Fermilab

SDC SOLENOID DESIGN NOTE 150

TITLE: Choice of Materials for Outer Vacuum Shell

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ABSTRACT:

Over the past two years we have looked at a variety of materials for the outer vacuum shell. We eliminated all but aluminum isogrid on the basis of calculations or an objective-subjective evaluation. We presently have a contract in place with PS Asociates, Inc. for the design of an aluminum isogrid shell.

In January of 1991, I (RF) made a list of every possible material I could think of which might be suitable for the outer shell. This design note gives essentially that list, with a paragraph about each item which gives some of the rationale for our not pursuing it further, except in the case of isogrid for which I give some of the reasons we chose it for more study.

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1. Aluminum Based Materials

1.1 Solid plate of uniform thickness

Using CGA-341 as the design standard, i.e. 30 psi collapse, with E = 10 Msi, the shell thickness t = 0.933", see DN-144.

Chuck Grozis obtained an estimate for a 1" thick aluminum shell, without end flanges from Halgo Field Services, Inc., an ASME Code shop in Irving, Texas. Using 6061-T6 alloy in 10' x 22' mill-run sheels, they estimated the material cost (at $2.18/pound) at $40k and the rolling and welding at $39k, for a total of $79k. With 4' x 12' sheets, their estimate is $96k. We believe this estimate to be low because neither a chimney nozzle nor machining the end to mate with the annular bulkhead is included. We recommend using $120k for comparison purposes.

The primary advantage to a solid shell is the low cost and high vacuum reliability. The main disadvantage is the thickness in radiation lengths, which for 22.5 mm (0.886") is 0.257 X_0 at 90°. (The radiation length of 6061 aluminum is 87.53 mm; SDC Solenoid DN-148.) We have not done anything more with this alternative; it is a fall-back technique if we have reliability or budget problems with the isogrid method.

1.2 Solid plate, aluminum alloy with E > 10 Msi

Early in the study we found an aluminum-beryllium alloy (Be-48%Al) called Lockalloy which has a modulus of 30 Msi, and a density of 2.09 g/cm^3. This alloy had been developed in the early 1960s for aerospace uses, but it is no longer commercially available. We did not consider it further and have not found any other aluminum alloys with modulus significantly above 10 Msi.

1.3 Solid plate, variable thickness for constant radiation thickness

This idea would have the greatest shell thickness at the axial center of the shell with the thickness decreasing either smoothly or in discrete steps toward the two ends. We have not investigated this possibility at all.

1.4 Solid plate with circumferential stiffening rings

The use of stiffening rings allows the shell to be thinner. CGA-341 gives equations for calculating the moment of inertia of metallic stiffening rings welded to the shell. This type of construction is commonly used for the vacuum shells of cryogenic storage tanks. For the SDC outer vacuum shell, however, the ring(s) would have to be so large in cross section that there would be a significant local increase in radiation thickness at the angle corresponding to the location of the rings.

I also thought of making the shell from aluminum extrusions. The idea would be to start with an extrusion 8-10'' wide by 42' long, which had ribs running lengthwise. This would be rolled into a one-piece, short cylinder. The short cylinders would be slid on a fixture and welded circumferentially. Figure 1 shows how the aluminum thickness penetrated by a particle from the origin varies as the angle with the collider beam. The dimensions of the vacuum shell in Fig. 1 are those of an early coil design, but the basic pattern is representative of this type of construction.

The non-smooth variation of thickness with angle for a shell with stiffeners is, in general, a disadvantage although many small stiffeners is better than a few large ones. Although we did not investigate how wide the extrusion might we, we discarded the idea of using extrusions because of the amount of welding required. We did not like the size of stiffeners required for the more conventional case and so rejected that method also.

1.5 Aluminum casting

We have not investigated this technique. A cast aluminum shell would have about the same thickness as one made of rolled plate. It might be cheaper to fabricate a quarter-length (7.5') cylinder by this method than by rolling and welding. It is hard to conceive of a mold 30 feet long to cast the shell in one piece.

1.6 Solid plate, aluminum metal-matrix composite

I got this idea from an article in the November, 1990 issue of *R&D Magazine*. The modulus is given for three metal-matrix composites under development at Toyota and Los Alamos. Toyota is working on an aluminum composite with silicon carbide or carbon filaments. The magazine article quotes a modulus of 22 Msi for 2024Al-61% SiC and 26 Msi for 2024Al-70%C. Los Alamos has reached a modulus of 63 Msi for $MoSi_2$-20%SiC, which has a density about twice that of aluminum. I made several attempts to contact the researcher at LANL, but was unsuccessful and did not pursue this idea further. Surely these materials are either not available as large plates or are very expensive (or both).

1.7 Vacuum brazed, perforated aluminum sheets

Lockhart Industries, Inc., located in Paramount, California (Los Angeles area), makes vacuum brazed aluminum heat exchanger panels. Chuck Grozis visited them on two occassions, the second time I went with him. They could make a sort of honeycomb panel by brazing hexagonally perforated aluminum sheets between solid aluminum face sheets (see Fig. 2). The advantage of this technique is that the resulting honeycomb is all metal, in fact the bond between the core and face sheets is a diffusion bond (the brazing temperature is close to the aluminum melting point); it cannot be "unsoldered" by applying heat. This means that vacuum brazed panels can be welded to each other.

This method appears to be quite costly since the core-face sheet sandwich is assembled by hand and since the vacuum brazing oven can take only relatively small pieces (30 x 110 inches). Engineers at Lockhart said they had produced small such panels with a density about 25% that of bulk aluminum.

Lockhart sent us an unsolicited proposal to design panels for our use and to produce five verification panels, the cost was $290k. They also estimated the cost of enough panels to make the full-size shell to be $1.1M. We took no action on this proposal because the development and fabrication costs of the brazed panels seemed high. The small panel size would also require much welding of formed panels to make the shell, and correspondingly high welding costs.

1.8 Epoxy-bonded aluminum honeycomb

This was the first "exotic" material we considered seriously. Akira Yamamoto (KEK) used this type of material for his balloon-borne superconducting solenoid. The aluminum honeycomb core is adhesive bonded to two face sheets. When making flat panels, the sandwich of core and face sheets is compressed in a fixture and cured at 250-300°F in an oven or autoclave.

Hexcel Corp. has been a source of honeycomb and honeycomb structures for 25 years or more. They publish several design guides for honeycomb panels. When we contacted them, they expressed no interest in our one-of-a-kind job. Nordam Corp. in Tulsa, Oklahoma, was interested and had, or had access to, an oven large enough to cure the entire SDC shell.

Chuck Grozis and I visited Plascore in Zeeland, Michigan and talked with them about the design the fabrication of our shell. A very preliminary calculation suggested that a honeycomb shell 1.25" thick, with 0.060 face sheets, and a 1/8" x 0.003 cell size might have a collapse pressure of 30 psi-external. They proposed laying up the shell on an inexpensive mandrel and curing the epoxy at room temperature. They gave us a rough cost of $100k for our shell. The thickness of aluminum through which a reaction particle passes as a function of angle for a honeycomb was approximated as thin stiffening rings very close together. The thickness of a honeycomb shell traversed by an exiting particle is shown in Fig. 3.

Our worries about this type of shell are: (1) end termination to the annular bulkhead, (2) vacuum leak tightness, (3) structural reliability of a shell cured at room temperature without much radial pressure, (4) the repairability in the event of a vacuum leak. As a result of these worries, we have not continued work on bonded aluminum honeycomb.

1.9 Integrally machined aluminum plate--isogrid

At this writing, we are concentrating all our efforts on this method. I will write a separate design note giving the story of our study, suffice it to say here that we favor this all-metal type of construction because we perceive it to be more predictible and reliable than any of the methods which use epoxy. A welded aluminum structure will also be less likely to suffer radiation damage.

2. Titanium Based Materials

2.1 Solid plate, 6Al-4V alloy

As shown in SDC Solenoid Design Note #126, the modulus and radiation length of titanium alloy combine to give a figure of merit of 0.5, compared to aluminum. This means that a solid titanium shell would be twice as thick, in radiation lengths, as a solid aluminum shell. A shell made of titanium would also be much more expensive than an aluminum one because of the higher cost of titanium plate and the higher machining and welding costs. For the SDC solenoid vacuum shell there is nothing to be gained from using solid titanium and so it was dropped from further consideration.

2.2 Brazed honeycomb

We contacted Eldim, Inc., located in Woburn, Massachusetts, which is a company speciallizing in brazed stainless and titanium honeycombs. They use titanium alloy 6.2.4.2 (Ti-6Al-2Sn-4Zr-2Mo). One of their titanium honeycombs is shown in Fig. 4. Eldim sent us an ROM estimate of $735k for the design, prototyping and fabrication of the SDC vacuum shell. We dropped this idea because of the radiation thickness issue.

3. Stainless Steel Materials

A shell made of solid stainless plate would be three times as thick in radiation lengths as one made of solid aluminum plate, see SDC Solenoid DN-126. Although we discussed stainless honeycomb with Eldim, Inc., we quickly dropped stainless materials from consideration.

4. Magnesium and Magnesium Alloys

Magnesium has a modulus of 6 Msi and a radiation length of 145 mm (M.A. Green, LBL Report M5009, 1976). A shell made of magnesium plate would be 30% thinner in radiation lengths than one made of aluminum plate. However, we did not investigate these materials, since we thought the plate would be more expensive and more difficult to machine than aluminum.

5. Foamed Materials

5.1 Flat sheets, formed into cylinder

I briefly investigated Rohacell foam, which has been used at Fermilab for the vacuum vessels of some liquid hydrogen targets. Rohacell is available in 4' x 8' sheets, which can be thermoformed. The modulus of the thermoformable sheets is 22.7 ksi for type 110IG, which has a density of 10.6 lbs/cu.ft. A 160-inch diameter by 360-inch long shell would have to have a wall thickness of 10.65'' to satisfy the CGA standard (30 psi collapse). This wall thickness is unacceptable since the total annular thickness of the magnet cryostat is 12'' and therefore I did not study fabrication details.

5.2 Foamed in place shell

My idea here was to pour a foaming material into the annulus between two aluminum tubes. The material would foam and harden in place. This idea has the same insurmountable problem as sheet foam--a modulus which is too low.

6. Composite Based Materials

6.1 Single-component composites

The advantages of carbon-fiber reinforced plastic (CFRP) are that its modulus is between 10 and 40 Msi (it is non-isotropic) and the radiation length is very large (280 mm, see SDC Solenoid DN-135). Using a modulus of 10 Msi, the thickness of a CFRP shell could be 35% that of aluminum. The coefficient of thermal expansion of CFRP is very small.

The outer vacuum vessel of the superconducting solenoid for the Venus experiment at the Tristan collider at KEK (Japan) was made of CFRP. The designer of the shell, Masayoshi Wake, was a visiting scientist at Fermilab during 1991. He and I spoke at some length about the Venus vacuum shell. The shell was hand laid-up using pre-pregged carbon-fiber cloth--it was not filament wound because of the concern that the epoxy would begin to react at room temperature during the winding process. Different grades of cloth were used, with a high modulus, low epoxy fraction cloth used on the inside for low outgassing. The layup was cured every 2.5 mm of thickness. The shell had no nozzles, the service chimneys came out the annular bulkhead. Wake had considered an aluminum liner on the inside as a vacuum barrier, but he decided that the thickness (30 mm) was enough to prevent leakage. The inner vacuum shell of the Venus magnet was aluminum, the annular bulkhead was stainless steel. It was necessary to use a large-diameter bellows to de-couple the two shells and isolate the inner shell from stresses arising from temperature changes in the experimental hall, see Fig. 5. CFRP was chosen for Venus as a technology development project for Japanese industry (the shell was made by Mitsubishi Electric Corp.) and so cost was not of primary interest. Operationally, the Venus shell has been successful.[3] After an initial out-gassing period, a helium gas permeation rate less that 1 x 10^{-11} torr-L/s-cm^2 was measured. A leak detector on the vacuum space of the magnet with a sensitivity of 10^{-8} torr-L/s did not detect a leak.

Our first step in considering CFRP as a shell material for the SDC magnet was to contact and visit Structural Composites Industries (SCI), in Pomona, California. SCI utilizes wet filament winding exclusively and makes a wide variety of pressure vessels for industrial and aerospace customers. Wet means that the fiber bundle passes through a bath of epoxy before being wound on the mandrel. They have been working with Fermilab on the development of the folded compression support post for SSC dipoles. They wind E-glass, S-glass, Kevlar and carbon, depending on the vessel requirements. Figure 6 gives some of the properties of their filament-wound CFRP, taken from their booklet, "Advanced Composite Structures". Their present capability for filament winding and curing is 10' diameter by 100' long. In conversation, SCI engineers thought they could modify their winding machine to accomodate the 13.5' SDC shell, but they do not have a curing oven large enough for this diameter. In February, 1991, SCI made a proposal for the engineering design of a vacuum shell 160" diameter by 30' long and the fabrication of a test cylinder 24" diameter by 54" long. We did not respond to this proposal by negotiating a contract.

We also visited Addax, Inc., Lincoln, Nebraska, who has supplied Fermilab both CFRP support posts and tension struts for SSC dipoles. This company is a small, rather low-cost operation (they use dollies for moving parts around the plant rather than cranes), dedicated to applying aerospace composite technology to automotive and less sophisticated problems where a low-weight and high-stiffness material is beneficial. They use wet filament winding only. We were impressed by their recognition of the need for simple, inexpensive tooling. For example, we saw a 3' diameter winding mandrel made out of two Sonotubes with 2" PVC pipes in the annular space between them. We did not think that Addax had sufficient depth in their engineering group to undertake the SDC job, especially when we learned that their engineering manager, who proposed to do the engineering for us, was leaving Addax to start his own company.

The Electronic Systems Group of Westinghouse Electric Corporation, in Sunnyvale, California is a supplier of filament-wound structures for military and aerospace uses. They make launch support tubes for guided missiles and torpedos. They are presently developing filament-wound CFRP isogrid cylinders, of which Fig. 7 is a photograph. Although this is an interesting technique, it does not appear that it is quite ready for application to the SDC job.

6.2 Multi-component composite structures

By multi-component composite I mean a material that is part CFRP and part something else. For example, Fig. 8 is a photograph of an epoxy/glass-graphite/honeycomb under development at Westinghouse-Sunnyvale for an externally pressurized vessel for underwater use. It has CFRP inner and outer shells, with a glass-epoxy overwrap on the outer surface to enhance durability in handling operations. The honeycomb is a phenolic-coated Nomex paper. The Westinghouse cover letter with the photograph continues, "For your application, a similar but much larger structure could be produced with a thin aluminum barrier incorporated in the inner shell for vacuum tightness, and an aluminum honeycomb could be used."

We also visited the Composite Products Group of Hercules, Inc., in Salt Lake City, Utah. The group is very large, occupies about 100 acres, and makes a variety of CFRP products for military and commercial aircraft and for NASA and military rockets. They do both wet filament winding and what they call fiber placement with pre-pregged ribbon. The fiber placement technique permits fabrication of concave items, their seven-axis fiber placement machine is shown in Fig. 9. The fiber placement machine and the curing autoclave (Fig. 10) are adequate to produce the SDC vacuum shell. The group has both design/analysis and fabrication engineering sections. They suggested that we consider multi-component structures, such as that shown in Fig. 11, which has CFRP sandwiching an aluminum honeycomb, or a CFRP-balsa wood sandwich. They thought that a multi-component structure might be better from a cost and radiation thickness point of view than a monocoque CFRP shell. Hercules proposed an engineering study of the SDC vacuum shell which would provide us with material trade studies and a preliminary design of the shell. They determined that a shell consisting of 0.20" CFRP face sheets and a 1.25" thick balsa wood core would meet the 30-psi collapse and the axial vacuum load requirements; they proposed this as a baseline from which to begin the study for us.

6.3 Decision regarding composites

In summary, we investigated four companies (SCI, Addax, Westinghouse, Hercules) and received written proposals for a preliminary engineering study from all but Westinghouse. We were most impressed with the engineering and fabrication capabilities of the Hercules group. However, we decided not to proceed with an investigation of composites, even though a composite shell would probably be the thinest in radiation lengths and the most uniform, see Fig. 12.

We had several reasons for doing this: (1) We thought that it would be difficult to guarantee the leak-tightness of the shell. (2) We saw the connection between a CRFP shell and the aluminum annular bulkhead as a difficult problem and that solving it would require vacuum-tight epoxy joints, which we perceived as unpredictable and unreliable. (3) Given our limited R&D budget and the tight schedule for the prototype shell (full diameter by quarter length), we thought it better to pursue only the aluminum isogrid method.

Appendix

Companies and individuals consulted

Addax Inc., P.O. Box 81467, Lincoln, NE, 68501, (412) 435-5253
Jack Keester, president, Scott Hansen, prog mgr, Brian Spencer, engr mgr

eldim, Inc., 65 Holton St., Woburn, MA, 01801, (617) 729-1113
Steve Mullen, engr mgr

Hercules, P.O. Box 98, Magna, UT 84044-0098, (801) 251-5373
Al Vicario, mktg mgr, Mike Moore, mktg rep, Lenn Riddle, D/A engr

Lockhart, Inc., 15555 Texaco St., Paramount, CA 90723, (213) 774-2981
Iche Gewelber, vp-engr, Peter Kinney, vp-sales & mktg, John Catizone, R&D proj engr

Nordam, Inc., P.O. Box 3365, Tulsa, OK 74101, (918) 587-4105
James Sweedyk, bonded technology mktg

Plascore, Inc., 615 N. Fairview St. Zeeland, MI 49464, (616) 772-1220
Fritz Huebner, pres

PS Associates, Inc., 5755 Oberlin Dr, San Diego, CA 92121 (619) 453-3810
Paul Sylsh, pres, Lyle Swenson, vp-engr

SCI, 325 Enterprise Pl., Pomona, CA 91768-3268 (714) 594-777
Edgar Morris, vp & grnl mgr, Vicki Morris, prod line mgr-adv comp, Zach Taylor, prod dev engr, Lonnie Smith, engr mgr-adv comp

Westinghouse, 401 E. Hendy Ave, Sunnyvale, CA 94088-3499, (408) 735-2106
Richard Ryan, dir, comm prod dev, Tim Muller, mgr, comm bus dev

References--Fermilab SDC Solenoid Design Notes

DN-101 Thin Solenoid Design Ideas (1989)
DN-112 Design of Outer Vacuum Shell for SDC Solenoid using Solid Plate (1990)
DN-113 Design of Inner Vacuum Shell for SDC Solenoid using Solid Plate (1990)
DN-116 Vacuum Vessel Relieving Pressure (1990)
DN-121 Technical R&D Plan for the SDC Superconducting Solenoid (1990)
DN-126 CGA Equations for Homogeneous Outer Vacuum Shells; Shell Thickness for Typical Materials
DN-127 Feasibility Study of a Titanium Honeycomb Vacuum Shell (1991)
DN-131 Isogrid Outer Vacuum Shell for SDC Solenoid (1991)
DN-134 Report of SDC Solenoid Working Group (1991)
DN-135 Calculation of Radiation Thickness of Carbon Fiber-Epoxy Composite (1991)
DN-139 Presentation before SDC Technical Board, April 12, 1991 (1991)
DN-143 Report of Feasibility STudy of Aluminum Isogrid for Outer Vacuum Shell (1991)
DN-144 Thickness of Solid Aluminum Outer Vacuum Shell using CGA-341 and ASME Pressure Vessel Code
DN-146 Preliminary Investigation of an Isogrid Inner Vacuum Shell (1991)
DN-148 Radiation Thickness of Aluminum Alloys (1991)

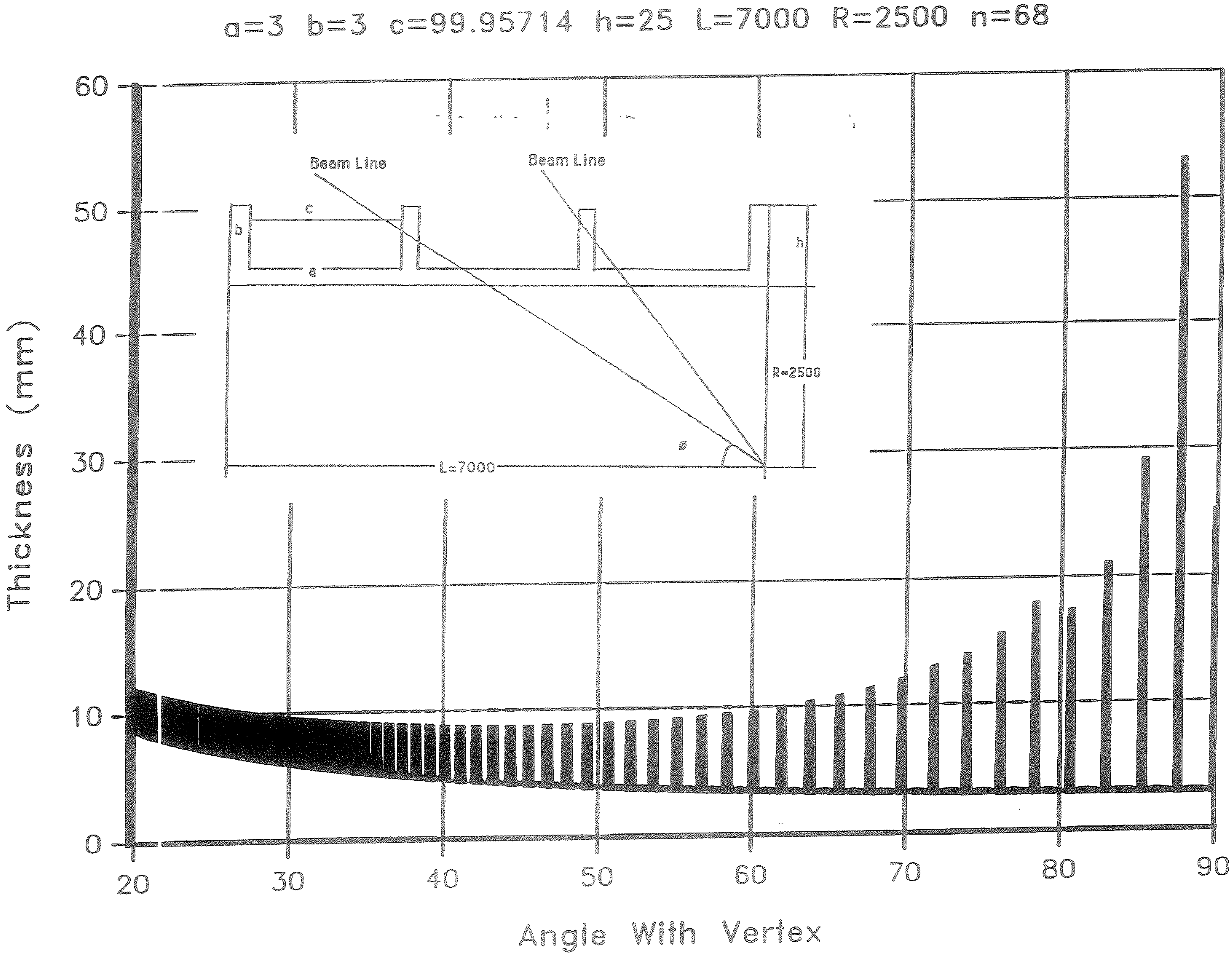


Fig. 1. Thickness penetrated by particles passing through extruded vacuum shell

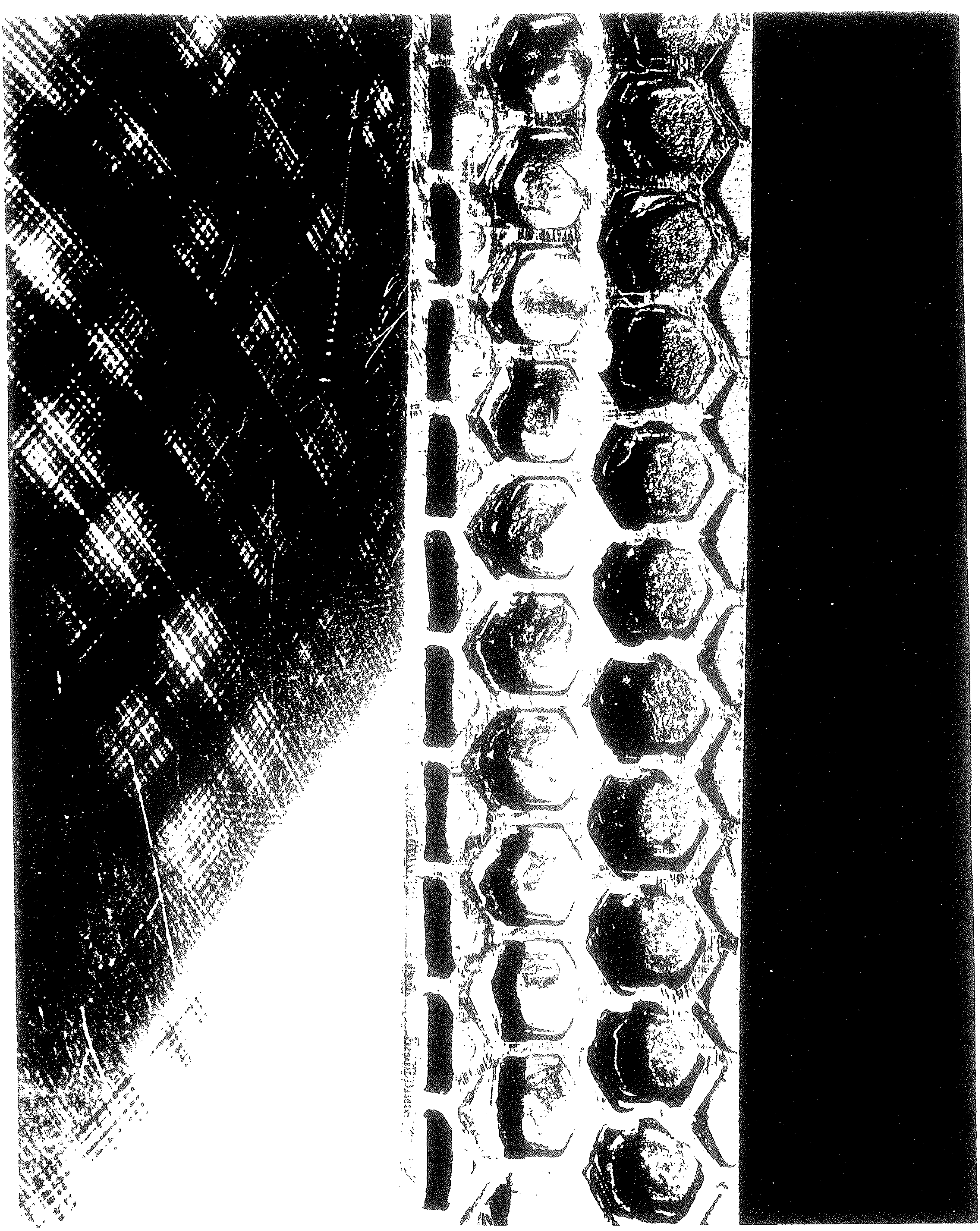
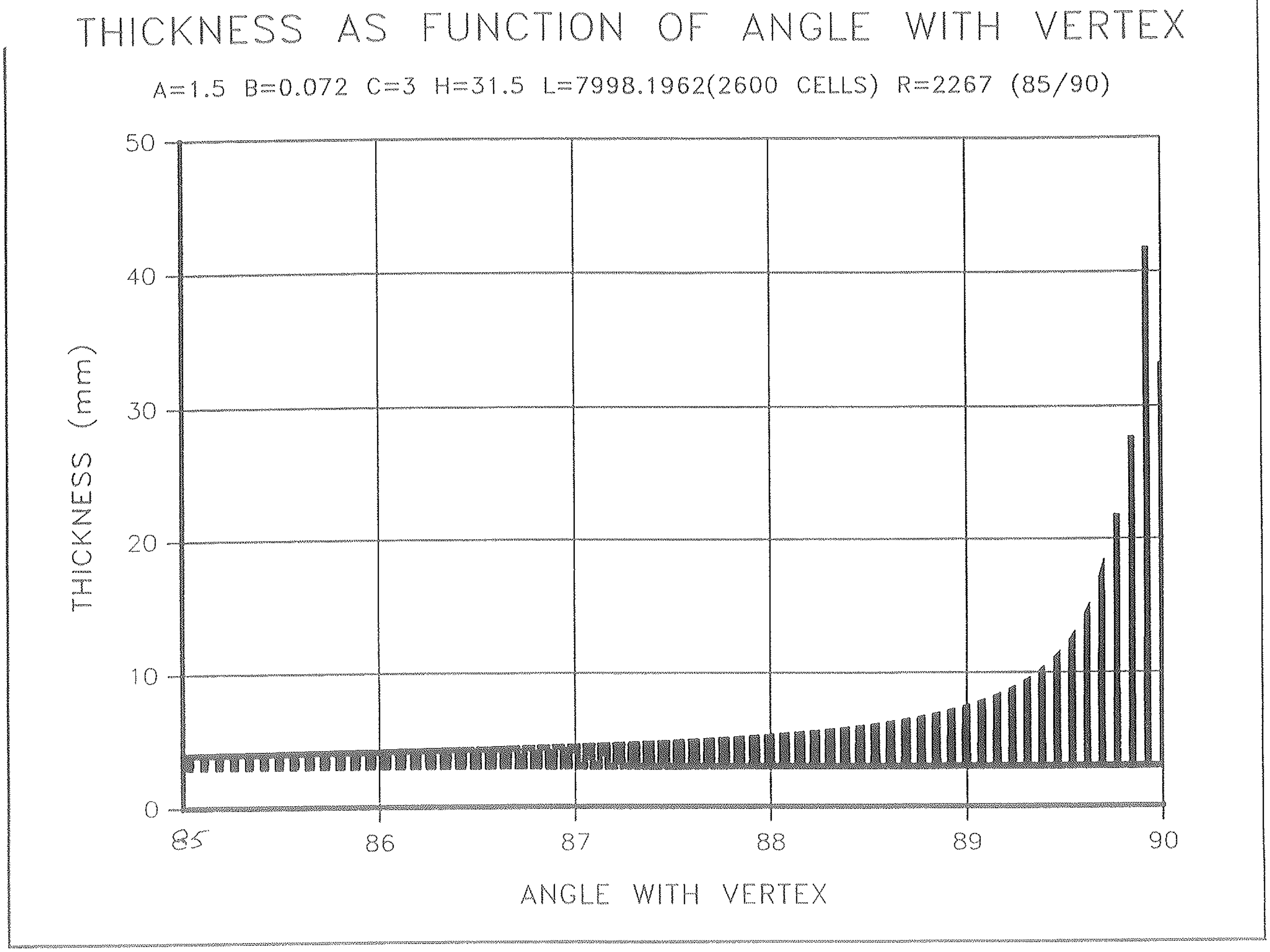


Fig. 2. Vacuum brazed aluminum honeycomb (Lockhart Industries)



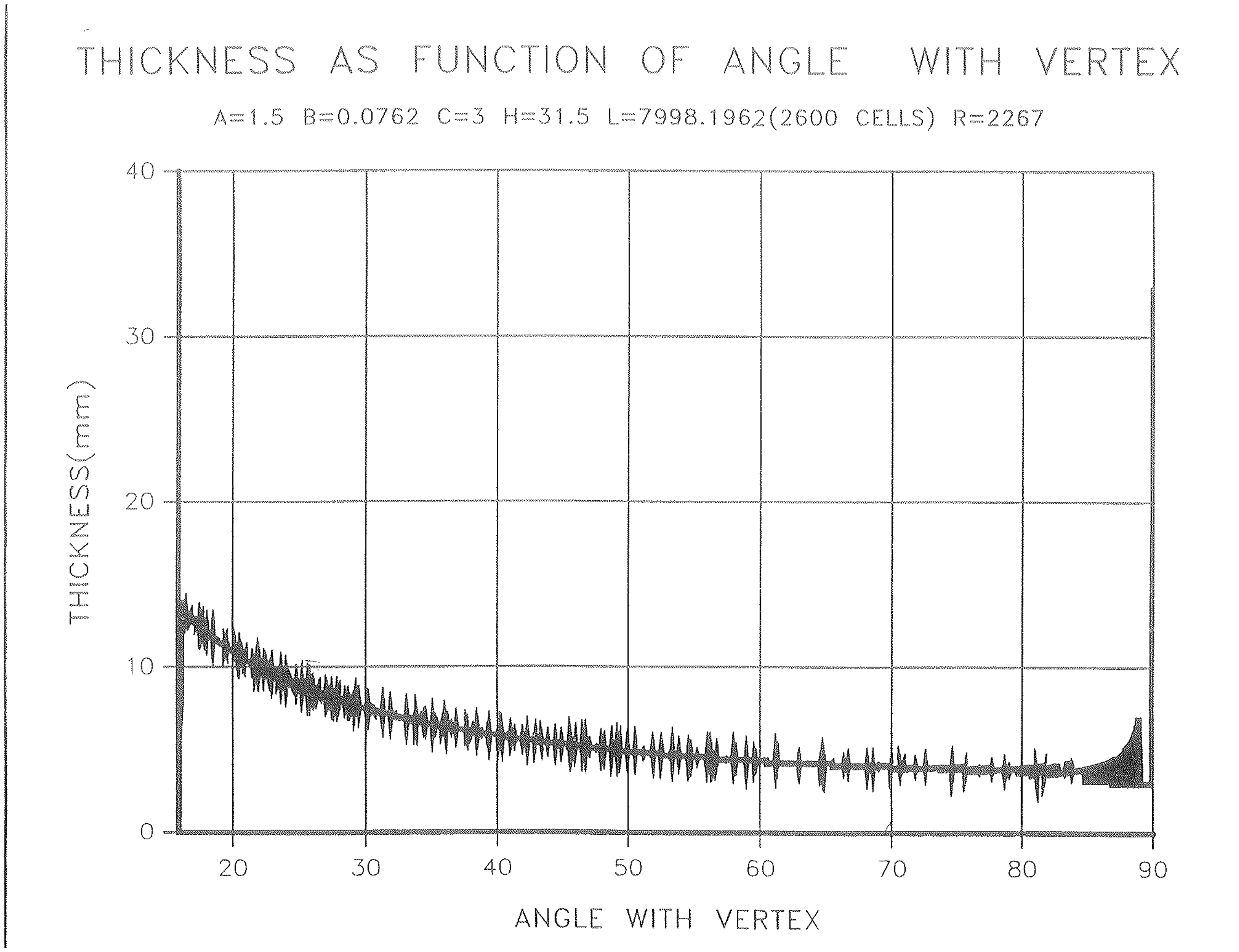


Fig. 3. Thickness penetrated by particles exiting honeycomb vacuum shell

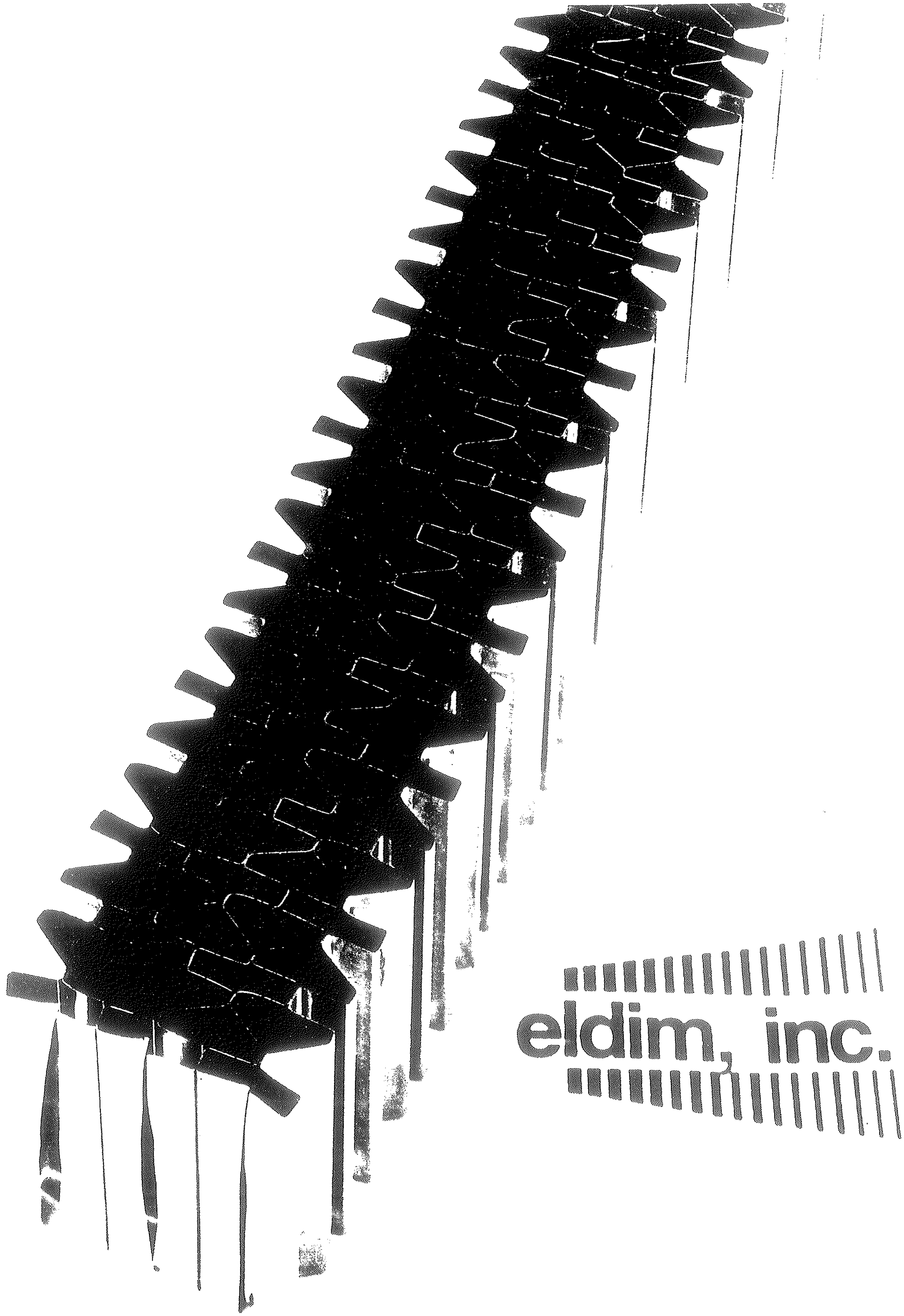


Fig. 4. Titanium honeycomb (eldim, Inc.)

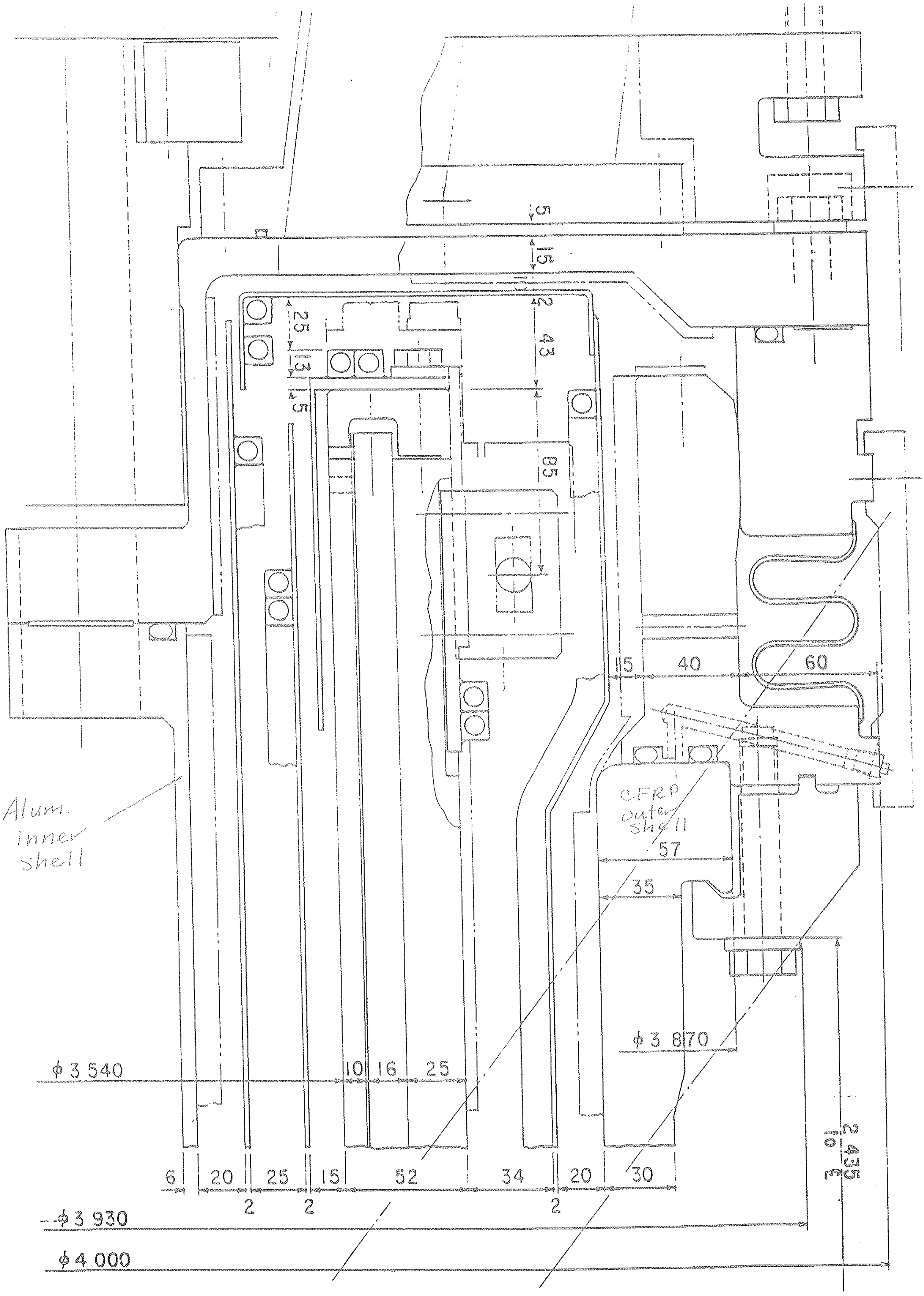


Fig. 5. End of Venus vacuum vessel

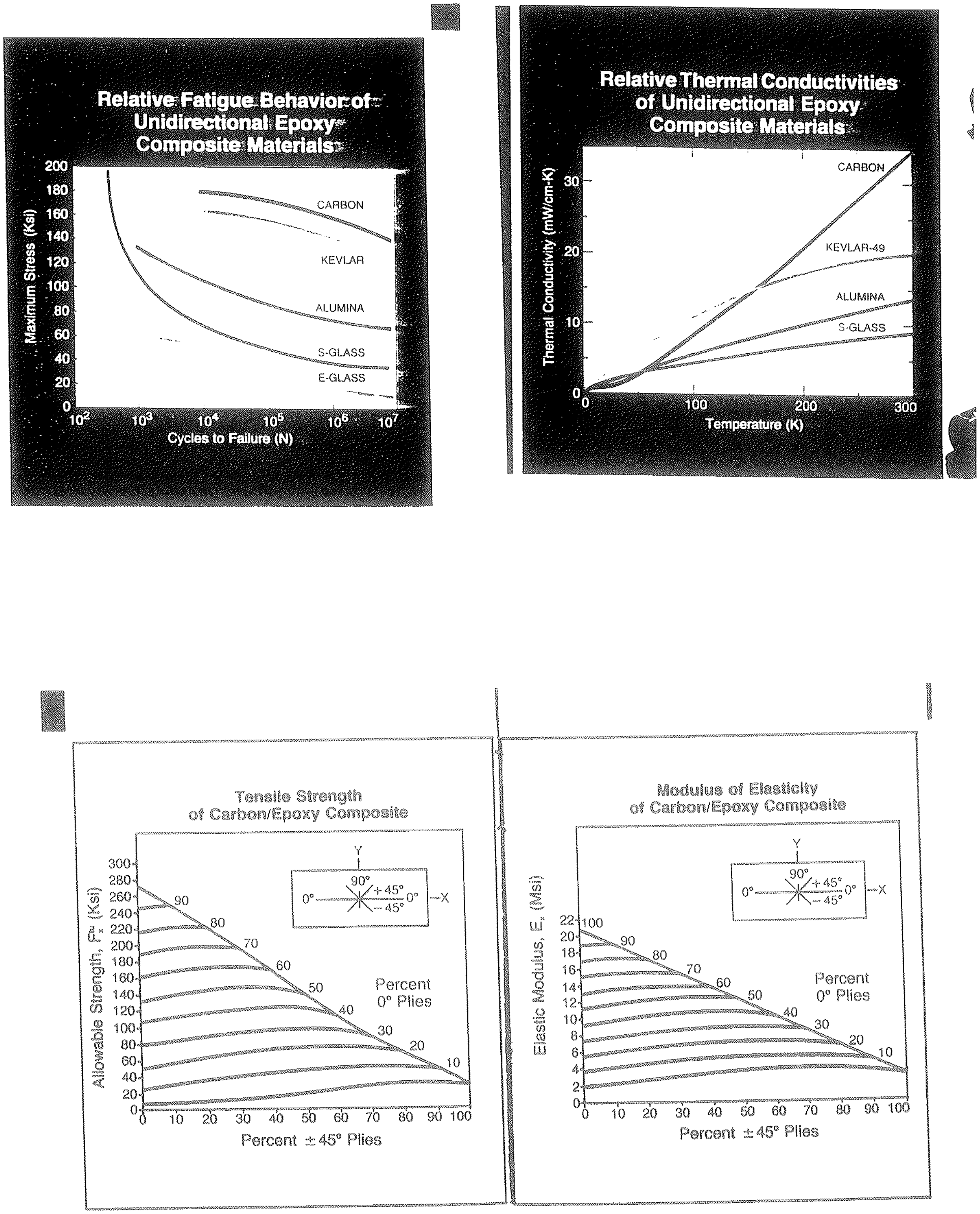


Fig. 6. Properties of CFRP (SCI)

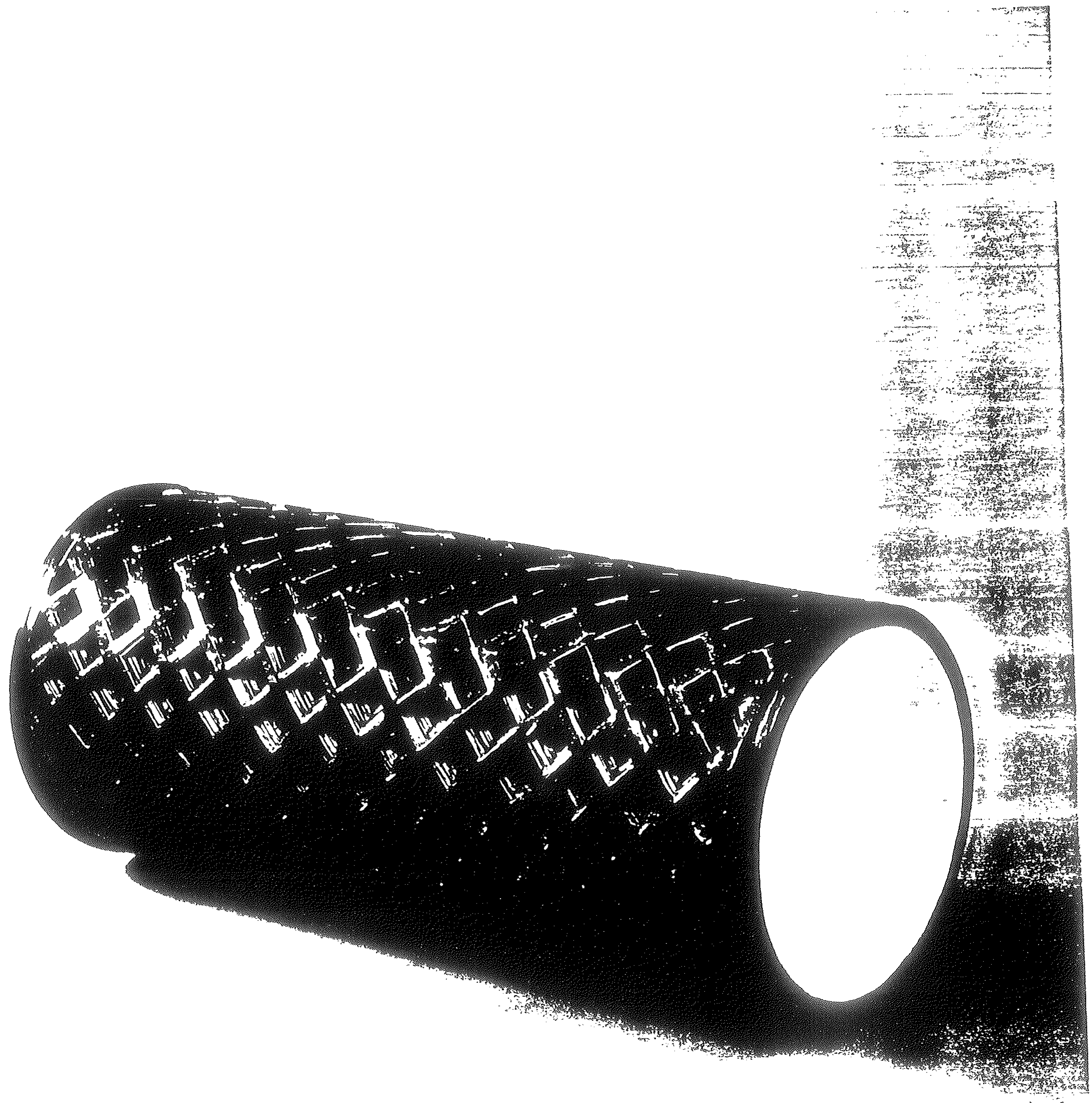


Fig. 7. CFRP isogrid cylinder (Westinghouse- Sunnyvale)

Fig. 8. GFRP/CFRP/Nomex honeycomb (Westinghouse-Sunnyvale)

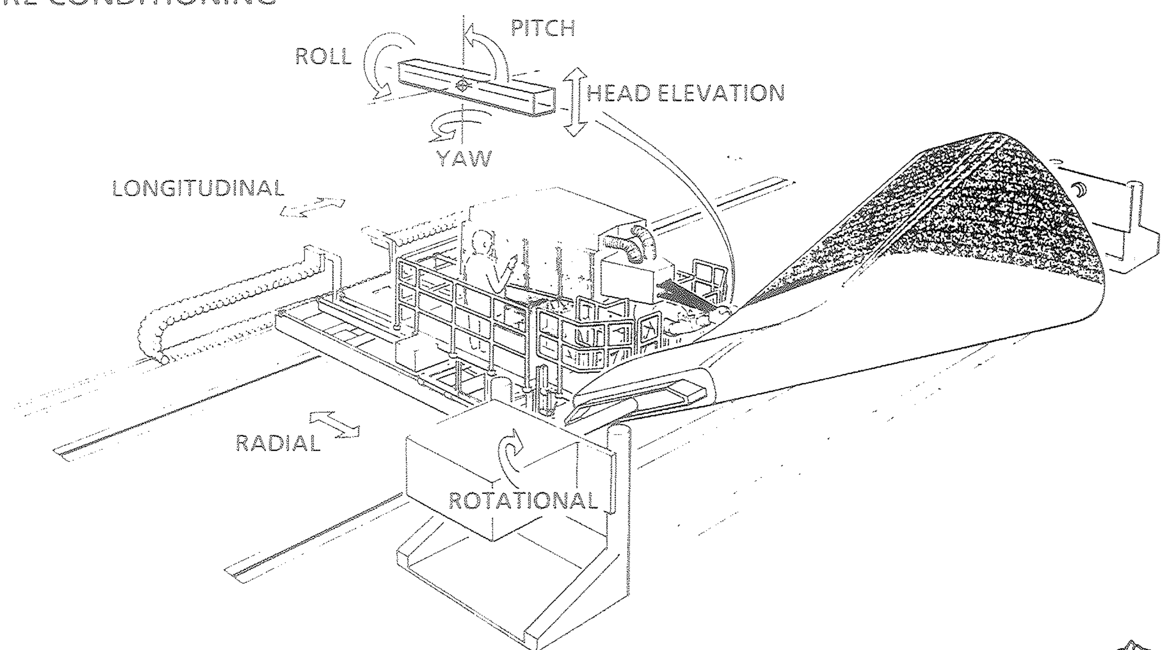
MULTI-AXIS FIBER PLACEMENT MACHINE

FEATURES

- PLY THICKNESS CONTROL (RIBBONIZING) IN DELIVERY HEAD
- TOLERANT TO TOW WIDTH VARIATION
- MULTIPLE RESIN TYPES
- INDIVIDUAL TOW CUT/ADD (32 TOWS)
- BAND CUT/ADD
- TEMPERATURE CONDITIONING

CAPACITY

- DIAMETER/MAJOR CHORD--14 FT
- LENGTH--33 FT
- 32 TOW DELIVERY
- MANDREL WEIGHT--40,000 LB



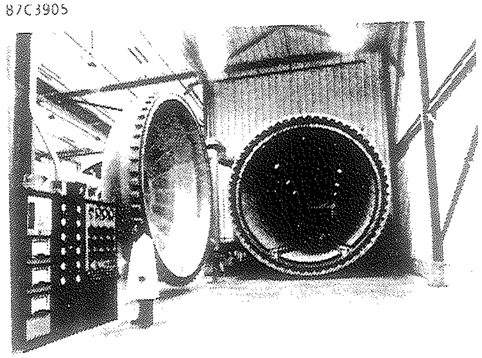
HERCULES

13-906

Fig. 9. Multi-axis fiber placement machine (Hercules)

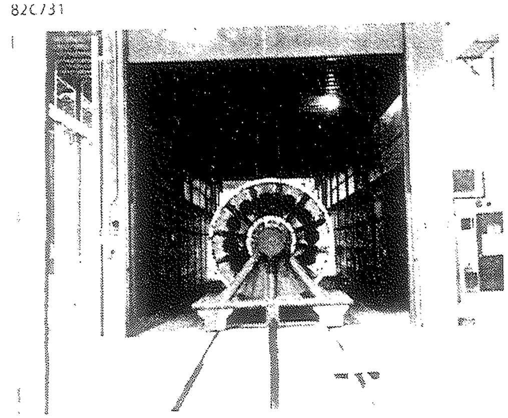
FACILITIES AVAILABLE TO PROCESS AND TEST A VARIETY OF STRUCTURAL COMPONENTS

87C3905



5 AUTOCLAVE, UP TO 15-FT DIA
BY 50-FT LONG

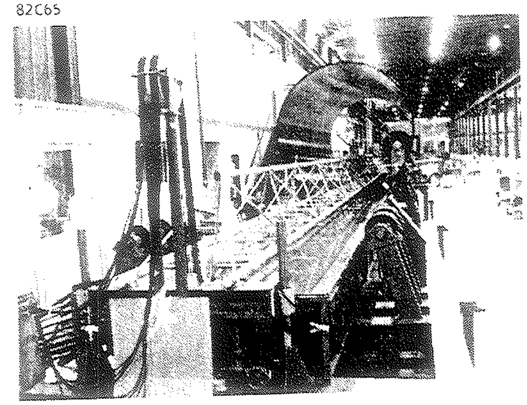
82C731



11 OVENS, UP TO 14-FT DIA
BY 50-FT LONG

- NDE
  - ULTRASONIC INSPECTION
  - THERMOGRAPHY
  - REAL-TIME X-RAY
  - COMPUTED TOMOGRAPHY
- TESTING
  - MECHANICAL
  - PHYSICAL
  - CTE

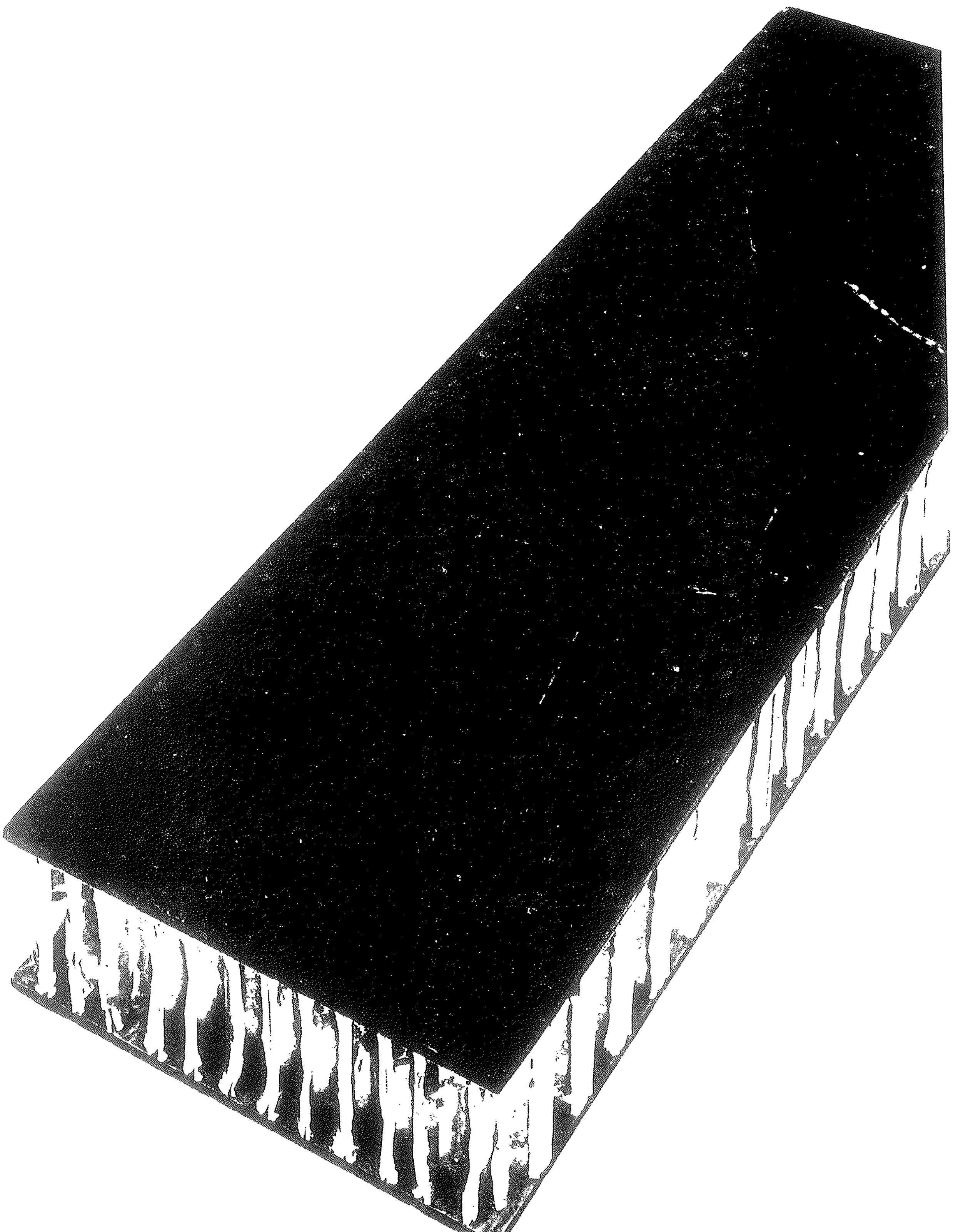
82C65



HERCULES

14-1793

Fig. 10. Curing autoclave (Hercules)



HERCULES

Fig. 11. CFRP-aluminum honeycomb (Hercules)

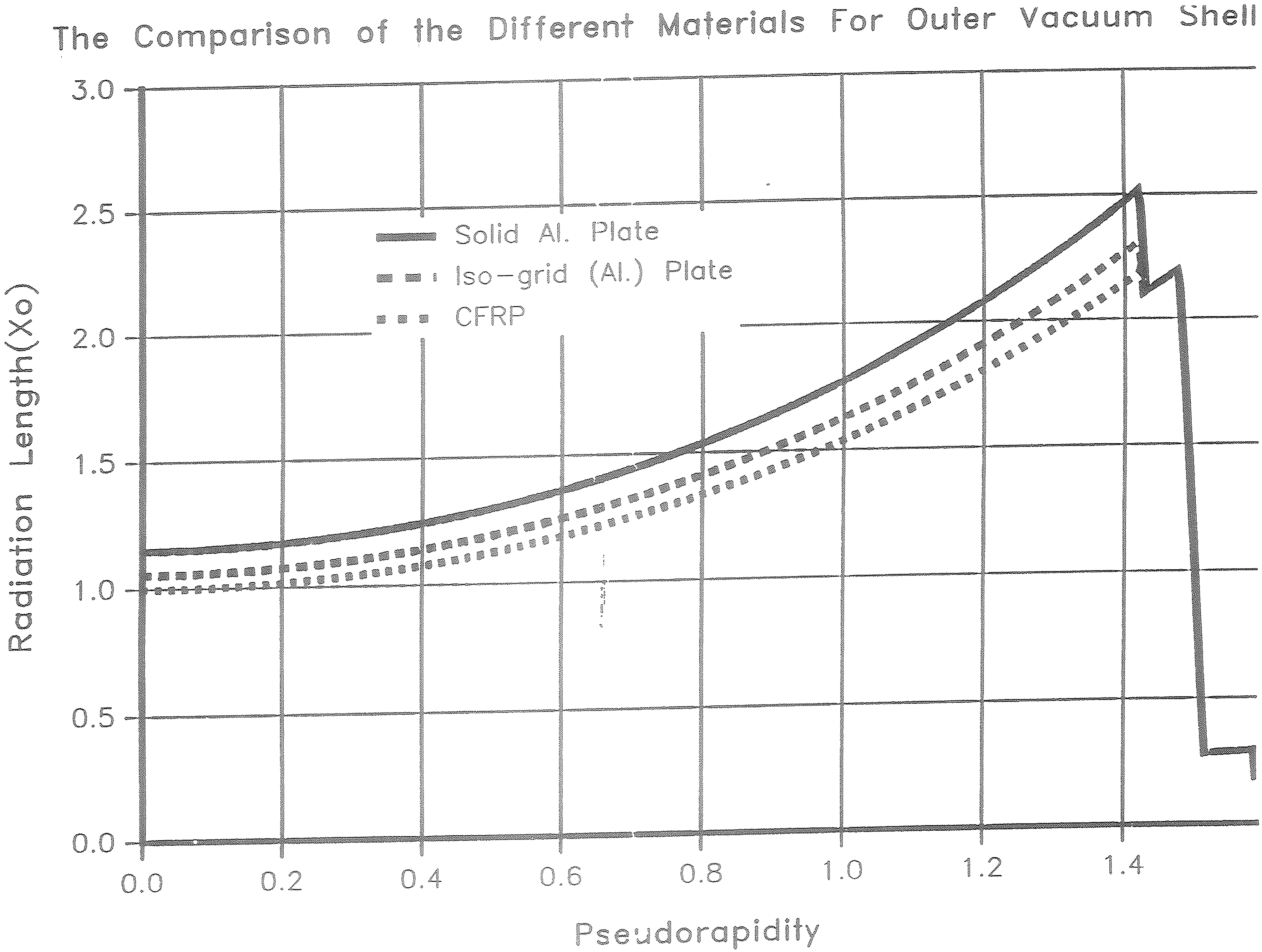


Fig. 12. Radiation thickness of three possible materials for outer vacuum shell