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ORNL 242

TECHNICAL DIVISION

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"BORAL: A NEW THERMAL NEUTRON SHIELD"

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FOR THE
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Technical Division

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BORAL: A NEW THERMAL NEUTRON SHIELD

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1.0 Abstract

A technique has been developed for making large sheets or castings of B_4C and aluminum complex for absorption of thermal neutrons without production of hard gamma radiation. The $\frac{1}{4}$" sheet has the following properties:

Boron Content: 50% B_4C (or 40% B) by volume
0.91 g B/cm^3 or 0.58 g B/cm^2 of $\frac{1}{4}$" sheet.

Thermal Neutron Attenuation of 10^{10} in $\frac{1}{4}$" (based on $\Sigma_{th}^{B} = 100 \text{ cm}^{-1}$).

Density: 2.53 g/cm^3 or $3\frac{1}{4}$ #/ft^2

Cost: 15-20 \$/ft^2

Tensile Strength: 5500 psi (10 times concrete, 1/10 mild steel, about equal best plastics).

Thermal Conductivity: Somewhat better than steel (more precise measurements in progress).

Can be sheared, sawed, welded, punched, drilled, tapped, rolled, and hot-pressed. Sheets 7' by 33' by $\frac{1}{4}$" are in preparation for shearing to 5' x 6' test sheets.

It is felt that this material will have many uses where a large thermal neutron flux must be absorbed without production of hard gammas, e.g. inner section of reactor shields, shutters for thermal columns, instrumentation.

2.0 Introduction

The absorption of thermal neutrons without production of hard gamma radiation can be a very important function. For example, if the radiation impinging upon a shield is such that the thermal neutrons outnumber the quanta of hard gammas by a factor of 100, and these thermal neutrons are absorbed in the shield to produce hard gammas (the usual result), then the incident gamma flux which must be shielded has been effectively increased by this factor, i.e., an additional 26" of concrete (or equivalent) must be added to the shield. If instead, these incident thermal neutrons were absorbed without hard gamma production (e.g. in a thin film of boron), the 26" of hypothetical concrete could be removed. E. Creutz of Carnegie Institute of Technology estimates that a comparable thickness of concrete added to the CIT cyclotron shield would have cost over $20,000 in materials and floor space. In a stationary reactor shield it might cost ten times this amount. It might tip the balance of feasibility in a mobile reactor shield.

The $B^{10}(n,\alpha)Li^7$ reaction is uniquely suited for such a function. Natural boron, containing 18.8% B^{10}, has a cross-section of 703 barns for this reaction at thermal energy, falling off as 1/v to about 0.1 barn at 1 MeV where the function becomes irregular. The residual activity is negligible and the 0.42 MeV gamma, which is emitted after 93% of the captures, is soft enough to be easily absorbed. Cadmium, by contrast, emits a 6 MeV gamma and leaves four unstable isotopes after irradiation.

Boron can be bought in many forms: Nearly pure crystalline boron at \$200 - 300 per pound, amorphous boron at \$15 per pound, and B_4C in various grades and prices starting near \$7 per pound. The crystalline B is quite pure, the amorphous B 60-80%, the B_4C 75-80% B. B_4C is not only the cheapest form of highly concentrated boron, it is also exceedingly refractory, chemically inert, mechanically hard, and atomically dense; in each of these properties it exceeds almost all other known materials. For \$8 to 10 per pound, it can be obtained quite pure.

Being difficult to work, it seems desirable to bind the B_4C with a more docile material for handling. Aluminum appears to be the most promising cementing agent: it has a low cross-section for the production of hard capture gammas, it is ductile and easily fabricated, has high thermal conductivity, is inexpensive, light weight, and corrosion resistant.

The question of radiation damage naturally arise. Since aluminum is the continuous phase, it should not suffer from destruction of the embedded B_4C particles. Radiation damage studies on aluminum show that, with the possible exception of warpage, no deleterious effects should be expected. The diffusion of helium (from the n,α reaction) through the aluminum is expected to take place without damage. Irradiation tests will be made.

3.0 Early Experiments

The objective was to achieve as high a fraction as possible of B_4C. In addition it was felt that no B_4C should be exposed at the surface and no loose B_4C should exist within the sheet. In this way it was hoped to minimize the possibility of escape of B_4C from the sheet due to blistering during operation or machining during fabrication. Arbitrarily a 1:1 ratio by volume of B_4C to aluminum was chosen. For a ¼" sheet, this is sufficient to give a 10^{10} attenuation of thermal neutrons, assuming a macroscopic cross-section for boron of 100 cm^{-1}, or for boral, 40 cm^{-1}. Actually a 1:1 <u>weight</u> ratio was used for the unclad material, giving a volume ration of 2.7 B_4C : 2.45 Al, but this is compensated for by the cladding on both sides which occupies a total of 16% of the thickness. It was found that a significantly larger fraction of B_4C could not be obtained without seriously impairing the mechanical and thermal properties of the material. In the rare cases where greater quantities of boron are needed, a thicker sheet can more easily be used.

Experimental work was started in December 1948 under Frank Kerze of the Engineering Materials Section and was shortly thereafter moved to the new Y-12 facilities of the Shielding Group.

3.1 <u>Foil and Powder Method (See Figure 1)</u>

B_4C powder was sprinkled in thin layers between ten .005" aluminum foils, around which was a wrapper of .064" 2S aluminum sheet. This was hot-rolled at 1130°F, reducing the laminated assembly .050" each pass through the rolls until the laminate had been reduced to ¼". The results of this experiment were unsatisfactory because only a small amount of the B_4C embedded itself in the aluminum foil, leaving most of the powder loose between the laminations. The loose B_4C prevented the bonding of the layers of foil and a considerable amount of powder blew out during rolling, preventing bonding of the outside wrapper. Figure 1 shows a sheared section of the finished sheet. Note that the laminations are not bonded to each other.

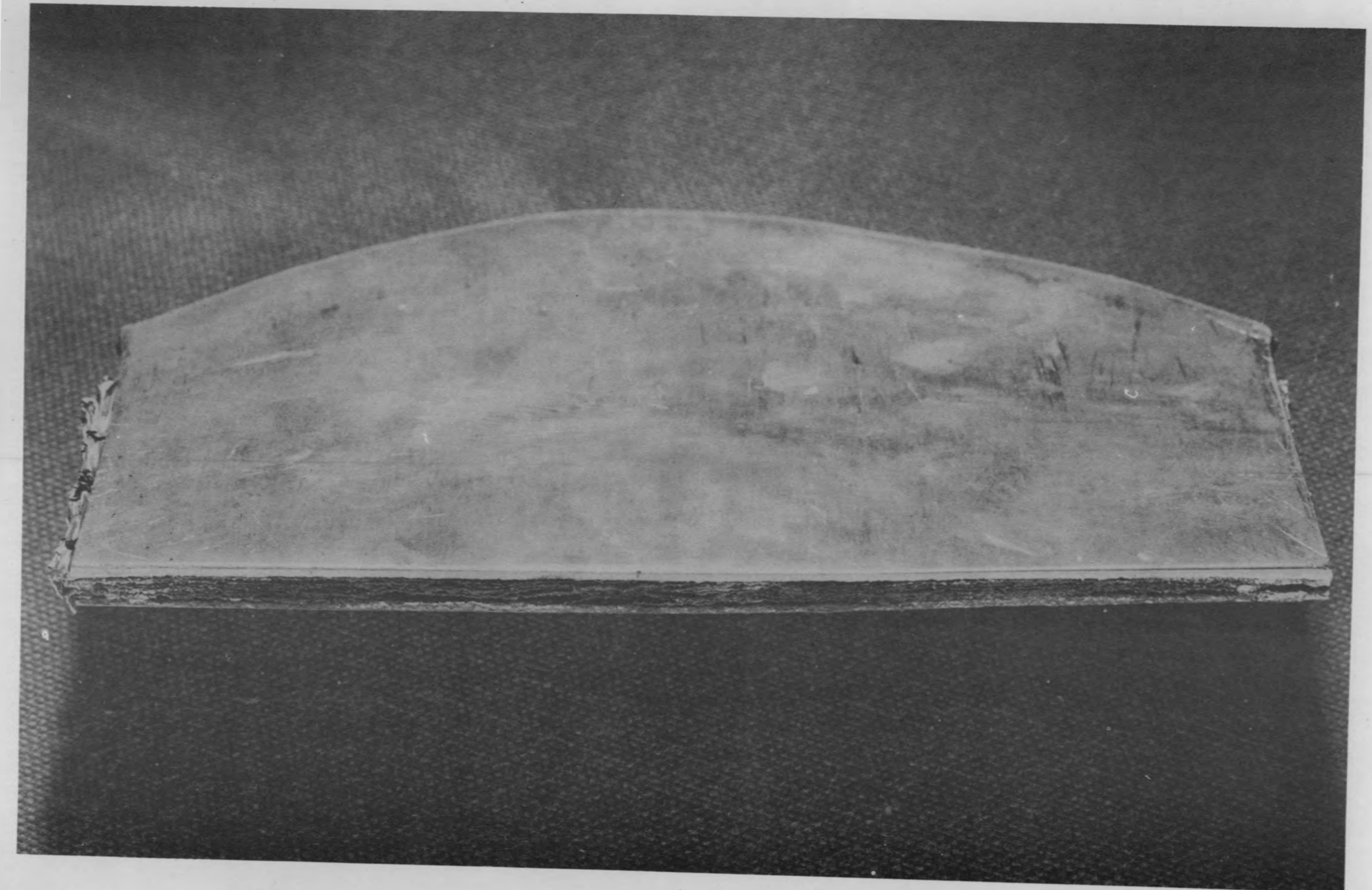

FIGURE 1. AL FOIL AND B_4C POWDER, HOT ROLLED

3.2 Two-Powder Method (See Figures 2 and 3)

A mixture of B_4C and Al powder was placed in an envelope of Al foil (to prevent dusting during rolling) and this mixture was fitted carefully into an aluminum "picture frame". The frame was covered top and bottom with a single 1/8" wrapper sheet, and the assembly was then soaked at 1130°F for one hour. It was rolled at this temperature, being heated 10 minutes between passes, and reduced to ¼".

The first attempts (see Figure 2) were fairly satisfactory, but several serious difficulties arose. The picture frame generally bonded to the wrapper on the first pass, trapping air in the powder mix inside. To minimize this, the envelope containing the powder was pressed within the picture frame on a 100 psi Studebaker pneumatic press, before heating and rolling. In spite of this, a large blister was formed and a vent hole had to be drilled through the wrapper. When the finished sheet was examined, it was found that the wrapper was not bonded to the inner material and there was considerable loose B_4C apparent. In an attempt to improve upon this, several sheets were made, varying the aluminum particle size from approximately 20 mesh to ¼" chips, and the B_4C from 100 mesh to 18 mesh. These gave no significant improvement.

A larger sheet was tried by this method, starting with a 9¼" x 9¼" x 1" (inside dimensions) picture frame (see Figure 3). In addition to the above difficulties, the wrapper became quite soft at the soaking temperature, and handling the large assembly proved quite difficult. It was decided at that time that large satisfactory

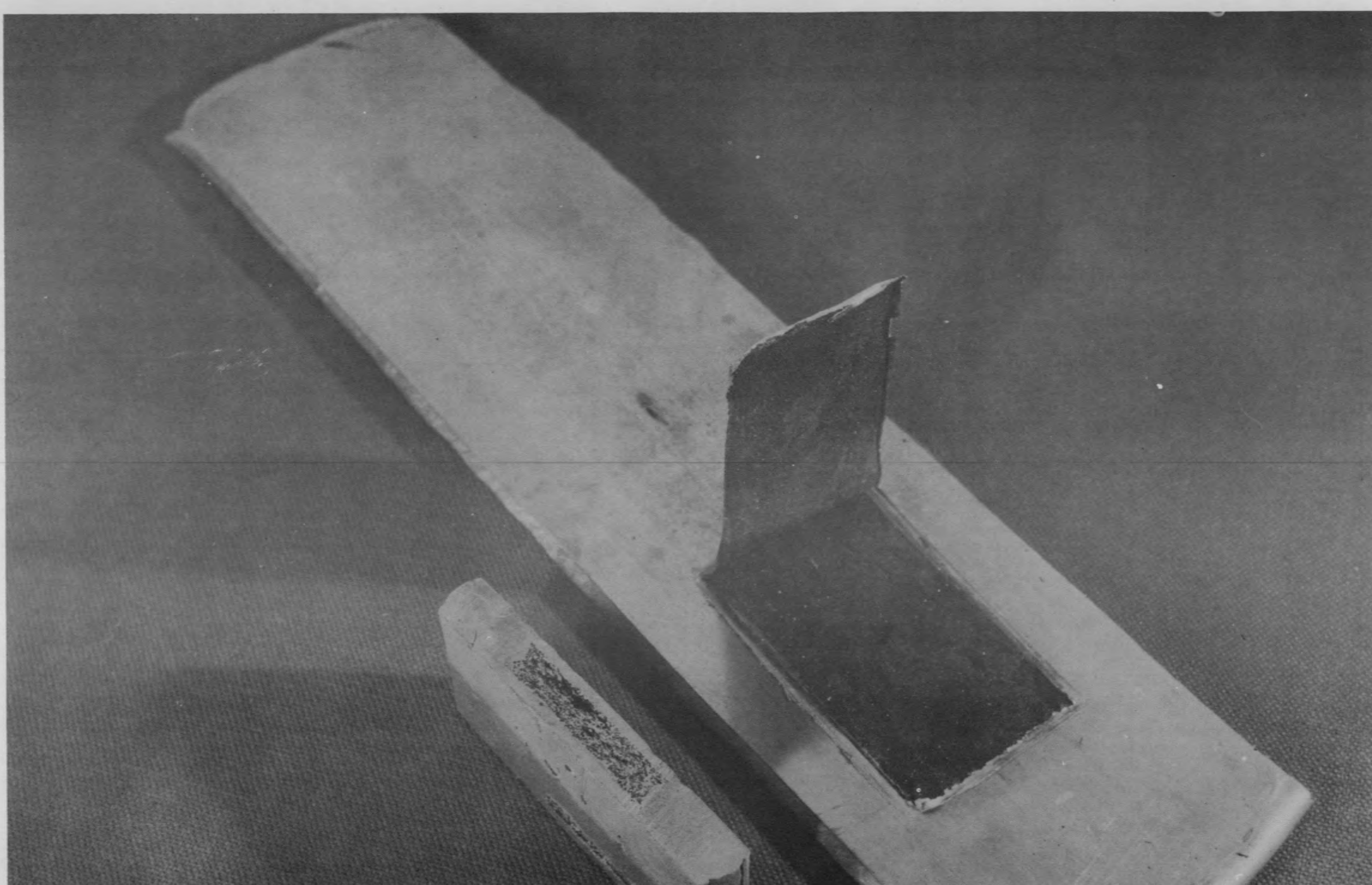

FIGURE 2. AL AND B_4C POWDERS IN PICTURE FRAME

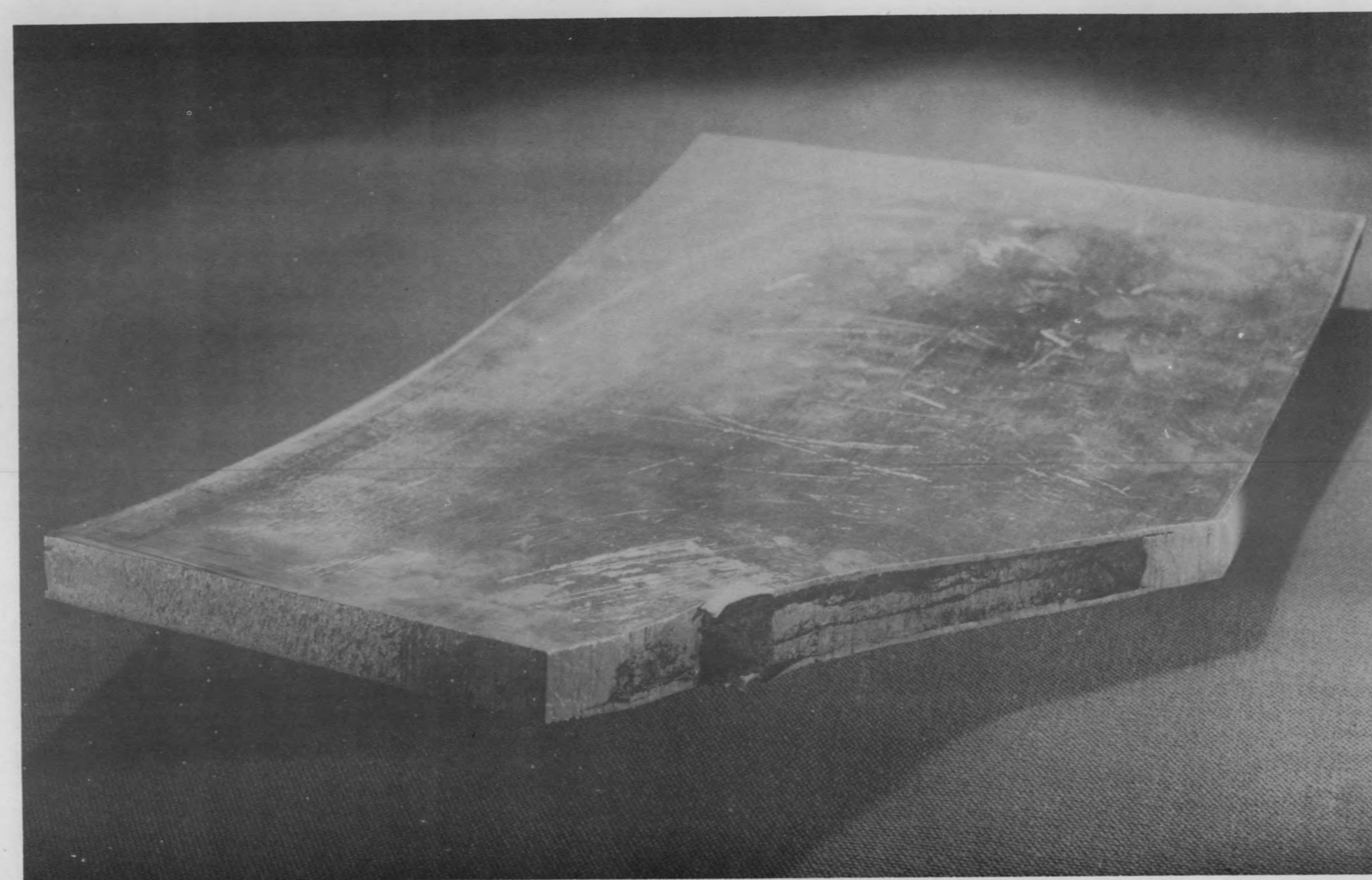

FIGURE 3. LARGE TWO-POWDER ATTEMPT

sheets could not be rolled unless the B_4C and aluminum were in the form of a rigid structure during rolling.

3.3 Cast Ingot Method (Figure 4)

Several small-scale attempts were made to mix B_4C powder with molten aluminum. The aluminum did not wet the B_4C and the resultant mix when cooled was crumbly and incohesive. Preheating the B_4C, precipitating B_2O_3 or Al_2O_3 on the B_4C surface, and varying the temperature range, had little effect. Attempts to make an ingot from B_4C and aluminum powder were equally unsuccessful. A non-oxidizing atmosphere seemed to make little difference.

Finally a successful ingot was made as follows: (Figure 4) Half of the aluminum, as powder, and all of the B_4C, were mixed cold and added slowly with stirring to the remaining aluminum which was molten. The temperature, which seemed critical, was kept at 1230°F $\pm$ 20. The resultant ingot was somewhat porous (density 2.25 g/cc), but very strong and homogeneous. The porosity was nearly eliminated during rolling, resulting in a sheet with a density of 2.53 g/cc. This method was refined and was the basis of the present fabrication technique.

4.0 Present Fabrication Technique (Figures 5 and 6)

The capacity of the rolling mill at ORNL limits the sheet width to 27" and the billet thickness (including wrapper) to $1\frac{1}{2}$". Therefore it has been decided to roll a billet $1\frac{1}{4}$" x 7" x 12", with an 1/8" wrapper on each side, which produces a trimmed sheet 20" x 20" x $\frac{1}{4}$". Since the B_4C powder alone stacks to nearly 50% voids, the boral ingot holds B_4C particles which are nearly touching, resulting in a very rigid mass which cannot be poured, even at high temperature. Therefore

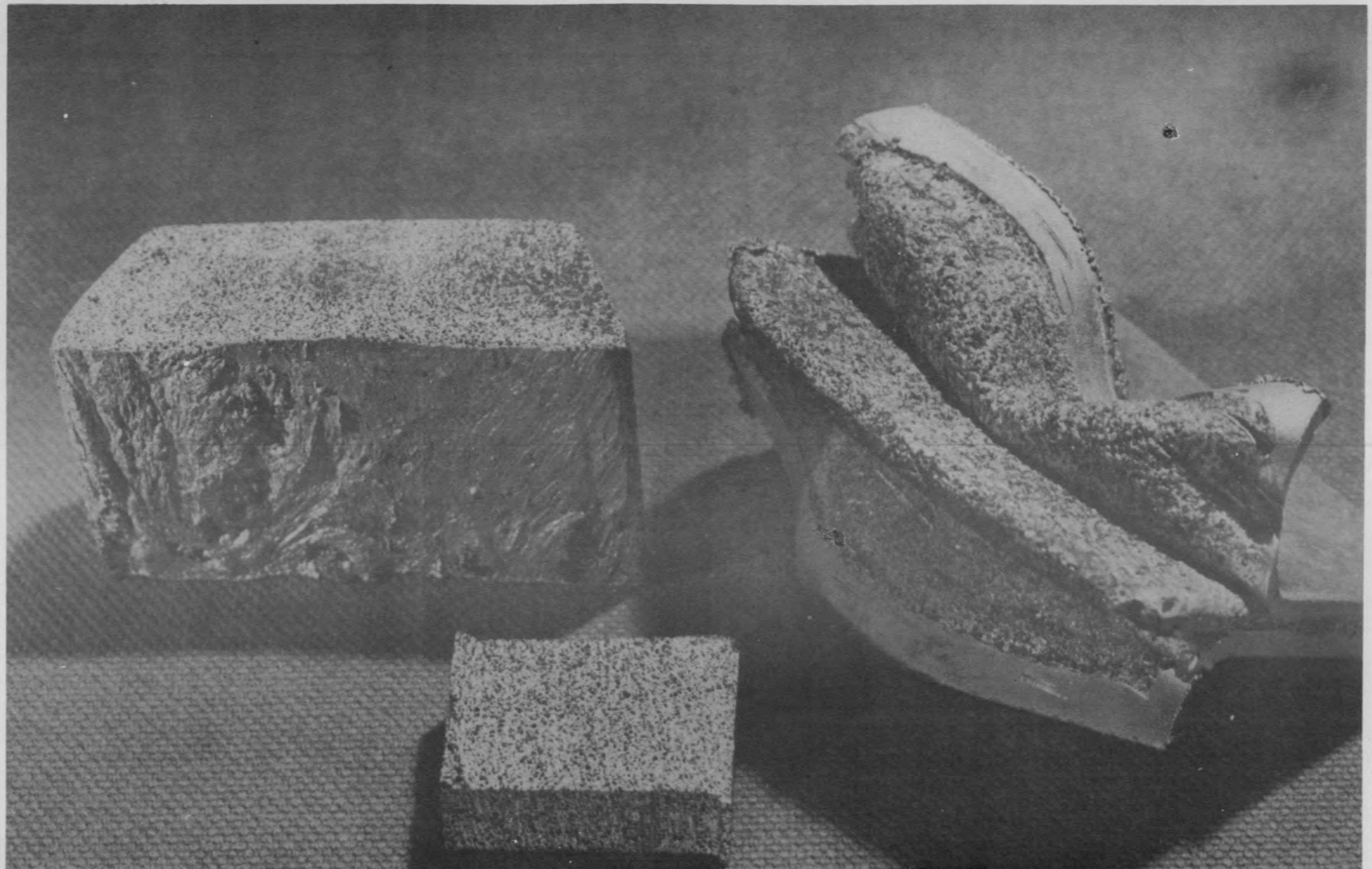

FIGURE 4. SECTIONS OF FIRST INGOT AND SHEET

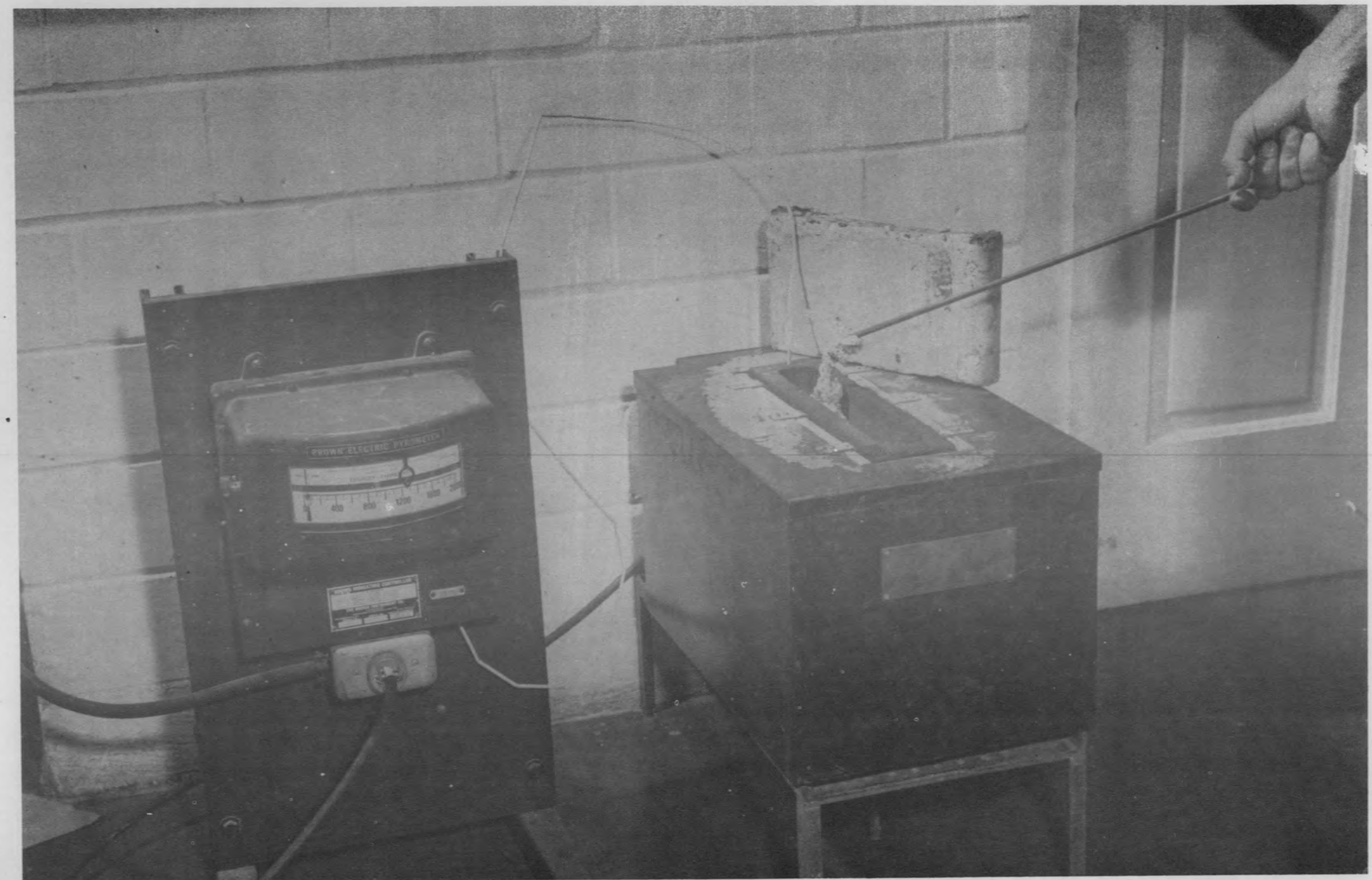

FIGURE 5. CASTING BORAL INGOT

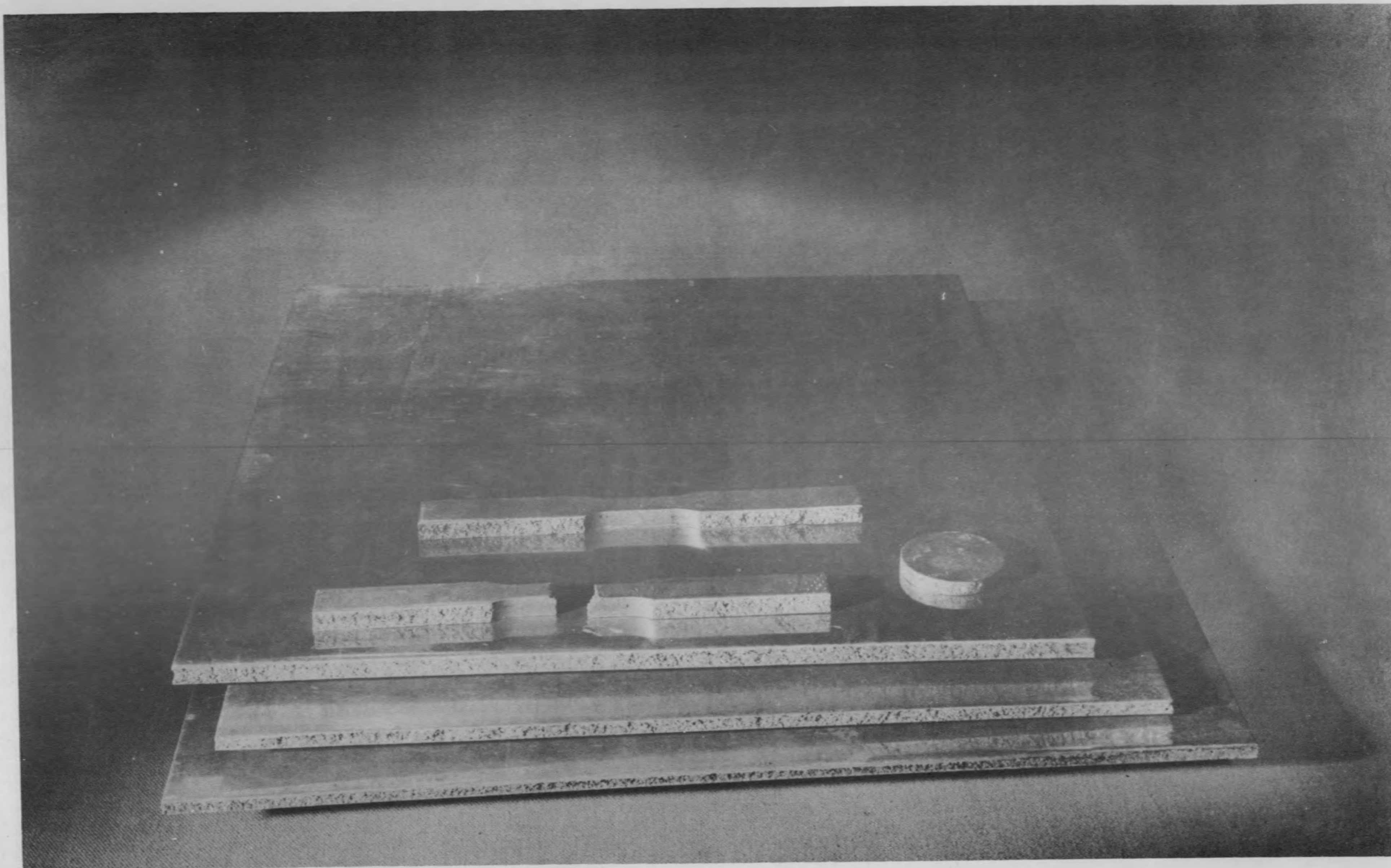

FIGURE 6. FINISHED BORAL SHEETS AND PIECES

it is desirable that the rolling billet be the original casting, and not recast from a larger pig. For this purpose, a special furnace has been built from two standard 6" x 12" muffle furnace elements, which heats a graphite crucible with inside dimensions 7" x 12" x 1¼" with 1/16" taper. The temperature is controlled by a Brown electric pyrometer from a thermocouple set in the graphite, and the mixed powders are stirred into the molten aluminum with a 3/8" steel rod, as shown in Figure 5. A typical ingot is shown on the furnace. To produce an ingot this size requires 825 grams of 2S aluminum pig. To this a cold mixture of 1650 grams B_4C (through 20 on 100 mesh) and 825 grams of aluminum powder (approximately 20 mesh), is added gradually while stirring in order to wet and suspend the B_4C particles in the molten aluminum.

After removing the ingot from the crucible mold, it is then metal-sprayed with a thin coat of aluminum to cover completely any exposed particles of B_4C. A wrapper of 1/8" 2S aluminum sheet, which has been wire-brushed to remove excess oxide and dirt to facilitate bonding, is placed around the ingot to form a cladding of approximately .020" on the 1/4" finished sheet. The assembly is then placed in a Lindberg forced-circulation electric furnace and heated to 1130°F for approximately one hour and rolled. The billet is reduced approximately 10% each pass through the rolls. The material retains considerable ductility at low temperatures and work-heats appreciably during rolling, so that reheating between passes is not necessary if the rolling is carried out at a reasonable pace.

The first heats were run with only the ingot and a wrapper sheet. Since there was nothing to confine the edges of the ingot during rolling, excessive crumbling, edge-cracking, and unevenness resulted. Present runs employ a welded aluminum picture frame to confine the ingot, and this technique yields straight edges, free from cracks. The edges of the wrapper sheet are bent over and tack-welded to the outside of the picture frame, which has several vent holes drilled through it.

5.0 The 250 ft^2 Sheets (Figures 7 and 8)

As indicated above, the maximum width which could be rolled at ORNL was 27". There is a need for several 40" x 43" shutters for the ORNL attenuation facility and several 56" x 66" sheets for experimental work. Arrangements have been made with the Lukens Steel Company of Coatesville, Pennsylvania, to roll two sheets 84" x 396" x $\frac{1}{4}$", from which ten 56" x 66" sheets and four 40" x 33" shutters can be cut. Two ingots, 6" x 36" x 32", weighing 450 pounds each, will be cast and wrapped at Y-12, then shipped to Lukens for rolling. The expenses for this job are being partly borne by NEPA, and the sheets will be used for the joint ORNL-NEPA shield tests in the ORNL attenuation facility.

The method of wrapping is essentially that described in paragraph 4.0 and is shown in detail in Figure 7. The special furnace for casting the ingots (Figure 8) is scaled up from that shown in Figure 5, except that a non-tapered steel crucible is being used. A separate report, ORNL-243, covering this project, will be written as soon as the sheets are rolled.

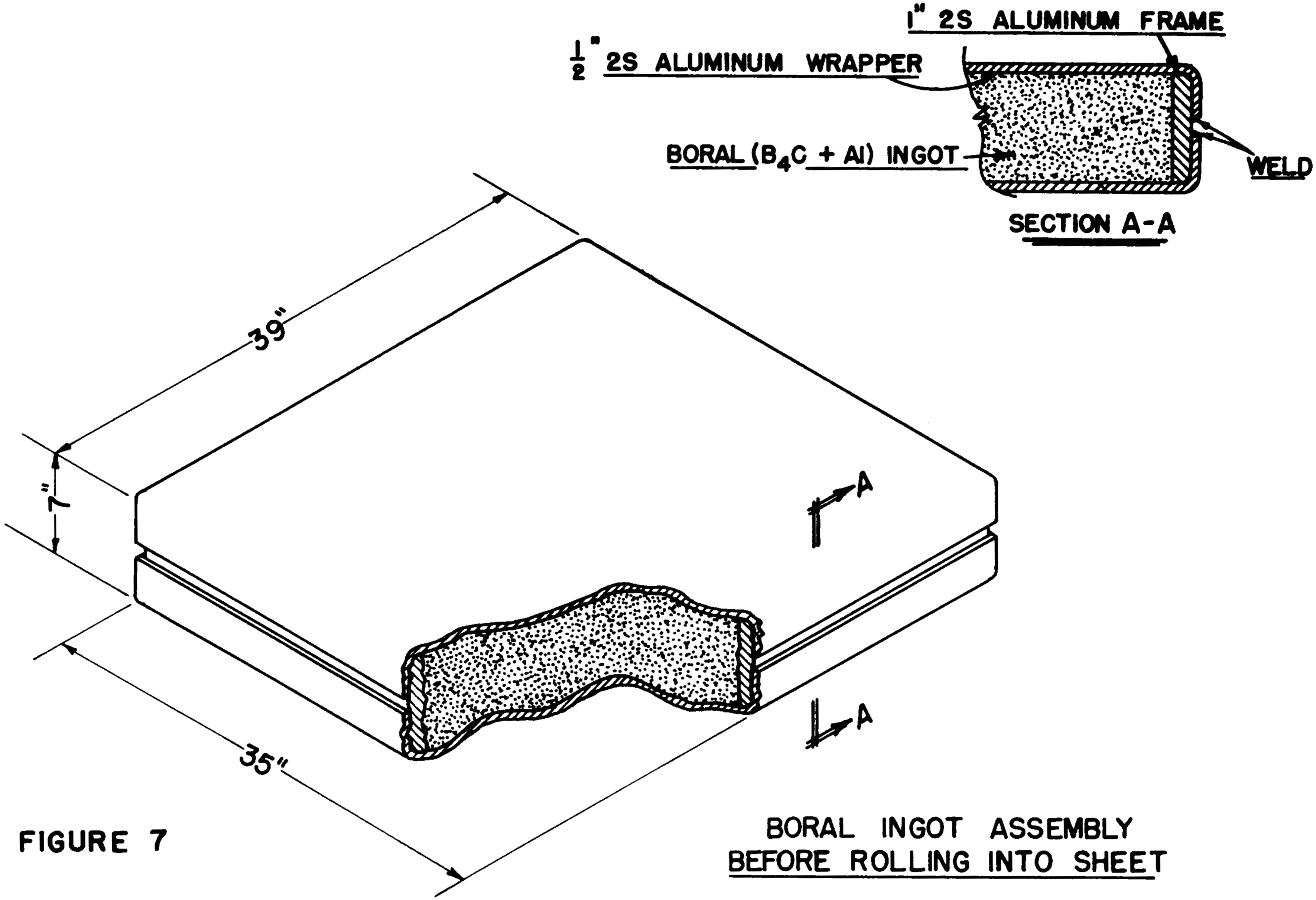

FIGURE 7

BORAL INGOT ASSEMBLY
BEFORE ROLLING INTO SHEET

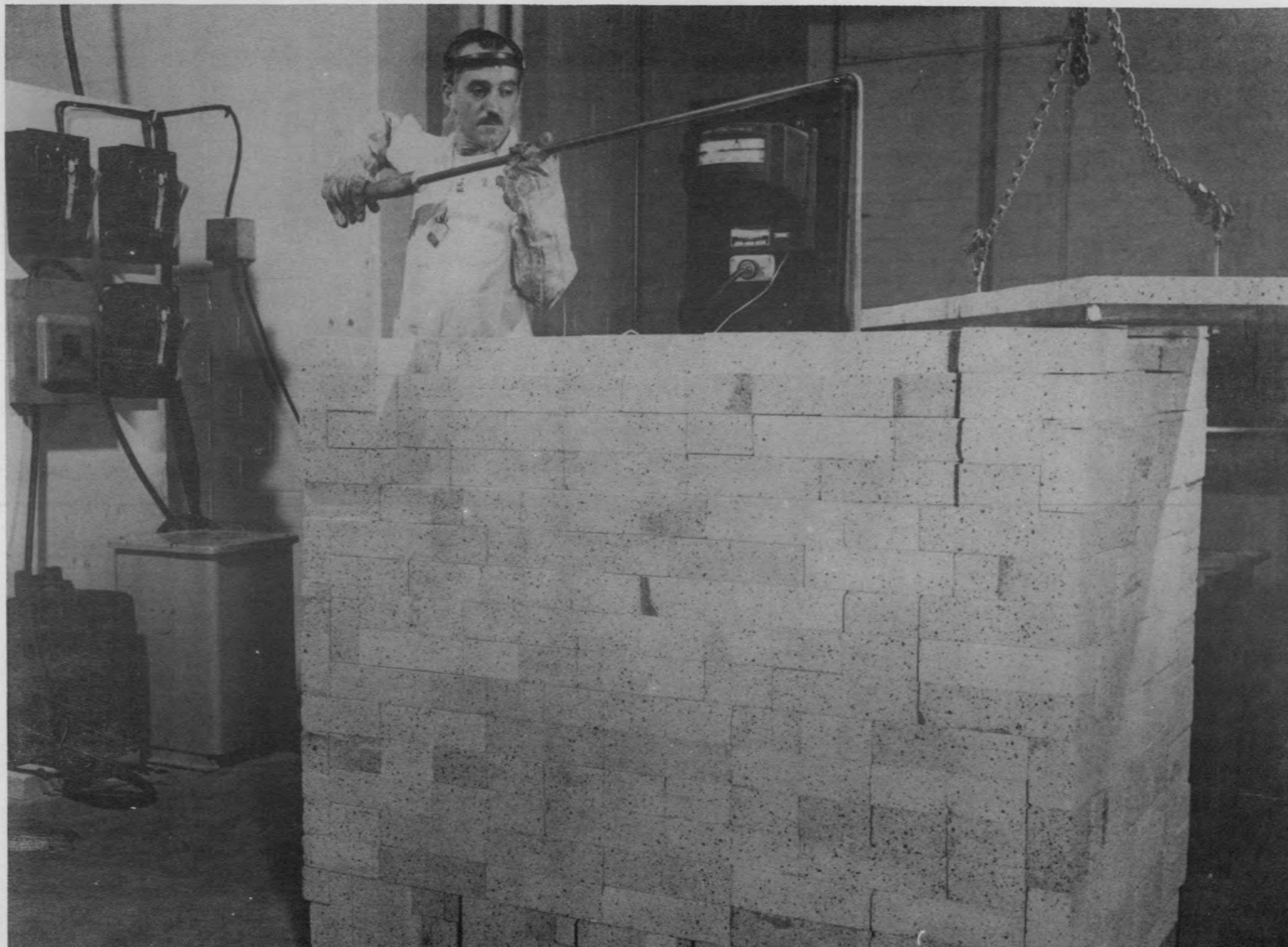

FIGURE 8. CASTING 36" X 32" X 6" BORAL INGOT

6.0 Physical Properties

6.1 Data

1. Composition (for ¼" sheet, including .020" Al cladding on each side) 50% (vol.) B_4C, 50% Al.

	% (wt)	mg-mol/cm^3	g/cm^3	g/cm^2
B	36.0	84.2	0.911	0.578*
Al	55.1	51.7	1.394	0.886
C	8.9	18.7	.225	0.143

* This is sufficient to give 10^{10} attenuation of thermal neutrons

2. Density: 2.53 g/cc
   0.09 lb/in^3
   3¼ lb/ft^2 for ¼" sheet

3. Strength

   a) Tensile 5,500 psi
   b) Elongation 0.4 %
   c) Shear 8,237 psi
   d) Welded tensile specimens did not fail at weld

4. Thermal Properties

   a) Conductivity: somewhat better than steel (more precise measurements in progress).

   b) Specific Heat: 0.175 Btu/lb x °F or g-cal/g x °C

   c) Melting Point: Maintains mechanical strength up to 1500°F (800°C), above which oxidation is excessive.

   d) Heat Generation from n,α Reaction: 7.4×10^{-10} watts/ft^2 x unit thermal neutron flux.

5. Cost: 15-20 \$/ft^2 for ¼" sheet.

6. Workability: Can be sheared, sawed, welded, punched, drilled, tapped, rolled, hot-formed, and experimentally die-cast.

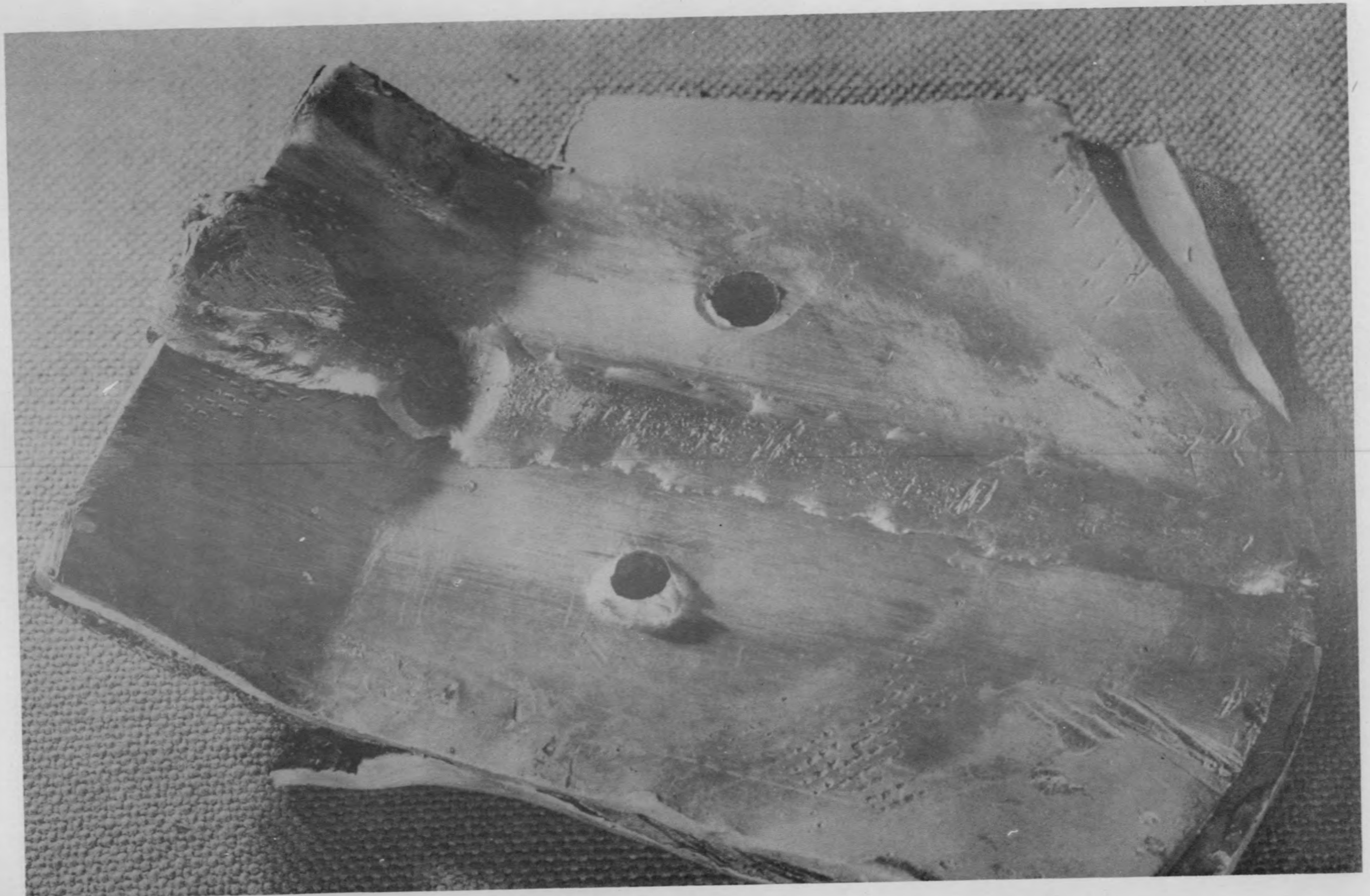

FIGURE 9. BORAL SAWED, WELDED, PUNCHED, AND DRILLED

6.2 Testing and Calculation Methods

1. Composition

   Calculations are based on 1:1 (vol) B_4C : Al composition. Densities assumed are 2.45 and 2.70 g/cc respectively.

2. Density is based on gross volume measurement and also water displacement, with no significant difference.

3. Tensile strength on 8 normal and 3 welded specimens, as per ASTM (e.g. B209-46T, 1946 ed, Part IB, p 572, fig. 1).

   Shear strength on three $\frac{1}{4}$" x 2" x 8" strips, in modified Johnson Shear Tool (ASTM C102-36, 1946 ed, Part II, p 228, fig. 1)

4. Thermal Conductivity was made by comparing temperature drops through Al rod, Al discs, and boral discs, through which a constant heat flux flows axially (see Figure 9). Comparison of the Al rod and discs gives an approximation of the temperature drop through the brazed interfaces of discs, and this correction, applied to the boral discs, gives the drop through boral compared to drop through Al for same heat flux. Precision was poor and precise tests are being made on new equipment.

   Heat Generation = 5 Mev α/n capture x 929 nv $\frac{\text{captures}}{\text{ft}^2 \text{ x sec}}$ x 1.6 x 10^{-13} $\frac{\text{watts}}{\text{MeV}}$

5. Cost: $12/ft^2 for B_4C, $0.40 for Al, $1 for rolling.

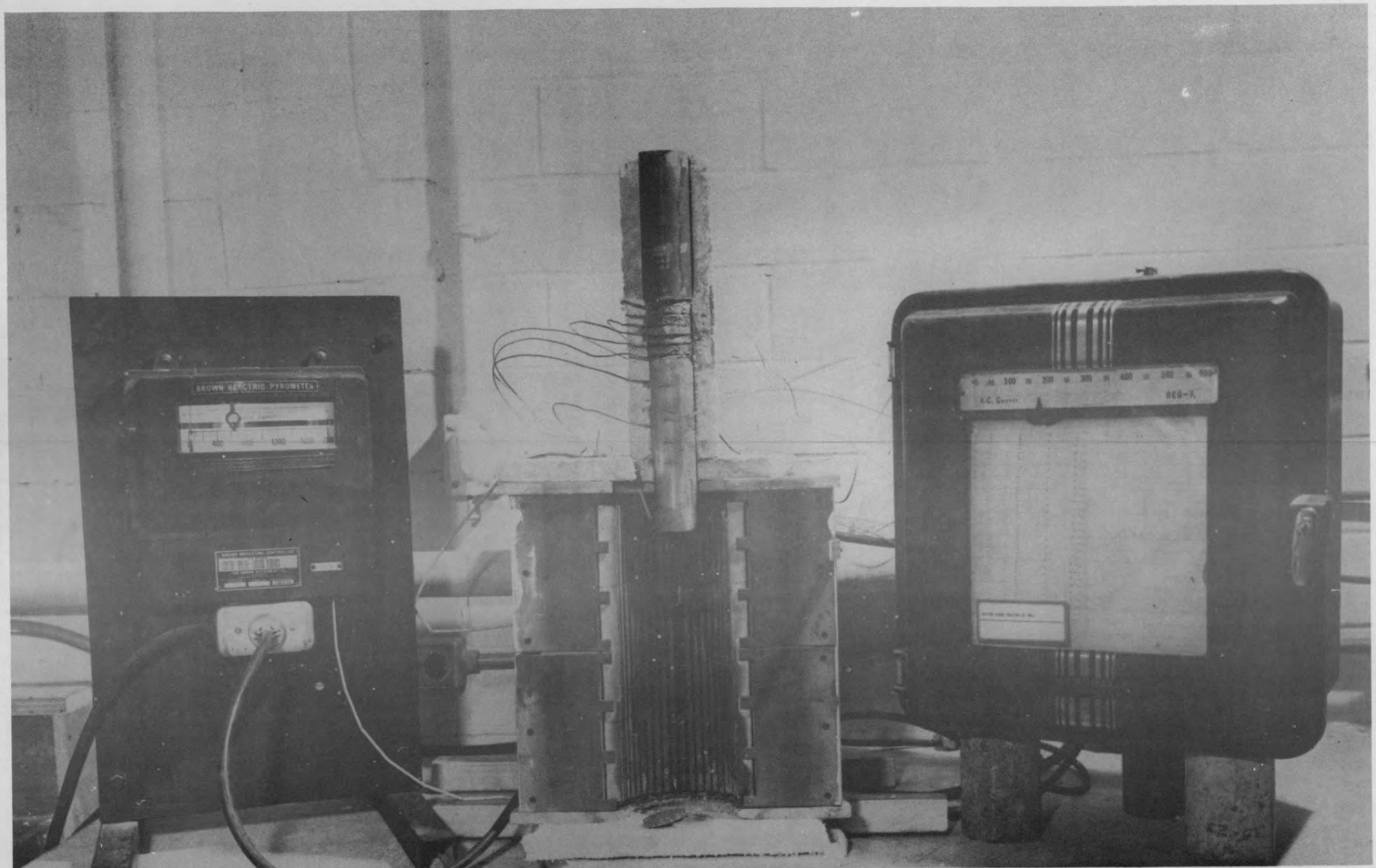

FIGURE 10. SECTIONAL VIEW OF THERMAL CONDUCTIVITY APPARATUS

7.0 Analyses of Raw Materials for Boral

	Al Powder	Large Al Pig	Small Al Pig	Boral
Ag	< .04%	T	--	T
Al	> .10	VS	VS	VS
B	< .015	--	--	VS
Be	< .004	--	--	--
Ca	< .08	--	--	--
Cd	< .15	--	--	--
Co	< .08	--	--	--
Cr	< .15	--	--	T
Cu	.08	W	W	S*
Fe	.15	W	W	M*
In	< .08	--	--	--
Mg	.04	M	W	S*
Mn	.04	T	T	W
Mo	< .15	T	--	--
Ni	< .08	--	--	T
Pb	.08	--	--	--
Pt	.08	--	--	--
Si	.20	W	T	W
Sn	< .08	--	--	--
Ti	< .04	--	--	--
V	< .08	--	--	--
Zn	< .31	--	--	--
Zr	< .15	--	--	--

*Chemical analyses being made

Symbols for spectrographic analyses:
- VS very strong
- S strong
- M medium
- W weak
- T trace
- -- not detected

Analyses were made for all elements listed

Wrapper sheet and spray-metal being analyzed

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Approved by: R. N. Lyon