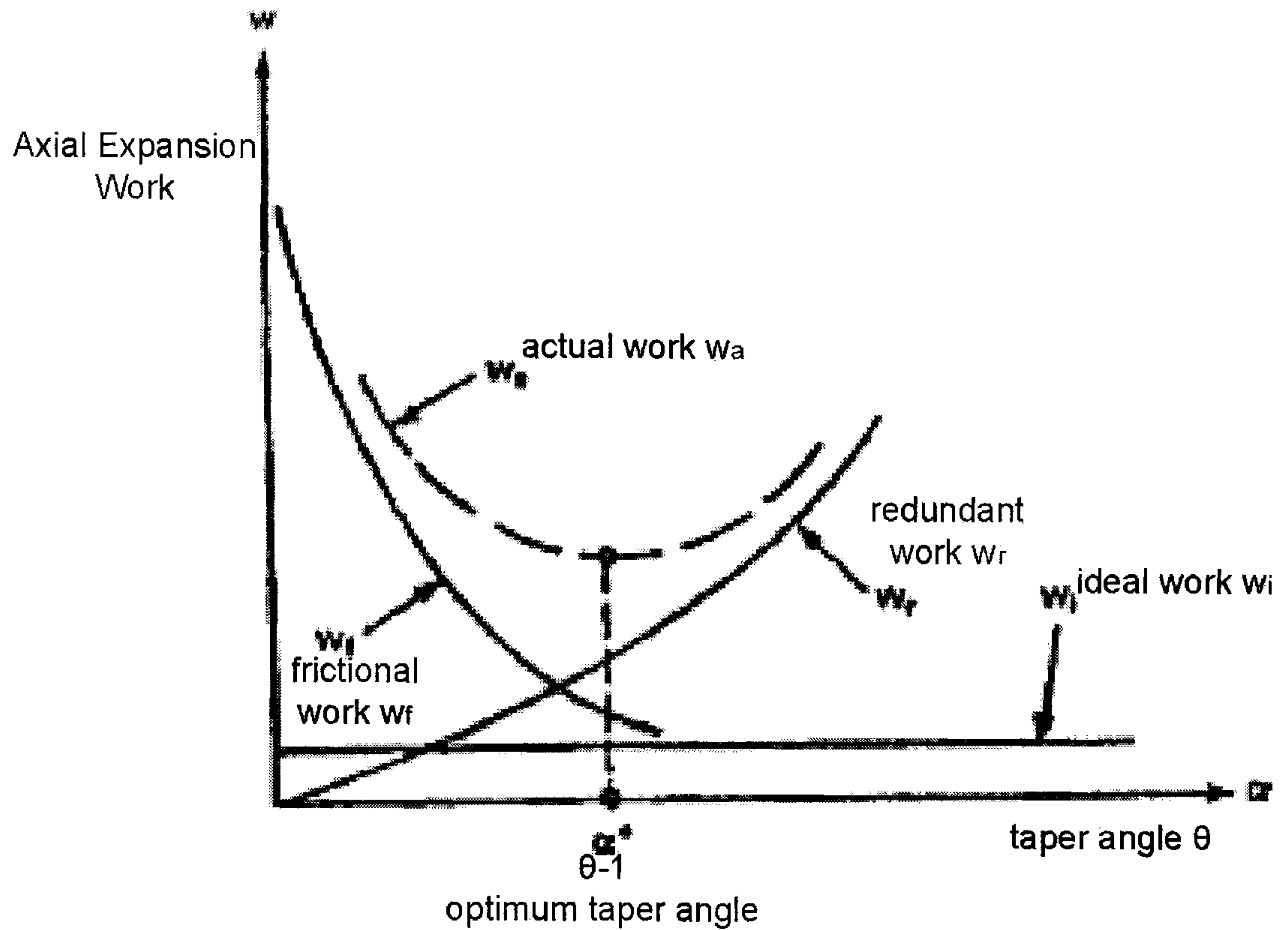


FIGURE 19

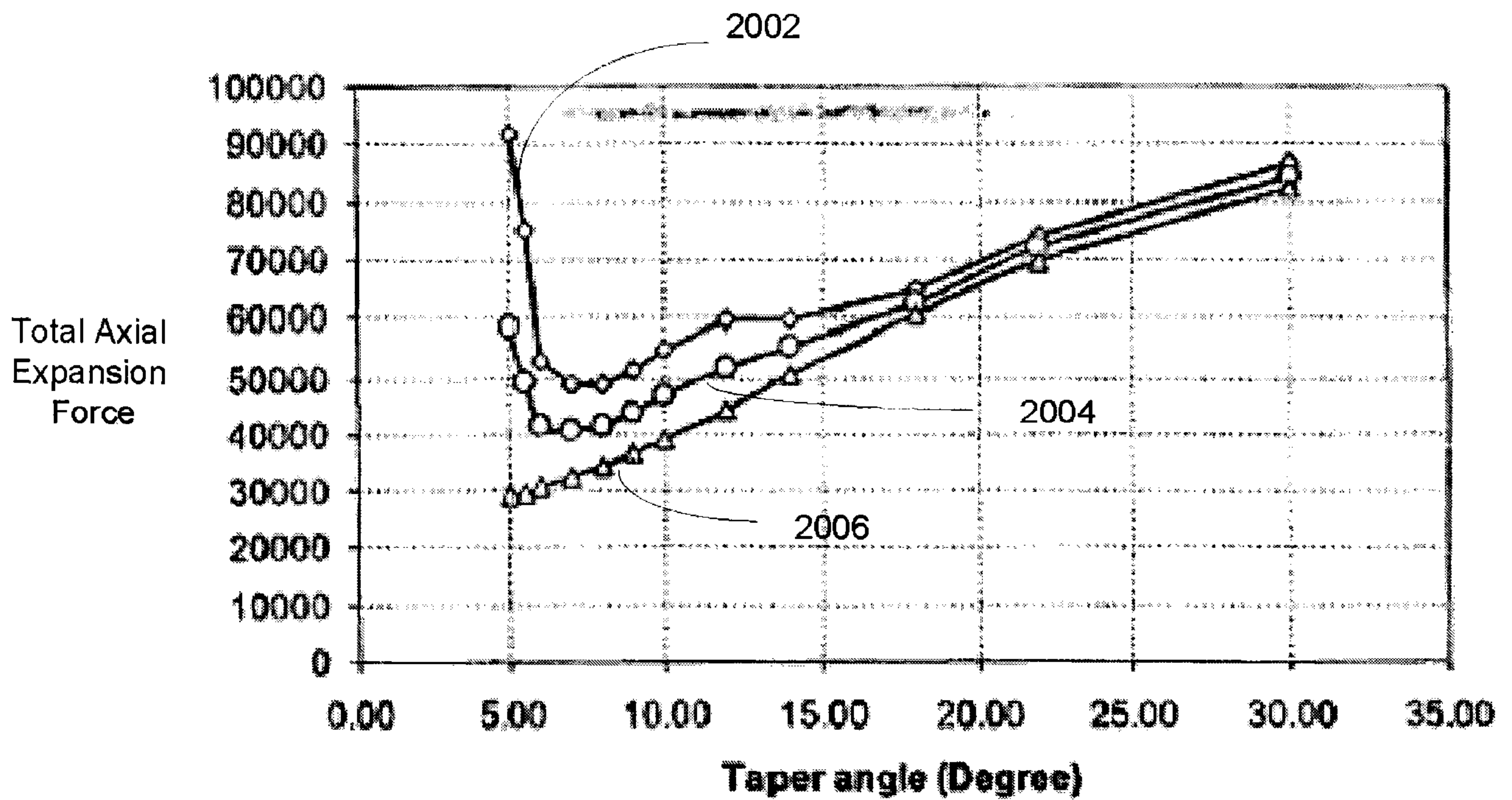


FIGURE 20

25791.259

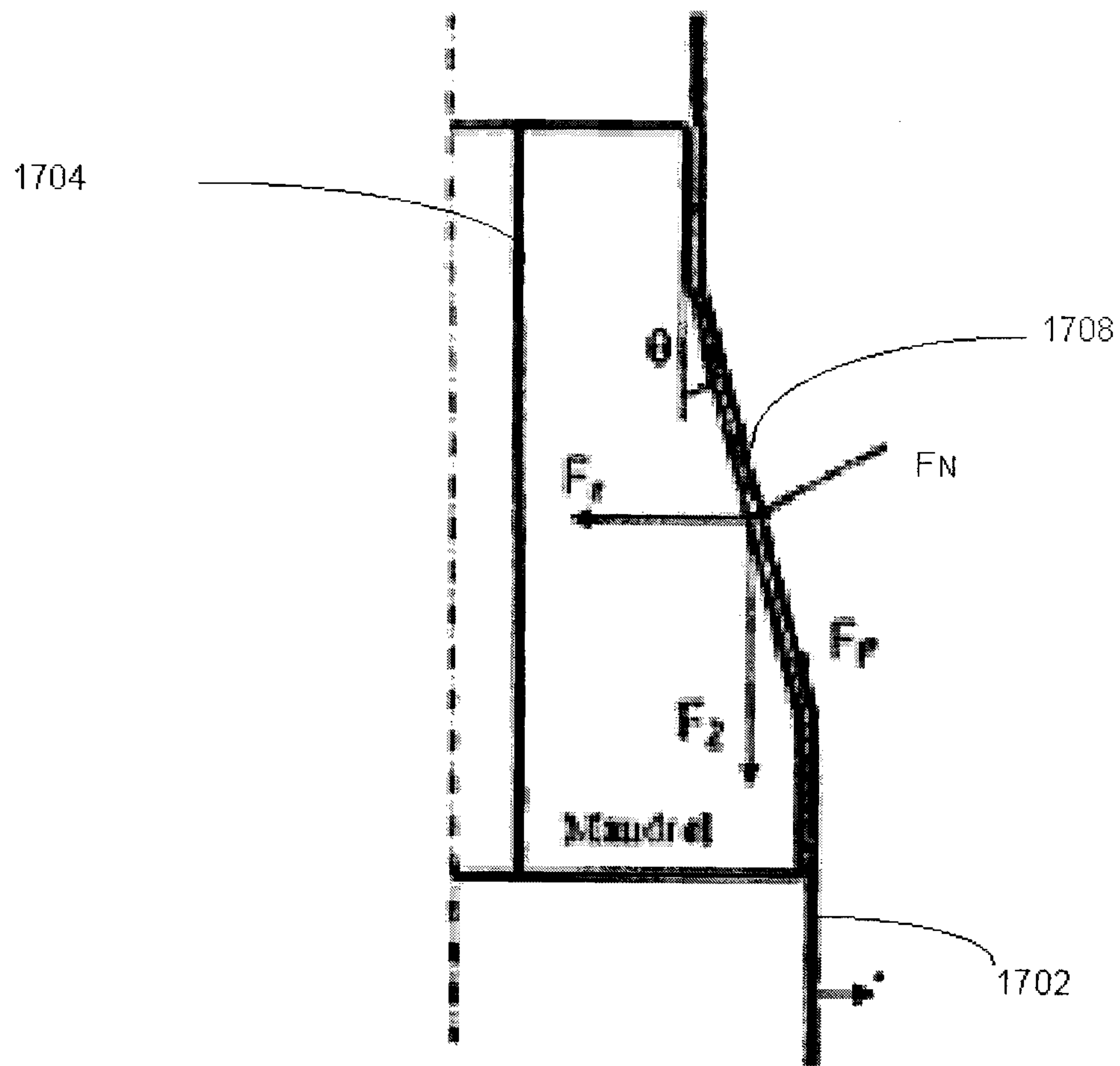


FIGURE 21

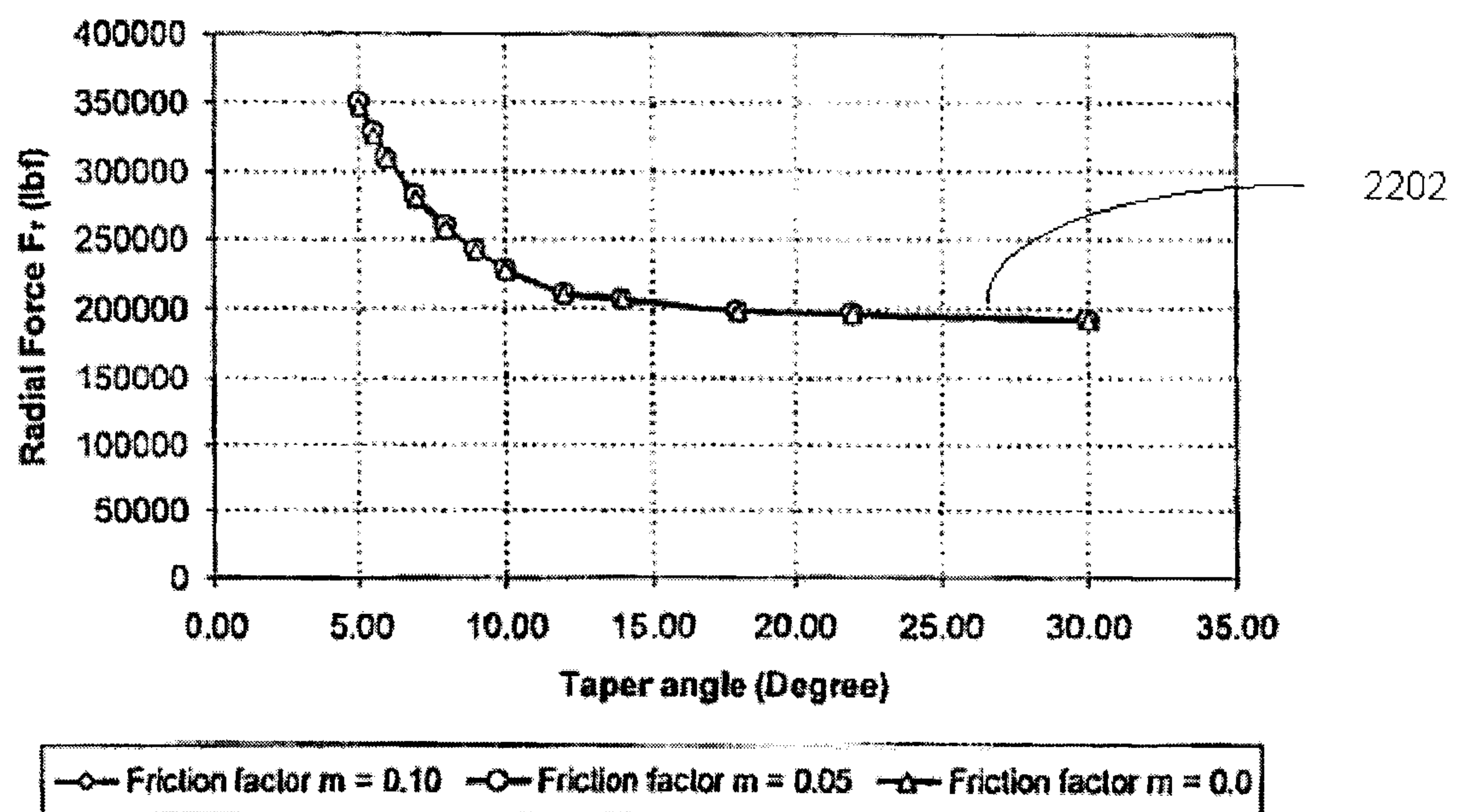


FIGURE 22

25791.259

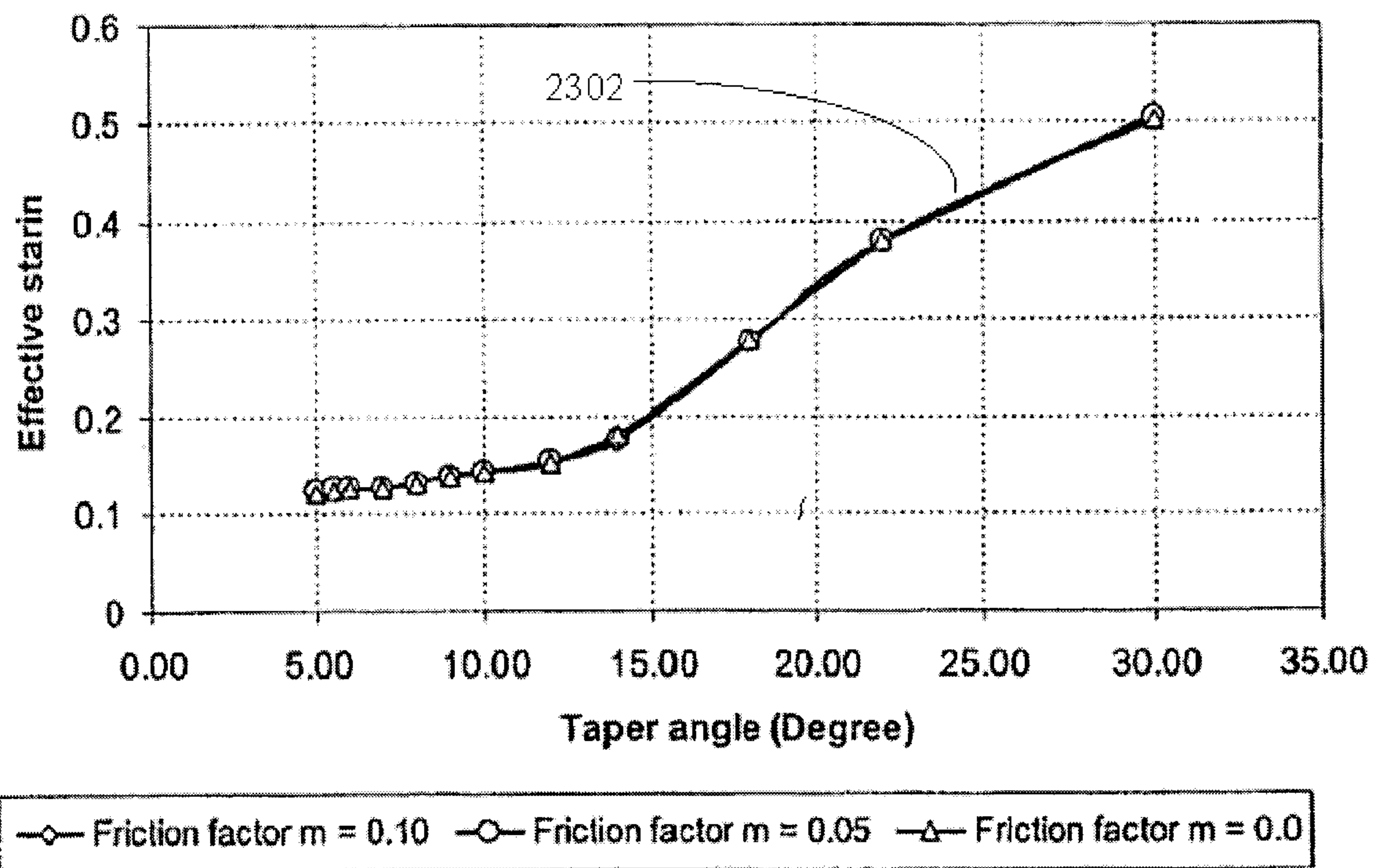


FIGURE 23

25791.259

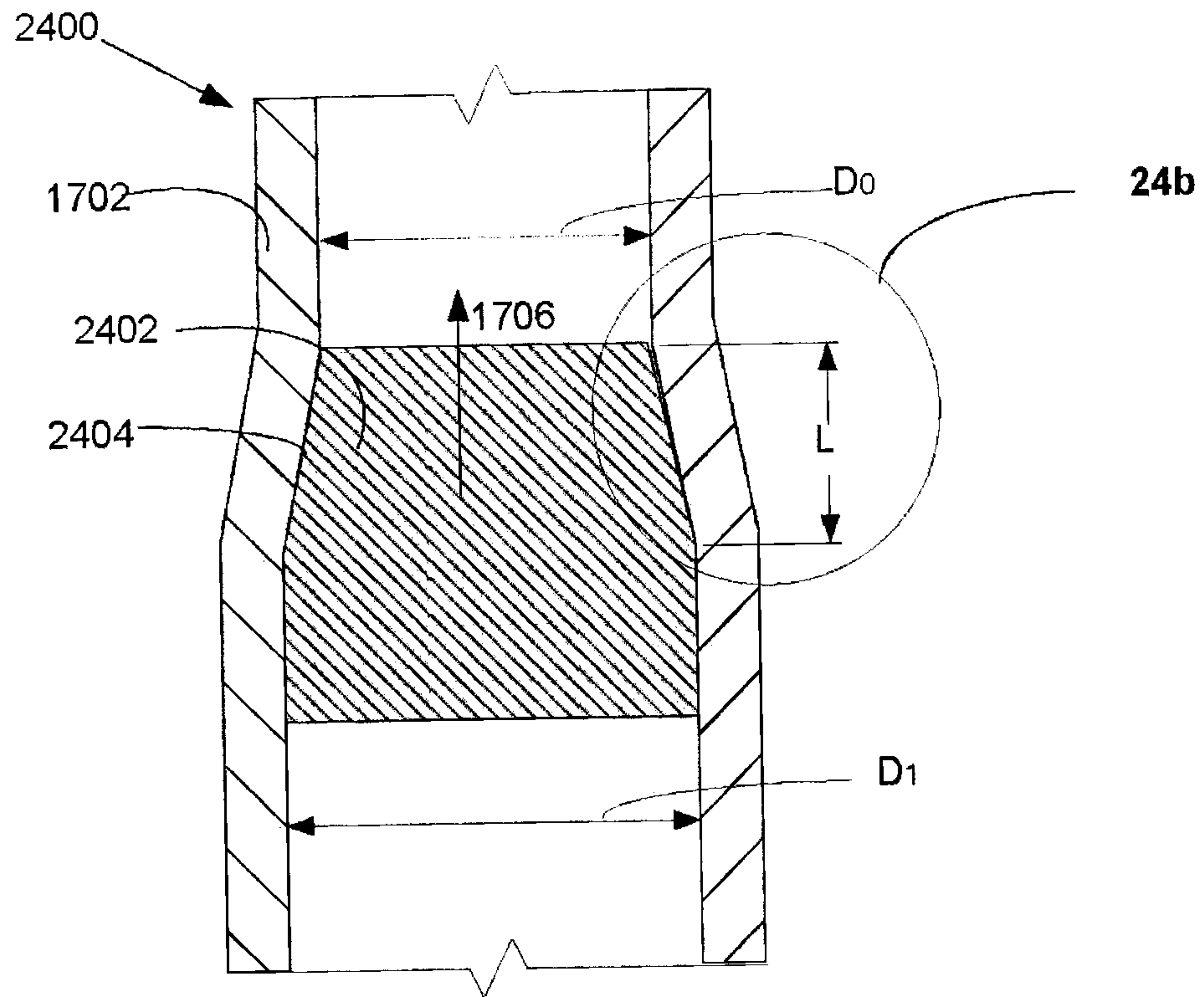


FIGURE 24a

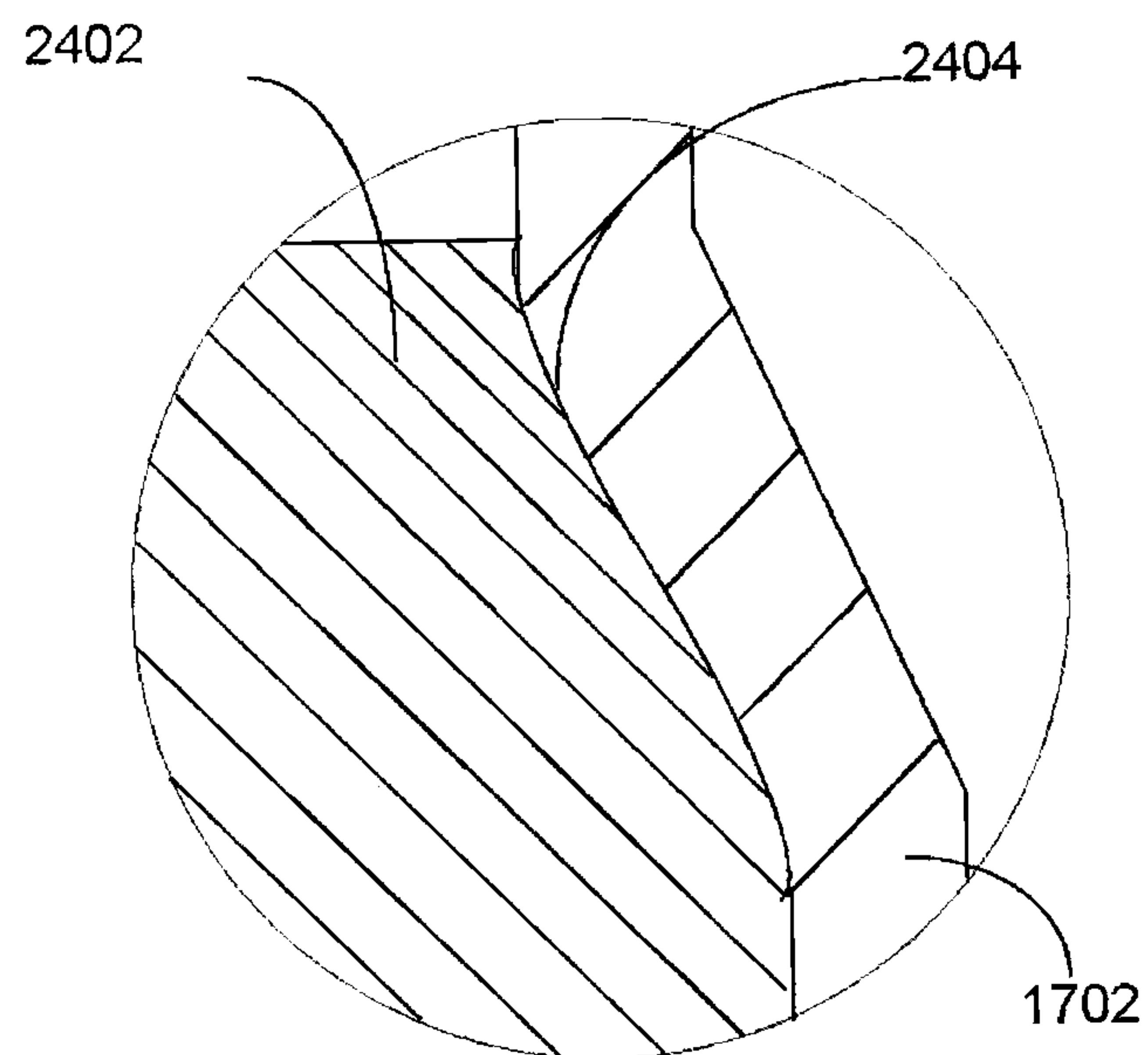


FIGURE 24b

25791.259

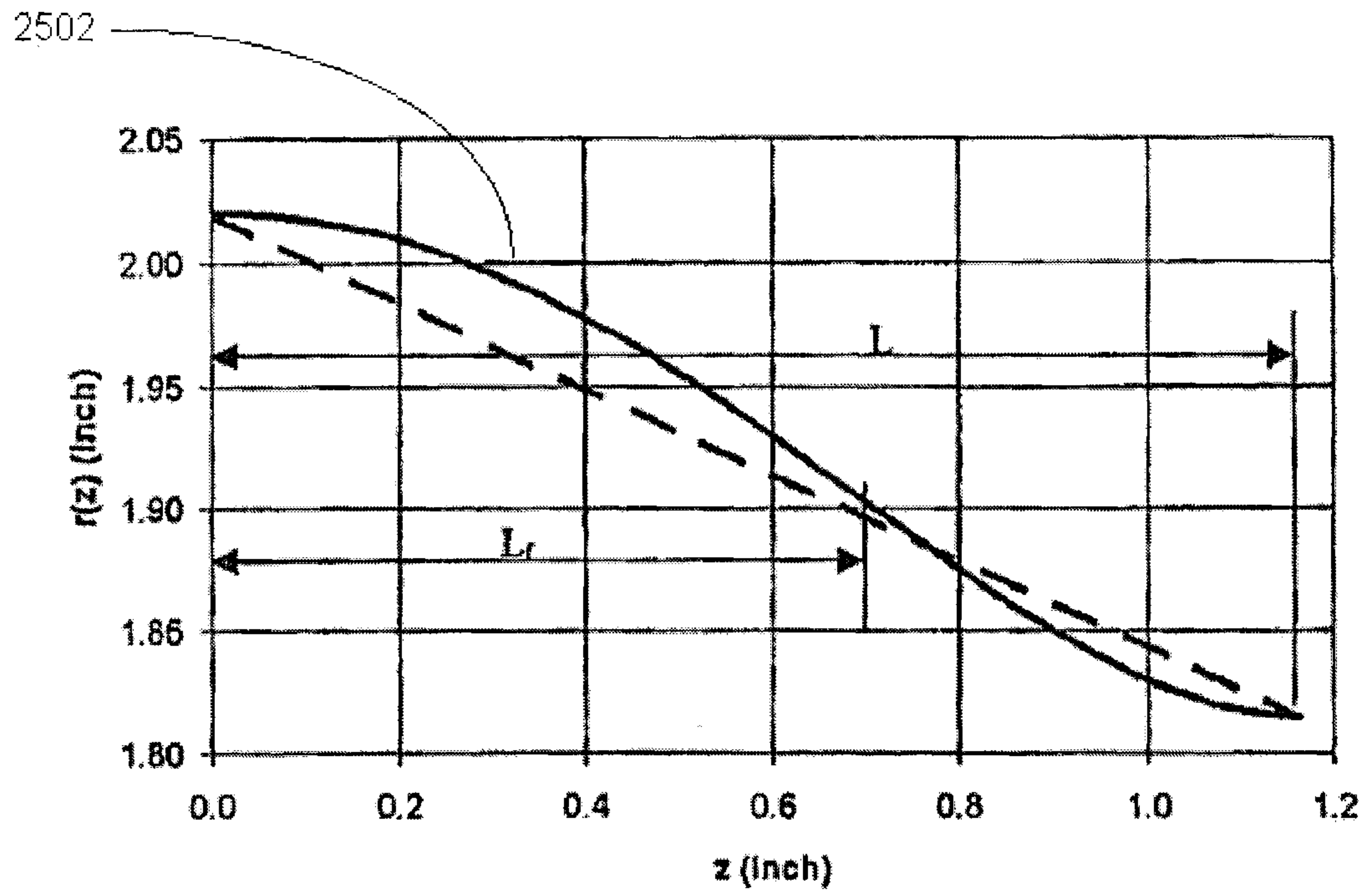


FIGURE 25

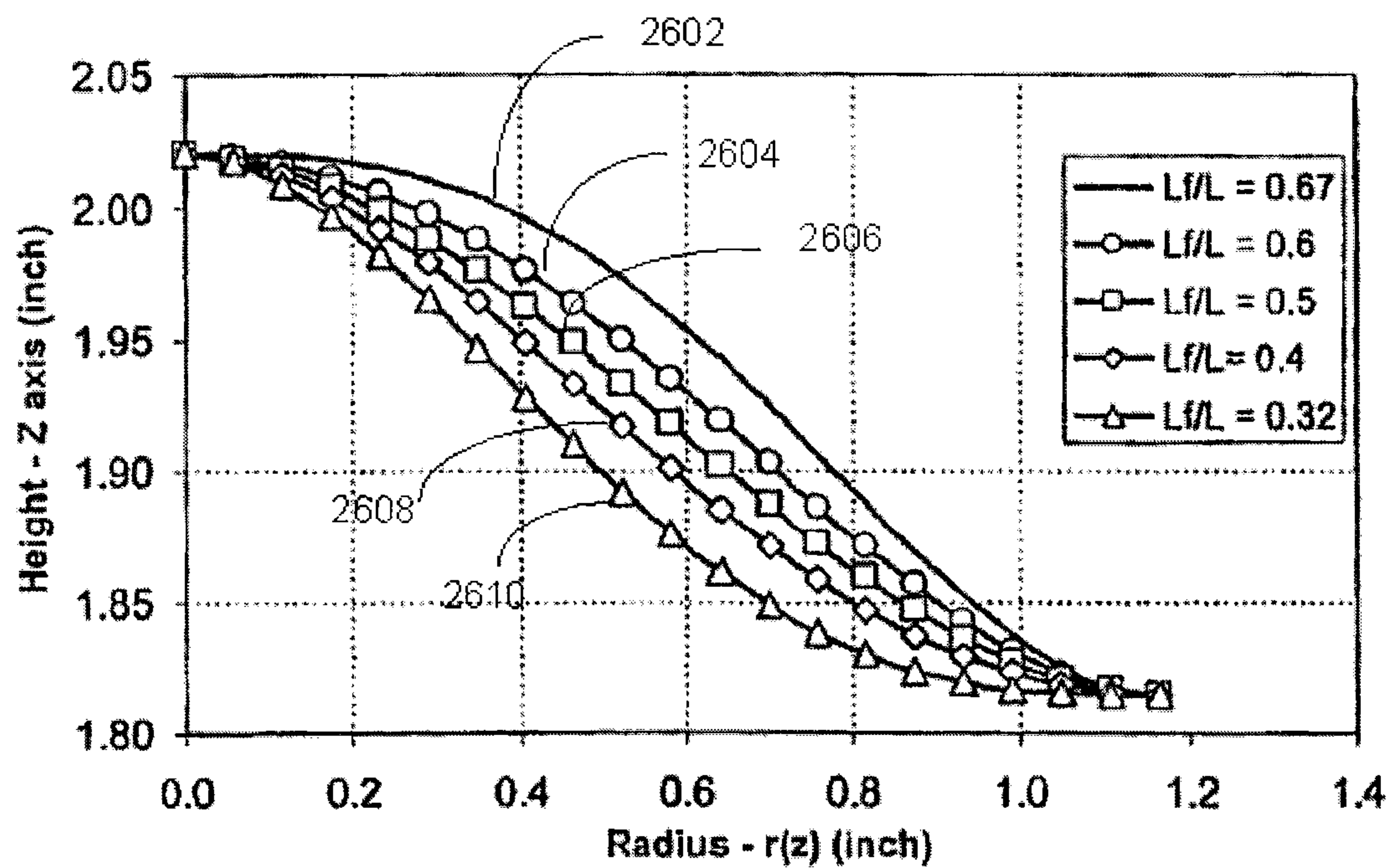


FIGURE 26

25791.259

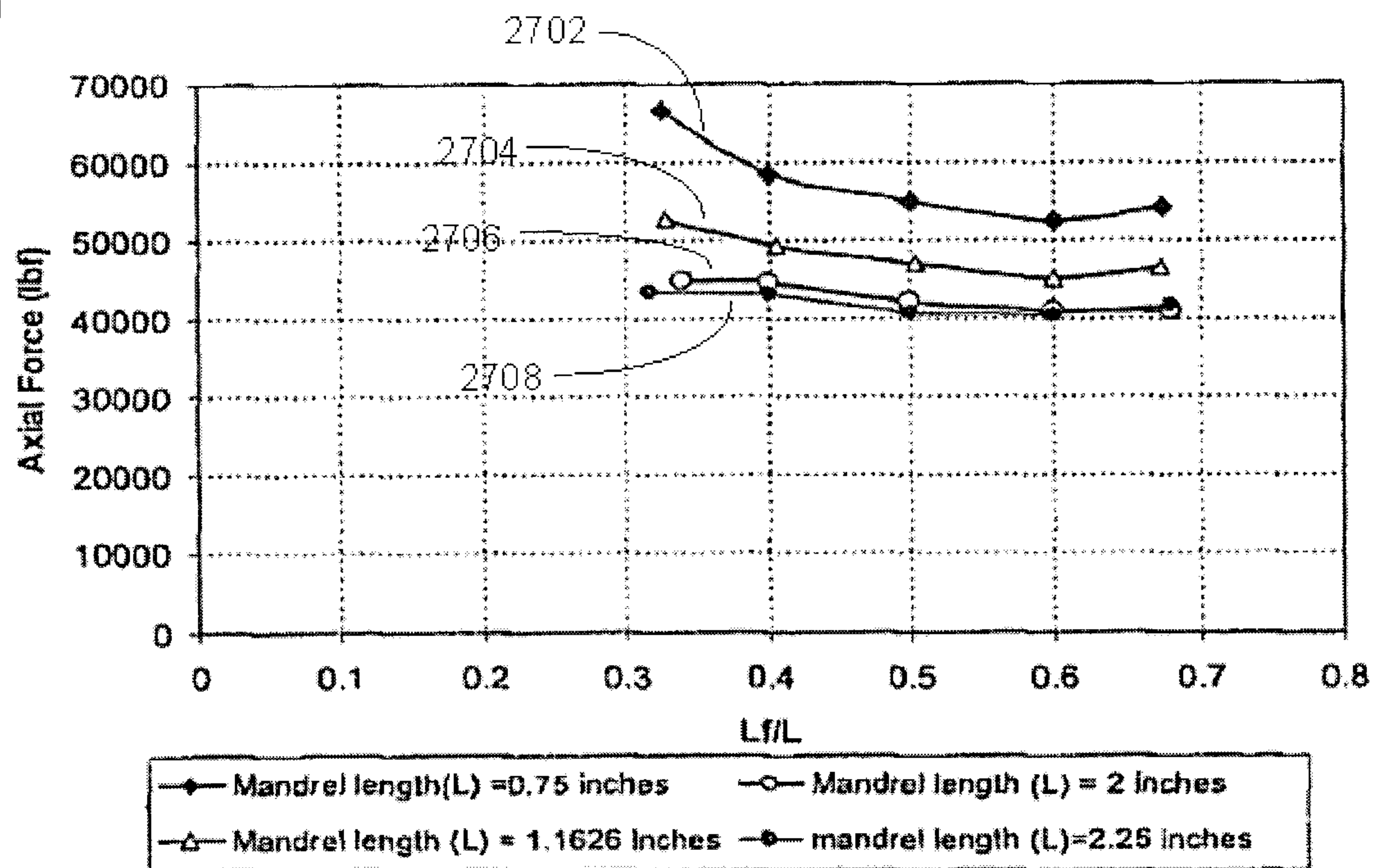


FIGURE 27

25791.259

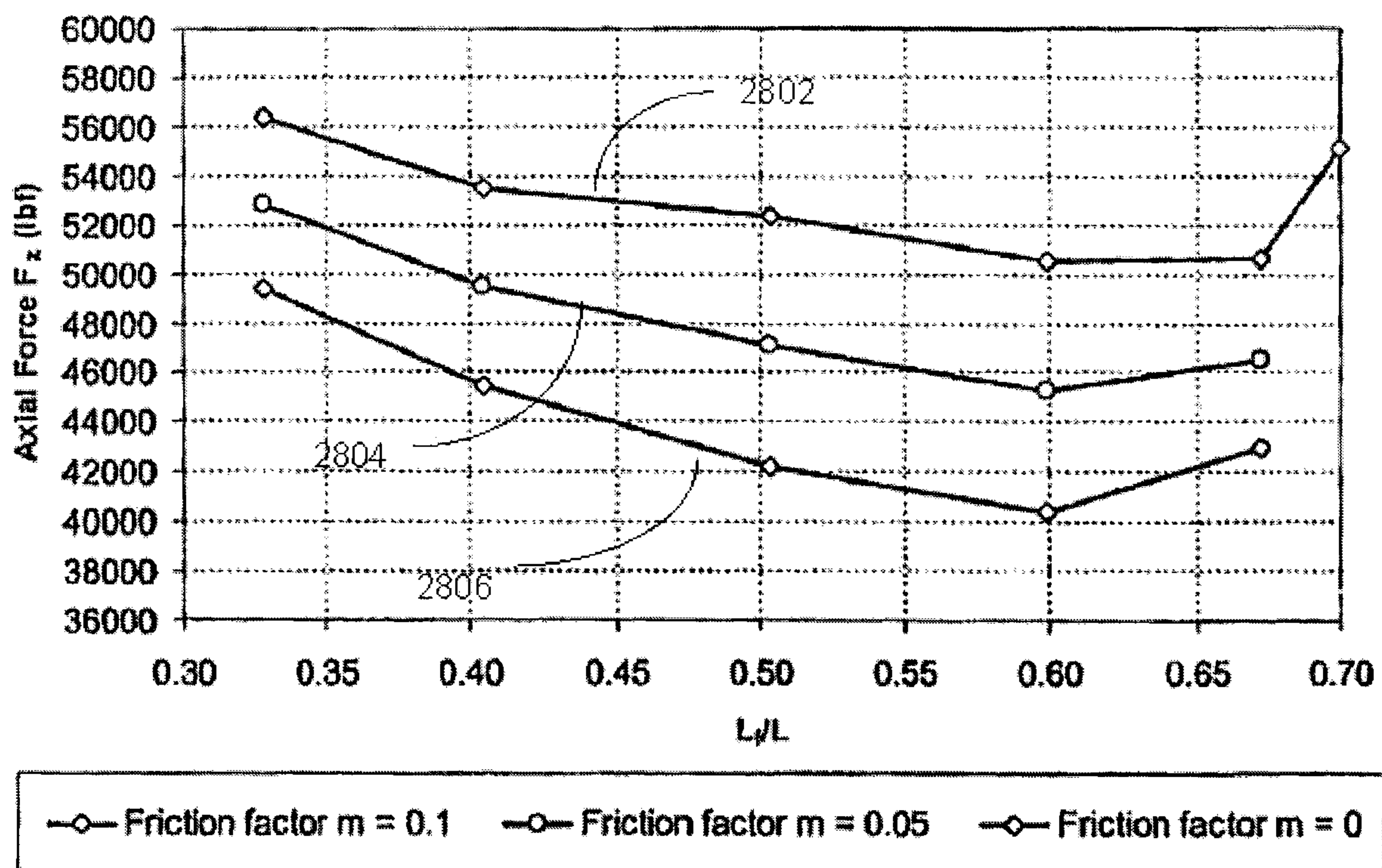


FIGURE 28

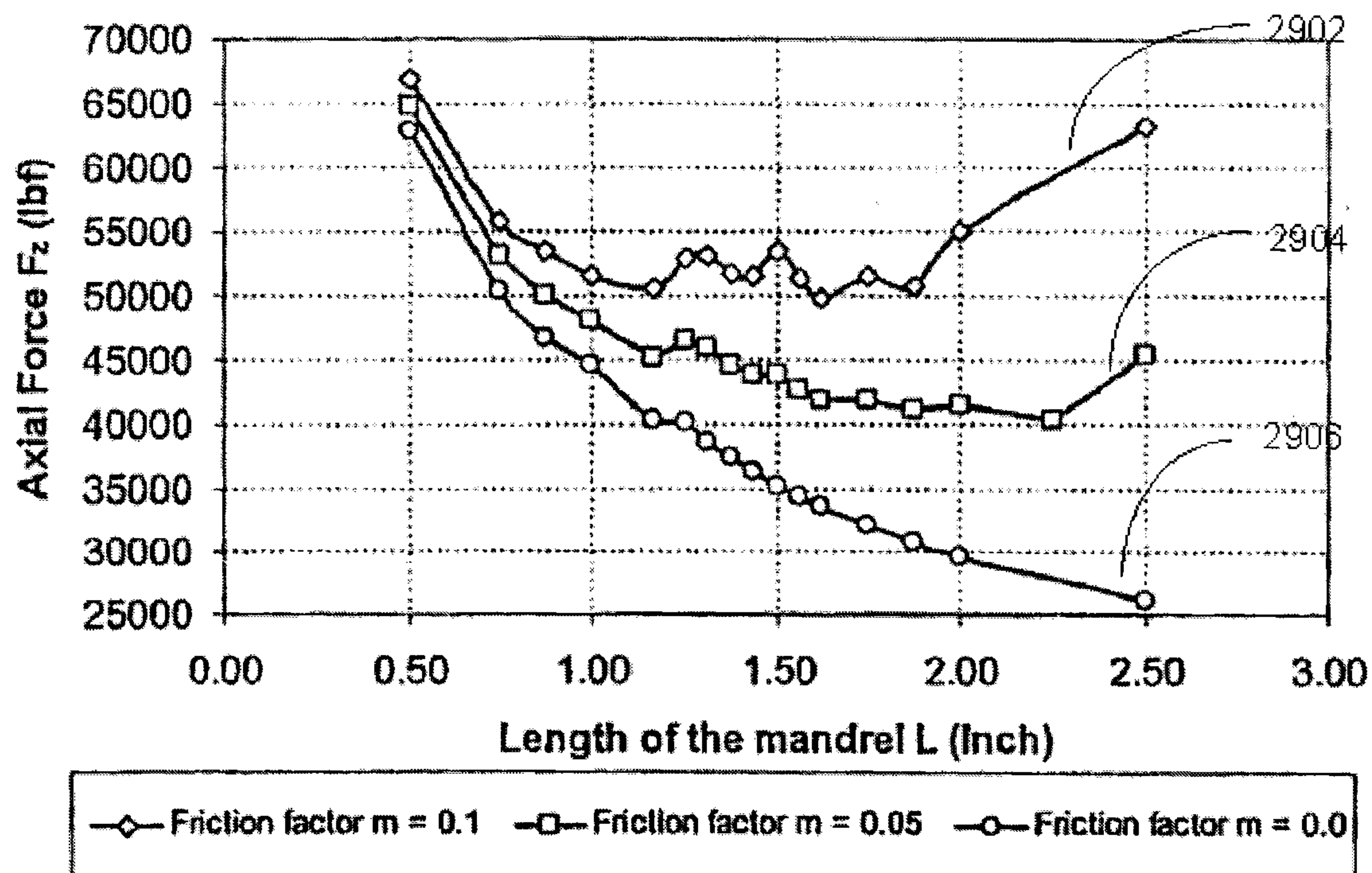


FIGURE 29

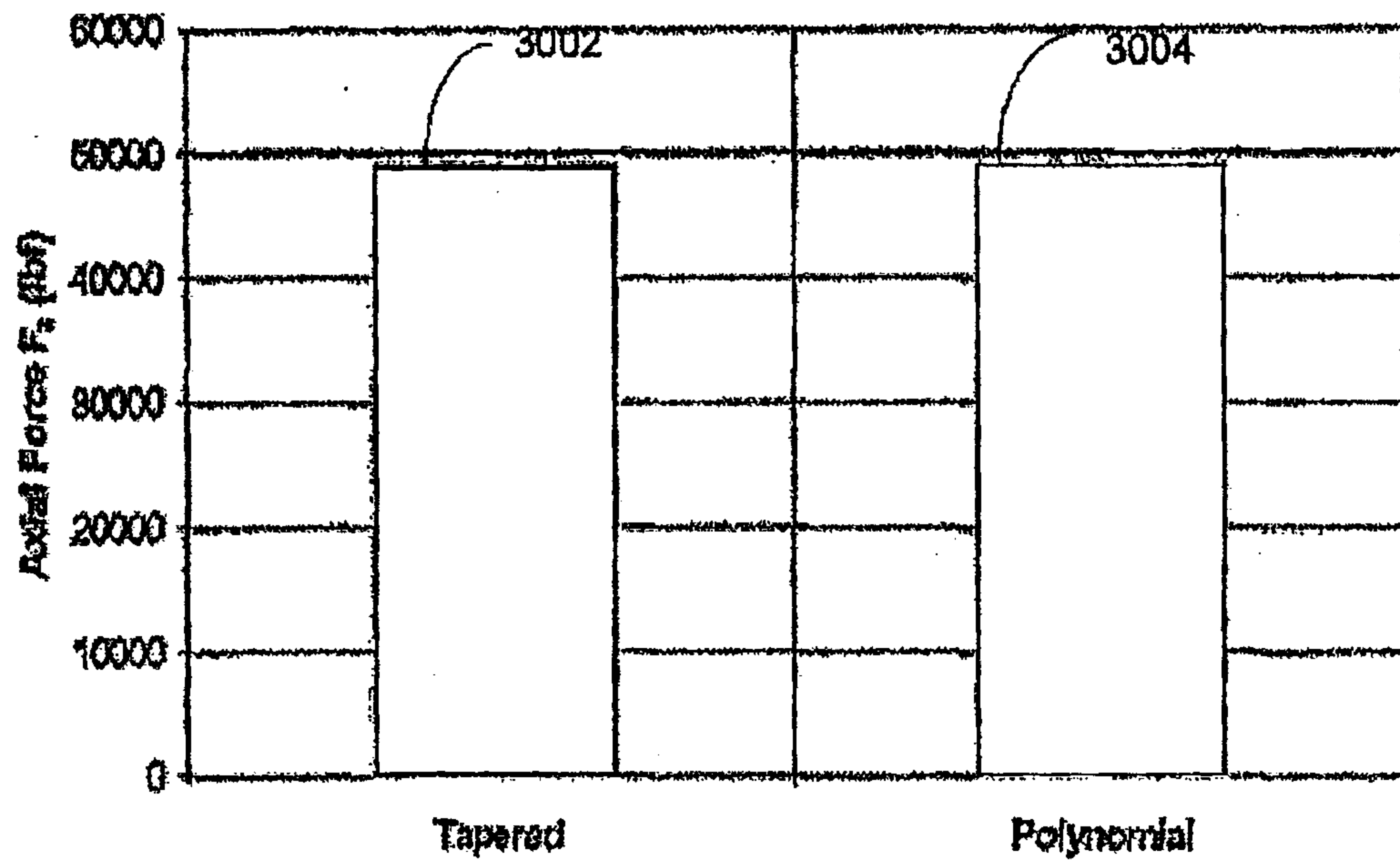


FIGURE 30

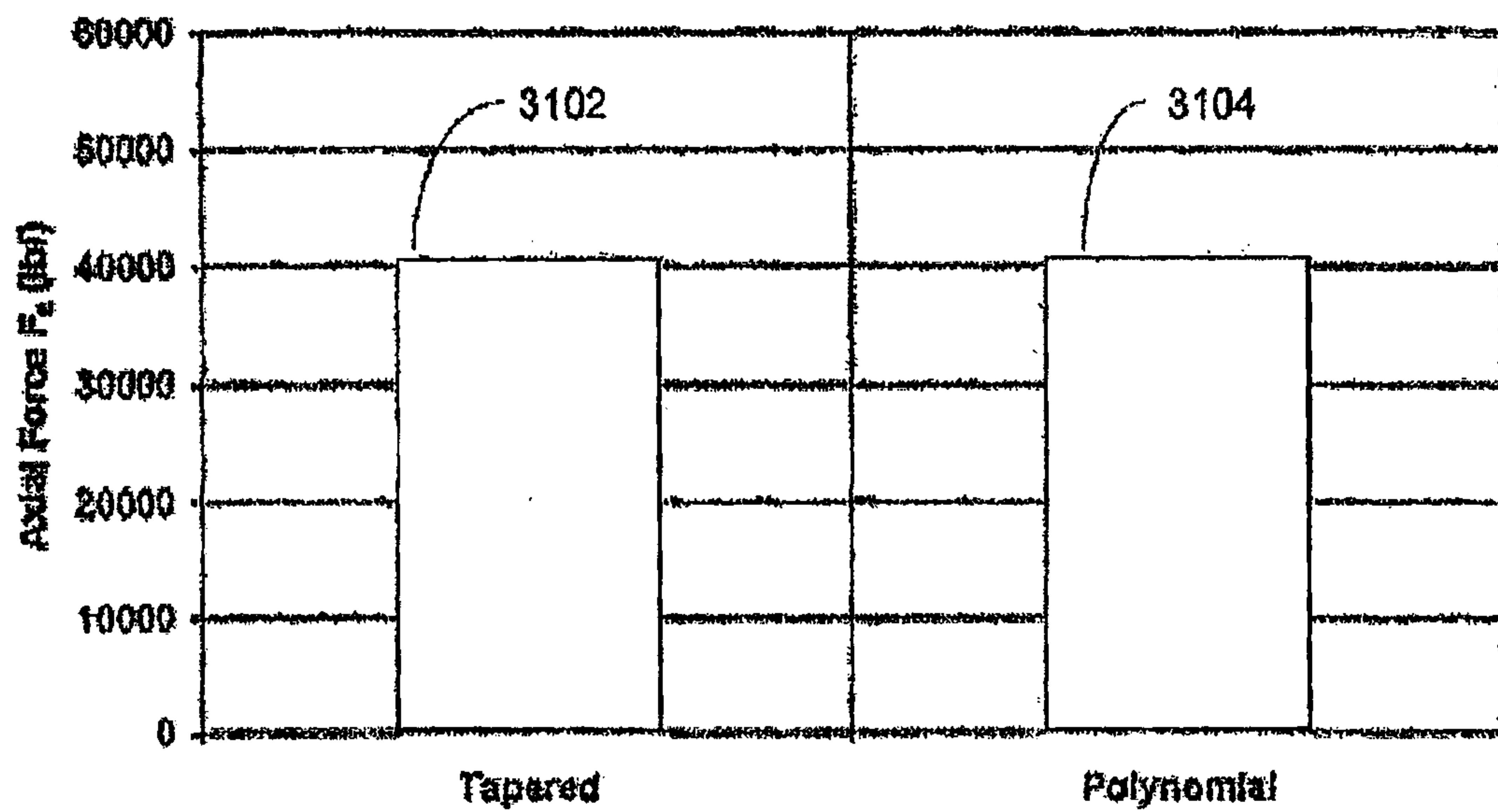


FIGURE 31

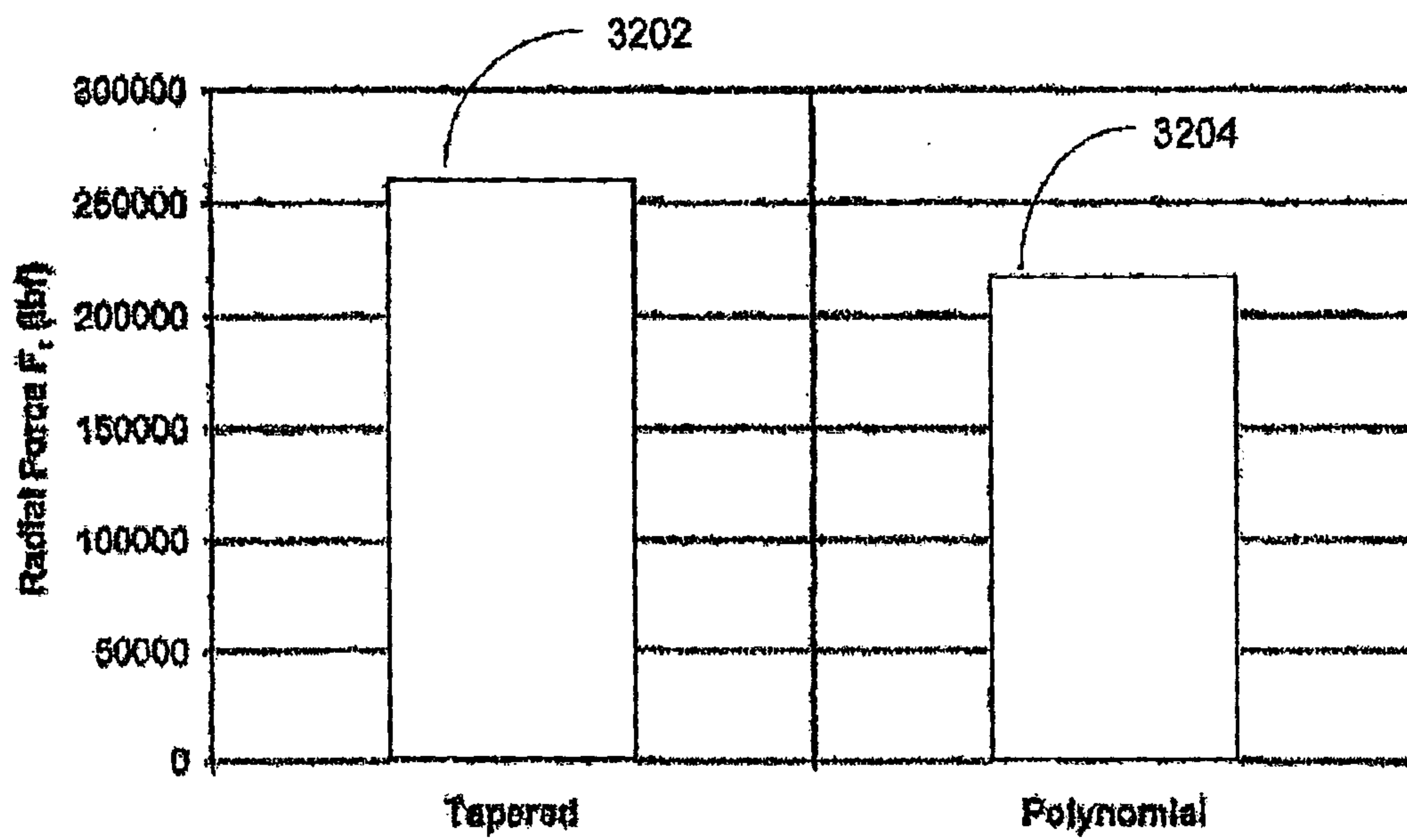


FIGURE 32

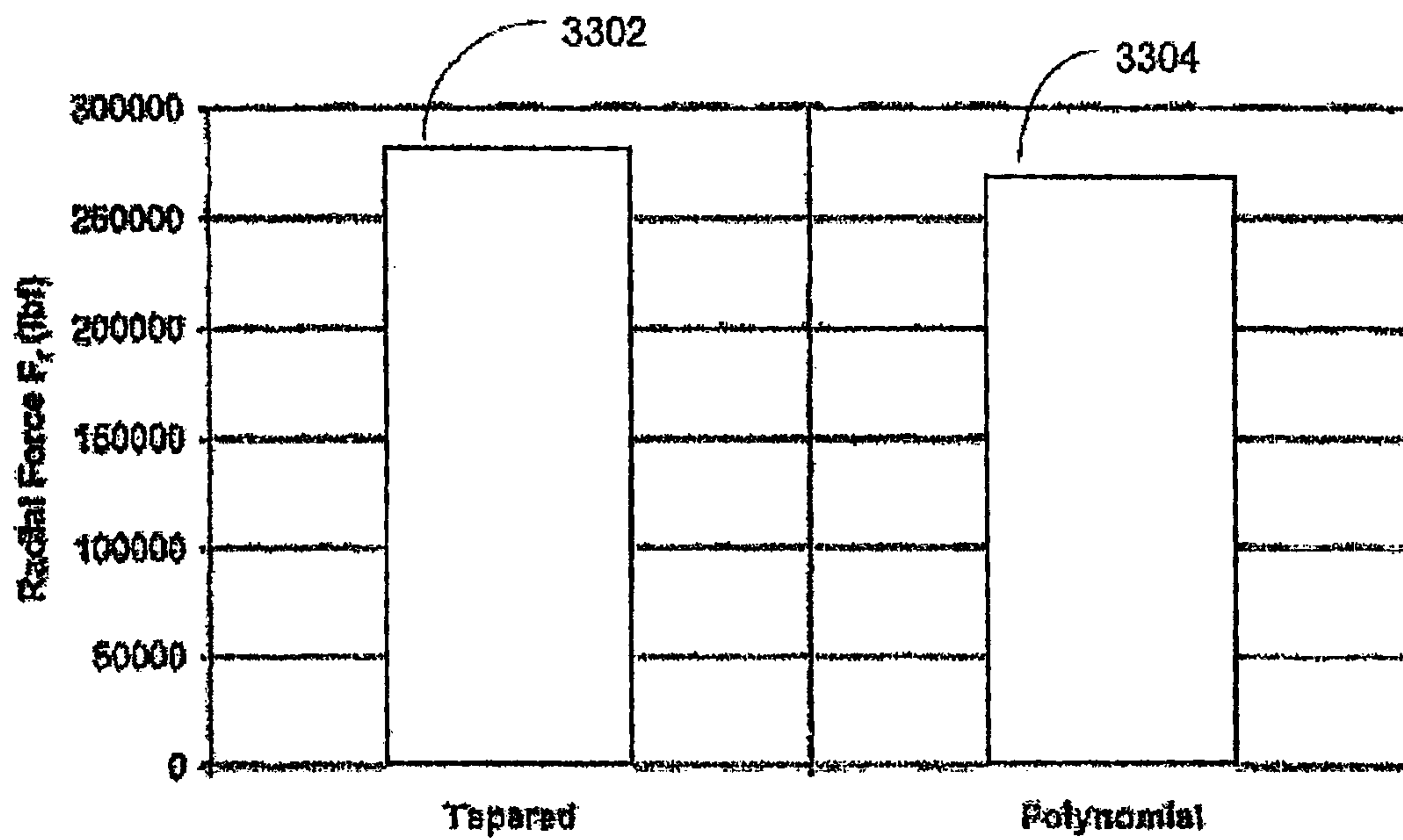


FIGURE 33

25791.259

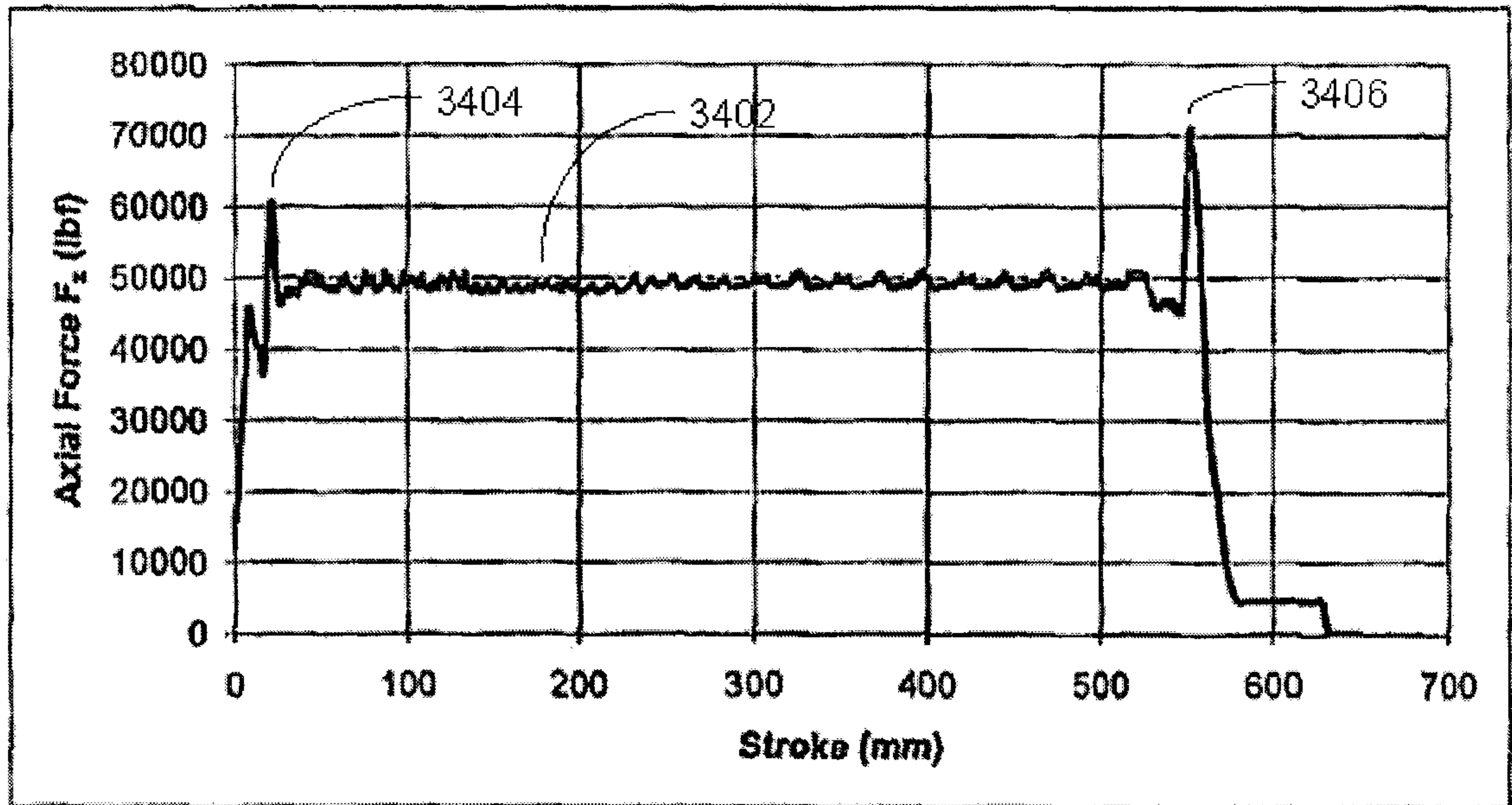


FIGURE 34

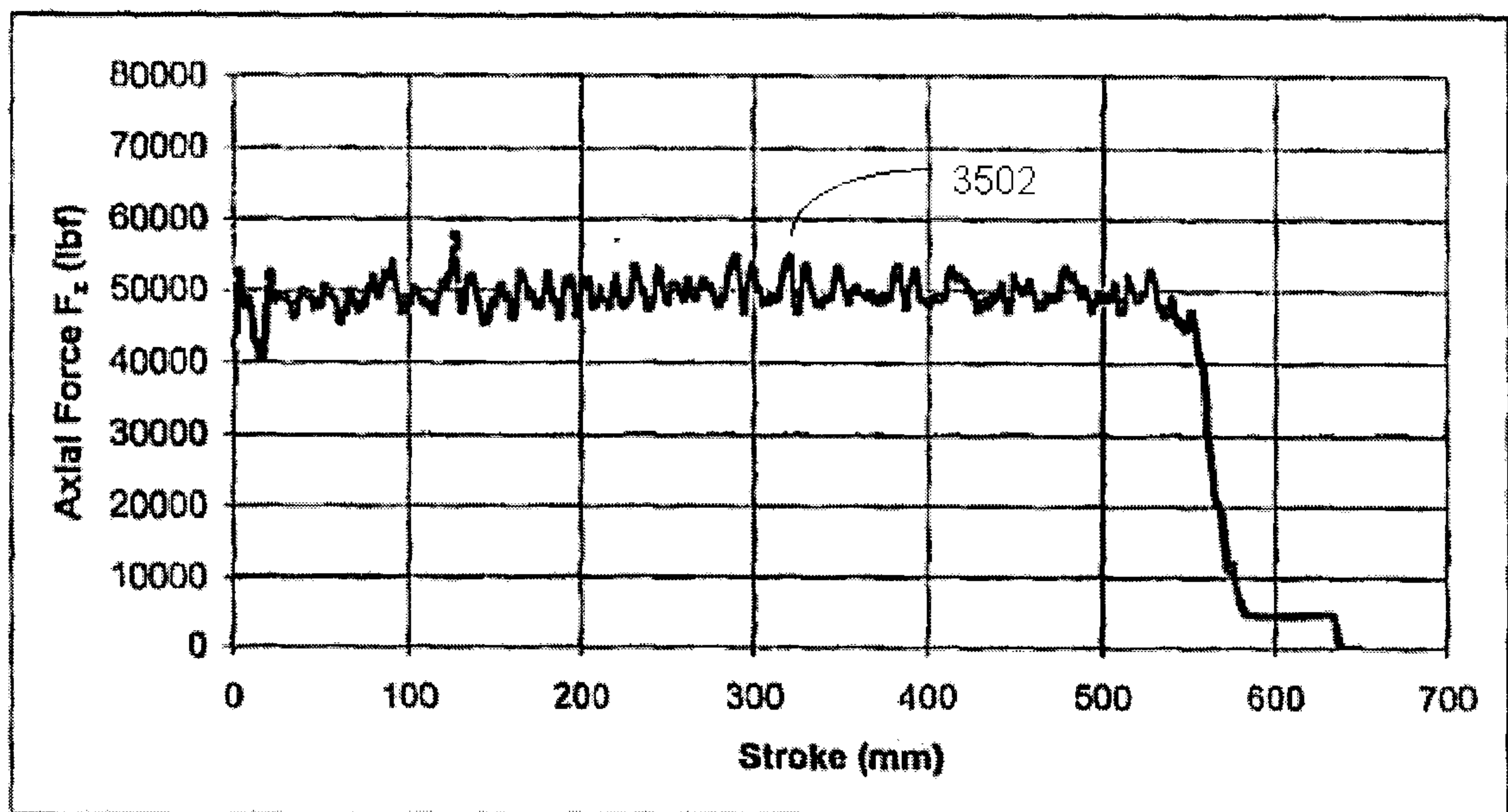


FIGURE 35

25791.259

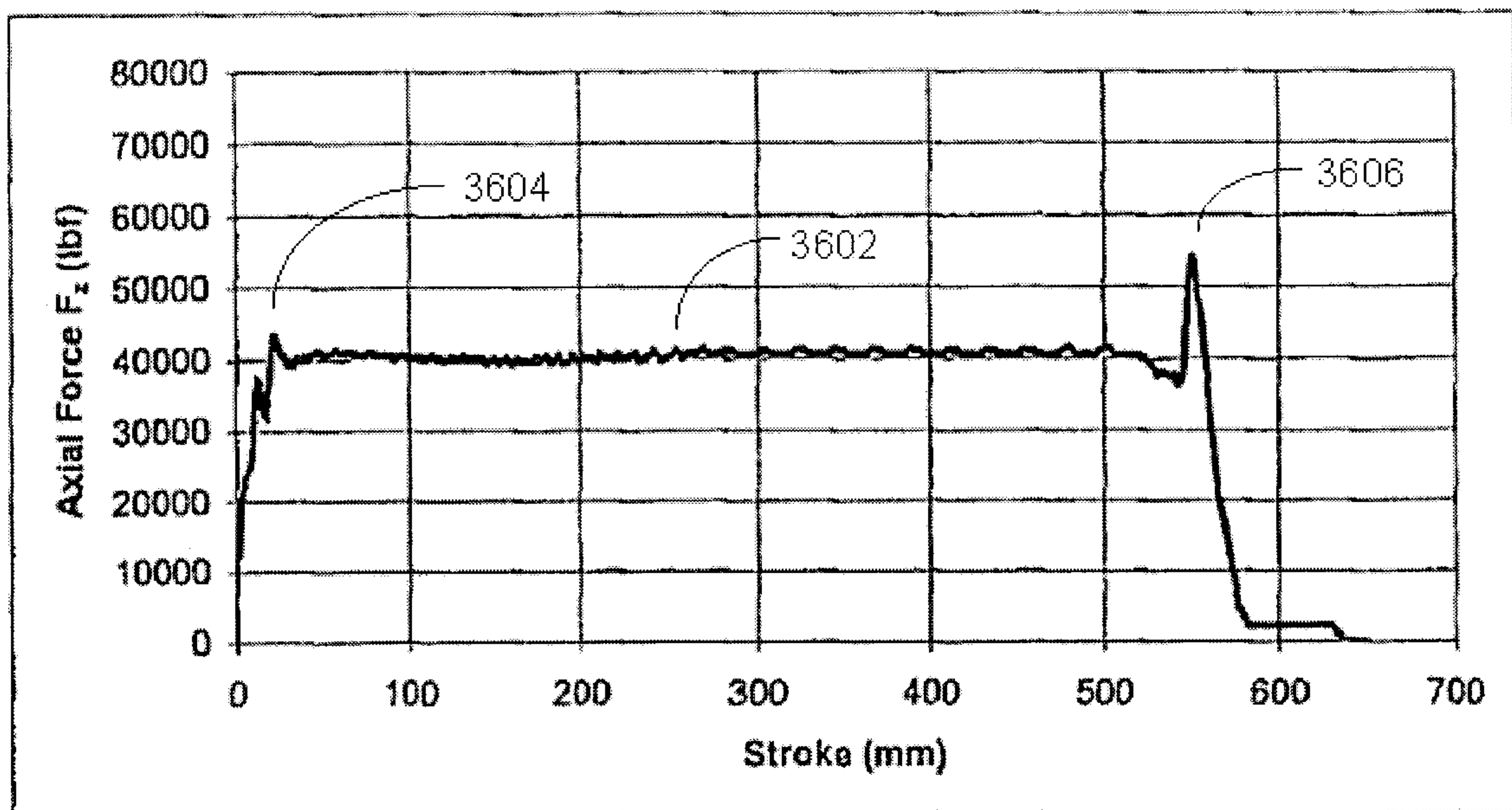


FIGURE 36

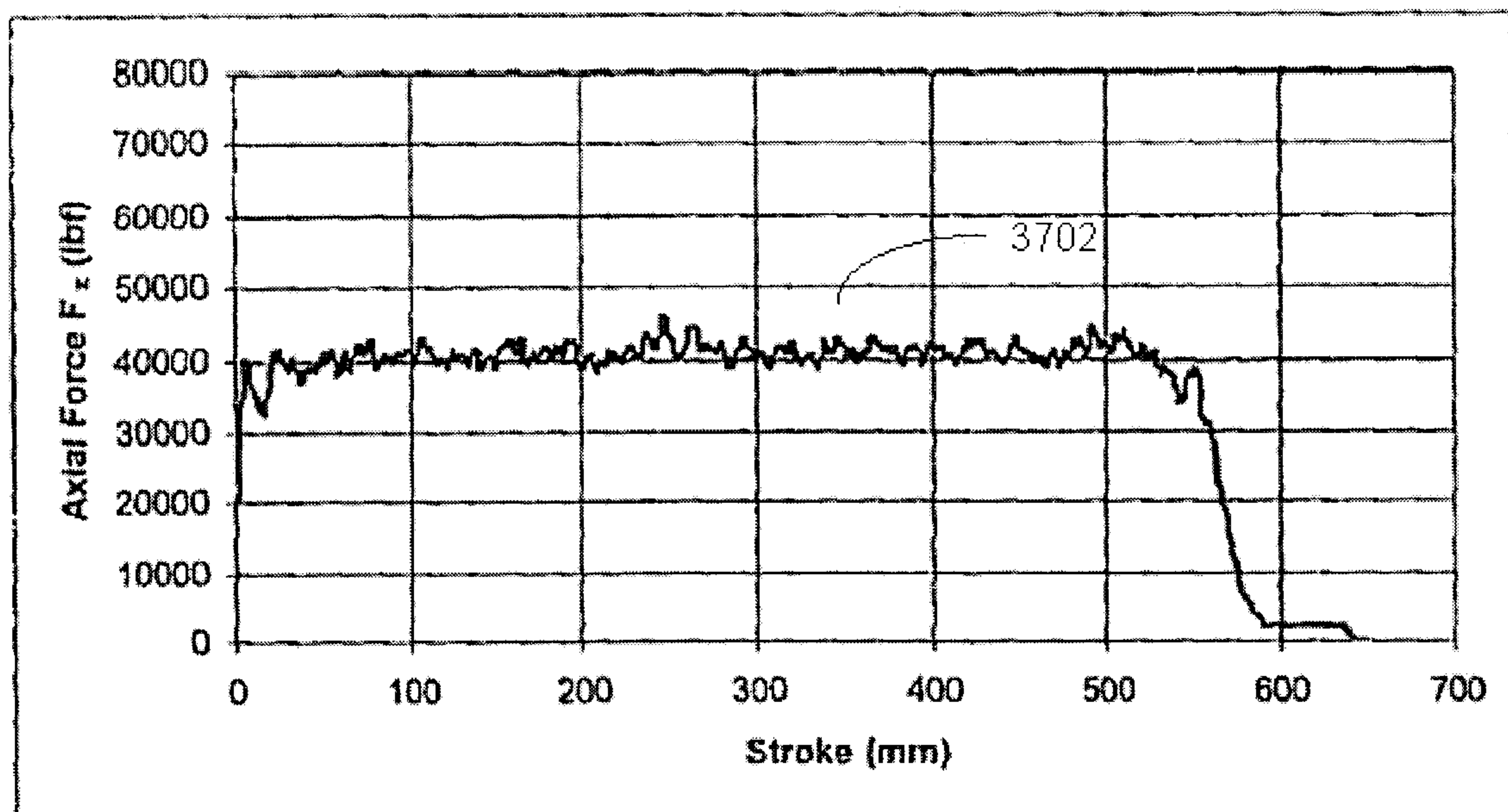


FIGURE 37

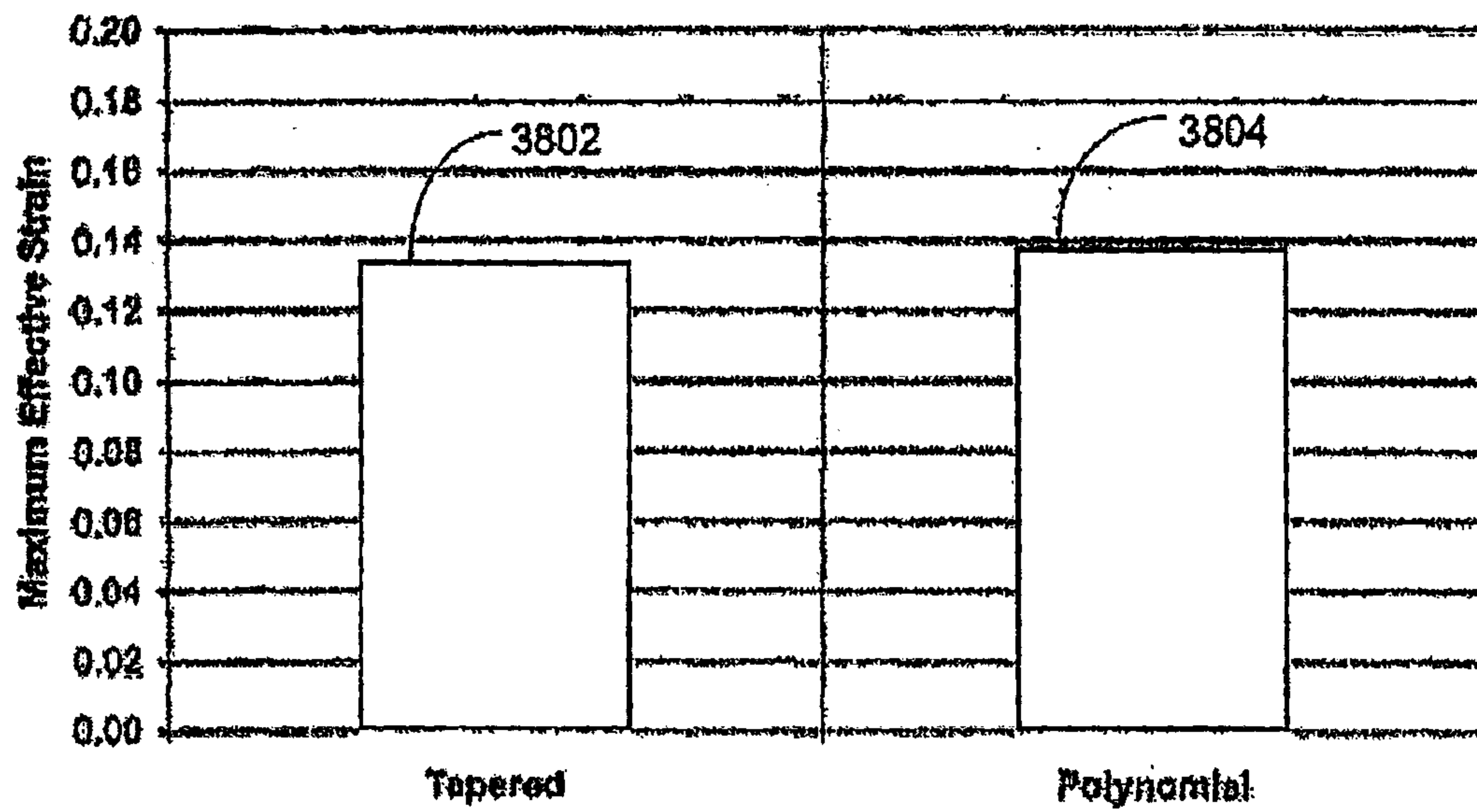


FIGURE 38

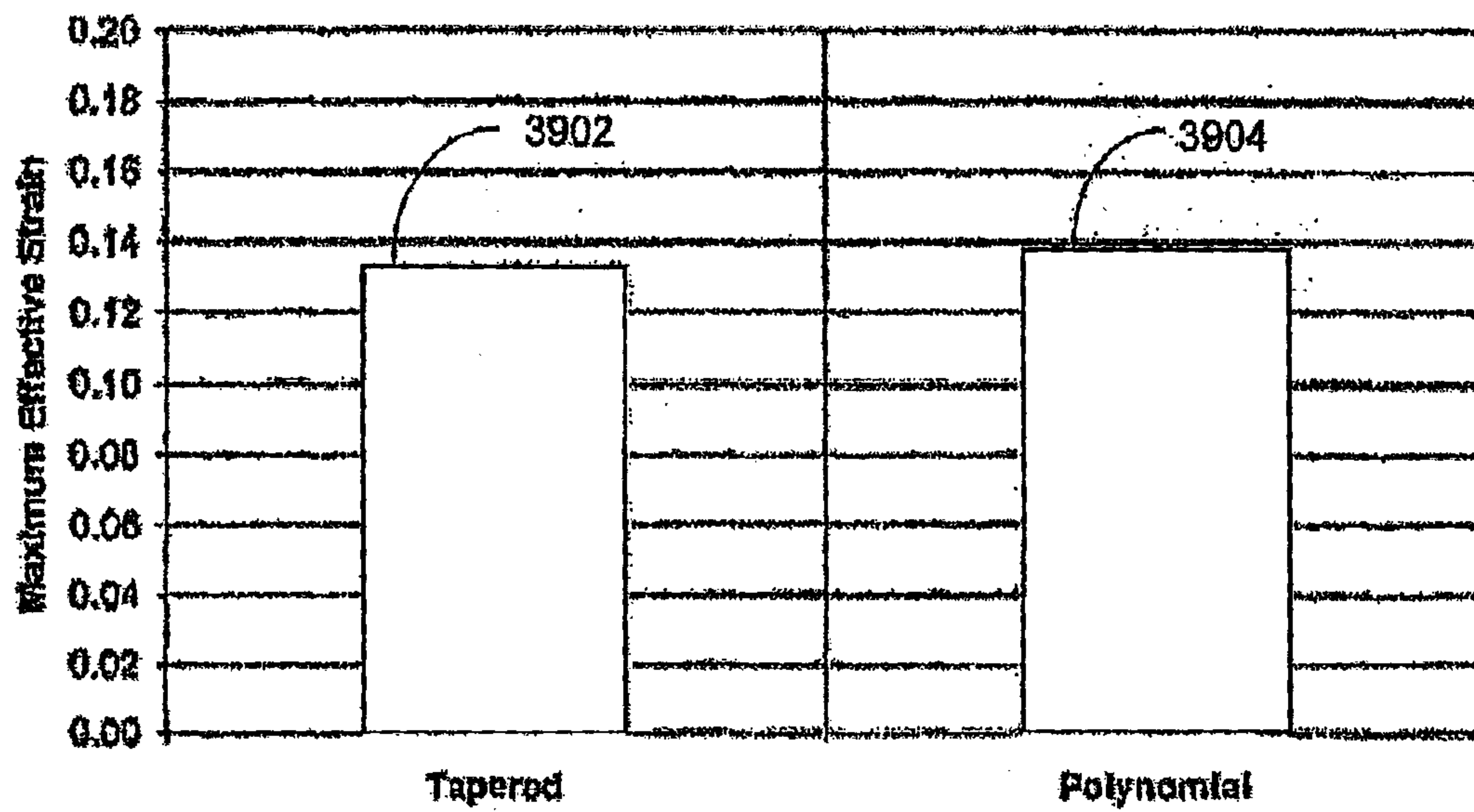


FIGURE 39

110

106

108

100

← 102

104

