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June 22, 1956

ROUGH DRAFT OF TECHNICAL DATA SUMMARY
COVERING PREPARATION OF INITIAL
MARK IIIA PLATES BY EXTRUSION CLADDING

The subjoined rough draft included several sections of a proposed Technical Data Summary covering the preparation and fabrication of the outer Mark IIIA plate and the plain Mark IIIA plate by extrusion cladding at SRP.

Will you please correlate this draft with the information to be supplied by the Laboratory in preparing a Technical Data Summary on the fabrication and testing of an interim Mark IIIA fuel assembly.

Attached to this memorandum is a working schedule of dates for the completion of this test program.

The attached draft is not be construed as directions for operating or manufacturing, but is issued for information and to elicit comments and suggestions.

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GOALS FOR EXTRUSION CLADDING OF PLATES

BMI - Data on end plugs July 1
 BMI - Data on extrusion speeds August 1

Building alterations (320M) Prior July 15

Tools delivered July 15

Set-up tools - Heat tests - Dry runs August 1

Ten runs with steel cores - narrow 3A design August 7

Nickel-plated 5-ft. length. No end plugs.
 Temp. tools, 1025-1050°F (552-566°C)
 Container, 1025-1050°F (552-566°C)
 Core, 975°F (525°C)
 Core speed - 4-10 ft/min.

Ten runs with steel cores - narrow 3A design August 15

Nickel-plated 14-ft. length.
 5 runs, integral end plugs.
 5 runs, leading end plug of steel attached.
 Conditions as above or revised from experience.

Changes to die and tip, if necessary August 15

Ten runs full length U plates - 3A narrow design
 evaluation to be made currently with extrusion August 15-20

Receive mandrel tip and die for wide plate September 15

Ten full length U cores, wide 3A design October 1

DISCLAIMER

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SECTION I - INTRODUCTION

This Technical Data Summary comprises the technical information that has been developed to date for the preparation by extrusion cladding of the outer plate (Figure 1, Drawing MDX1-437) of the contemplated Mark IIIA fuel plate bundle.

The Mark IIIA fuel bundle is designed to produce plutonium at higher power levels than is possible with the Mark I or Mark VII assemblies. The Mark IIIA and Mark V designs are being developed concurrently for the same purpose. The information, however, on the Mark IIIA design is at present far more complete than for Mark V, and equipment for producing Mark IIIA in test quantities is already available. The purpose of this Technical Data Summary is to have available the facilities for cladding, by an apparently attractive process, a Mark IIIA plate.

The approach to preparing Mark IIIA fuel elements has been three-fold, namely, (a) by hot step-pressing (DPSTM-700-III, 1/30/56; DPSTM-700-IIIA, in preparation); (b) by fluid pressure bonding; and (c) by extrusion cladding, which is the subject of this summary. From the data assembled in DPW-56-197, April 10, 1956, the extrusion cladding approach is decisively the most economical. It appears that the last process is the simplest and most practical of the three.

SECTION II - SUMMARY

The Mark IIIA fuel element is an assembly of natural uranium plates designed with a ratio of surface to volume that is about 2.5 times that of the standard slugs in a quatrefoil. The assembly is designed for operation with a coolant flow of about 250 gpm and at a pile power of 1800 to 2000 MW. The assembly contains five aluminum-clad plates (including two different core sizes and three different cladding cross-sections) assembled in an aluminum housing tube, and is a direct replacement of the quatrefoils.

In order to establish at the earliest possible time the working data and know-how on which to build a manufacturing process to extrusion-clad Mark IIIA plates, the outer ribbed and plain Mark IIIA plates (Figs. 1 & 3) will be extrusion-clad and bundled in a Mark III "B process tube" for evaluation and test. It is not expected that Mark IIIA process tubes in which to put the Mark IIIA plates will be available until October, so it is desirable to use the expedient of employing Mark III tubes temporarily in order not to delay the test program.

SECTION III - ADVANTAGES OF EXTRUSION CLADDING PROCESS

The extrusion cladding process for plate fuel elements appears more attractive than step-pressing, fluid pressure bonding, roll cladding, or other methods of sheathing for the following reasons:

- a) No preformed sheaths are required. These are an expensive item with a long delivery; they require careful handling, expensive storage, special cleaning, and involve difficult inspection procedures, especially for the internal bore.
- b) No assembly problem exists. With preformed sheaths, both cores and sheaths must be segregated into different dimensional groups within the manufacturing tolerances set for each, because a core at the maximum tolerance will not fit into the smallest I.D. sheath; under the reverse circumstances, too loose a fit occurs that results in seams and laps in the sheath.
- c) The soundness of the cladding over the core is better assured by bonding it to the core as the aluminum is extruded, instead of extruding separately a hollow sheath over a fixed mandrel that could be scoring or gouging during the process.
- d) With extrusion cladding the sheath thickness can be varied at will, and reduced to the thinness desired from the physics viewpoint, while maintaining the same integrity of metal. Other things being equal, an equally thin preformed sheath could not in practice survive the necessary handling.
- e) Stronger bonds have been obtained more consistently by the extrusion cladding process than by other cladding methods.
- f) Extrusion cladding involves less steps, fewer mechanical operations, and is all-around a more rapid cladding method than other processes.
- g) All of the foregoing have shown in cost estimation that extrusion cladding will develop an appreciable saving in fuel element costs.

SECTION IV - DESCRIPTION OF THE FUEL ASSEMBLY

A. The Assembly

The Mark IIIA assembly contains five plates of natural uranium clad with aluminum in an aluminum housing tube. Drawings of the Mark IIIA plates, housing tube, and assembly are shown in DPSTM 700-IIIA (in preparation at SRL). Since IIIA housing tubes are not expected to be available for the initial extrusion-clad uranium plates, this summary is based on employing for the interim assembly a Mark III process tube, and fitting into this an edge-planed Mark IIIA plain plate held between two Mark IIIA outer ribbed plates, which in turn are spaced away from the "Dees" of the Mark III process tube by aluminum shims. This interim assembly is shown in cross-section in Figure 2, and will contain three instead of five plates.

The assembly is made of three-piece top and bottom fittings, a housing tube called a "B process tube," and a bundle of three uranium plates. The plates are supported by the bottom fitting and are stabilized laterally by the chordal membranes ("Dees") of the "B process tube". Coolant channels are maintained by ribs that are an integral part of the aluminum cladding of the outside plates.

B. Active Components

The fuel for the Mark IIIA assembly is a bundle of five plates of natural uranium clad in aluminum, as described in DPSTM 700-IIIA (in preparation at SRL). The fuel, however, for the interim Mark IIIA assembly described in this Summary will be three plates (instead of five) of natural uranium clad in aluminum. The dimensions and specifications for these plates are shown in Figures 1 and 3 (Drawing Nos. MDX1-437 and MDX1-439). The overall thickness of the plates and the specifications for straightness are critical for loading the plate bundle into the process tube.

Since it will be necessary in this interim assembly to employ a Mark III "B process tube," into which the unribbed Mark IIIA plain plate does not fit until modified, it is necessary to mill off the beveled edges of the cladding shown in Figure 3 to produce the rectangular cross-section on this clad plate shown in Figure 4. The small, ribbed Mark IIIA plates shown in Figure 1 can be fitted into the Mark III "B process tube" without necessity for modification.

C. Structural Components

1. Housing Tube

It is not expected that Mark IIIA housing tubes will be available until October, so a Mark III "B process tube" will be used as housing tube; this is shown in Figure 5. It is an extrusion of 63S aluminum with two chorded membranes. The distance between these membranes and the membrane thickness of the tube are critical dimensions. The nominal clearance between the bundle of fuel plates and the membranes of the tube is 0.011 inch. This clearance is increased to about 0.026-inch over the ribs nearest the edges of the plates when the "Dee" sections of the tube are evacuated to about 28 inches of mercury.

During reactor operation the "Dee" sections are at a higher pressure than the coolant channels, and this differential pressure causes the membranes to deflect toward the plates.

Since the fuel bundle will contain only three instead of five Mark IIIA plates, and since the housing tube is a Mark III "B process tube," two aluminum shims are required to fill up the remaining space in the assembly. These shims will be used one on each side of the plate bundle between the outer ribbed plate and adjacent "Dee" membrane; their dimensions are shown in Figure 6, and their position in the assembly is shown in Figure 1.

Plugs are welded into the "Dee" sections of the "B process tube" as shown in Figure 7.

A solid plug, shown in Figure 8, is welded into the bottom of the tube and machined to provide a square surface for properly seating the bottom fitting. Each of the bottom plugs is drilled and reamed for a press fit with a stainless steel sleeve, Figure 9, that provides a leak-free connection from each "Dee" section of the tube to the bottom fitting.

After the chips and cutting oil are completely removed from the tube, the pre-drilled top plugs, Figure 10, are welded in place. The holes in the top plugs provide a means of evacuating the tube for loading, and permit coolant to enter the "Dee" sections during pile operation.

2. End Plugs

In order to assure an adequate cladding at each end of the uranium core, and in order to assure that there is sufficient metal in this end cladding to be able to weld thereto aluminum end fittings without alloying or thermally changing the metallurgical structure of the adjacent uranium core, it is required that the core have terminal end plugs preferably made of aluminum. These end plugs must be approximately of the same dimensional cross-section as the core, and a minimum of one inch long to provide sufficient metal for a weldment to the end fittings. A long end plug can easily be cut off to the desired length. The end plugs must be attached firmly to the ends of the uranium core in order to prevent deterioration of the joint by corrosion, to withstand rough handling, and to support the weight of the core. Both end plugs may be the same to avoid special front and rear handling of cores. A drawing of a typical end plug, showing the preferred methods of dovetailing to the end of a uranium core, whether integrally extruded or attached, is shown in Figure 11.

The most recent data from Battelle show that none of the common aluminum alloys have sufficient hot strength to resist "pinching off" when the plug is attached to the core and the assembly is subsequently subjected to extrusion cladding. This is particularly true of the

leading end plug; with the trailing end plug no difficulty is encountered, because the extruding aluminum follows the core through the die forming a bonded end plug, whether or not a separate end plug had initially been fastened to the core. When the leading end plug is made of steel or of metal with a higher hot strength than common aluminum alloys, no trouble is encountered; the aluminum cladding is then continuous over the core and end plug.

For this reason, the end plugs initially employed for this feasibility test will be made of carbon steel or of "SAP" (aluminum containing 12 v/o to 19 v/o aluminum oxide). Battelle is continuing, however, to look into other alloys of aluminum to see if something more suitable than steel can be found, and to develop integrally extruded aluminum end plugs. A "pusher mechanism" (a mechanical device incorporating two flat shoes to grip the core and push it about one-half to one inch out of the mandrel tip into the flowing aluminum) is being designed and built by the Mechanical Development Laboratory. This pusher will be placed at the entry side of the die block, so as to grip and push the core as close to the leading end as is practical. When this is operating satisfactorily, attached end plugs of carbon steel or of aluminum alloy will not be used, but integral end plugs will be extruded with the core with the help of the pusher. Consequently, Items 20 to 30 inclusive in the Flow Sheet will be eliminated with integral end plugs.

In order, however, to avoid last-minute delays in proving the feasibility of cladding full-length cores, planning has proceeded on using attached end plugs.

3. The Top Fitting

This is essentially as described in DPSTM 700-III, page III-3, except as may be modified for the higher flow rate of the interim assembly.

4. The Bottom Fitting

This is essentially as described in DPSTM 700-III, page III-4, but may require modification for the higher flow rate of the interim assembly.

SECTION V - ASSEMBLY

This is essentially as described in DPSTM 700-III, page V-1.

The principal exceptions are: a) In order to assemble the two sizes of plates in the Mark III "B process," it is first necessary to remove from the center plate (Figure 3), by dry machining, the beveled aluminum cladding to change the cross-section of the plate to that shown in Figure 4. This is

necessary in order to make the center plate fit inside the "B process tube". b) In order to take up the excess space between the two outer plates (Figure 1) and the chordal "Dees" of the "B process tube", it is necessary to use two of the aluminum shims shown in Figure 6. These shims are required for this initial feasibility test because only three of the eventual five plates will be employed in the assembly.

SECTION VI - DISASSEMBLY

This is essentially the same as described in DPSTM 700-III, page VI-1.

SECTION VII - SEPARATIONS

It is intended to transport these Mark IIIA fuel elements to the 200 Areas as full-length elements. No cutting, with attendant contamination by radioactive products, is contemplated.

SECTION VIII - FABRICATION OF ACTIVE ELEMENTS

This interim Mark IIIA fuel element will consist of three individual cores of natural uranium 13 feet, 6 inches long and 0.180 inch thick when clad. The cores will first be coated with nickel 0.0004 inch thick and then bonded in an aluminum sheath of 0.030 inch wall thickness by extrusion cladding. Aluminum end plugs may be integrally extruded with the cladding, or may be attached to and bonded to each core prior to cladding; information needed to firm up this detail is being developed by Battelle, and will be available by July 1. The end closure is obtained by welding aluminum end fittings to the bonded end plugs. The width and rib-to-rib height of the finished plate are controlled by the extrusion die.

Handling the plates between operations is a problem requiring special care. The high density of the material and the thin section reduce the rigidity of a plate to the extent that it must be supported at many points to prevent bending. Whenever possible, plates should be handled with the width in the vertical position to minimize the possibility of bending.

The process information is presented under the following headings:

- A. Process Description
- B. Process Data (Flow Sheet)

A. Process Description

1. Procurement of Components

Uranium Cores

The cores are rolled and machined by the Superior Steel Corporation. The experimental quantities of uranium plate required for this program will be

beta-transformed at Atlas Steels, Ltd. in Canada. For production quantities, it will be necessary to provide heat-treating facilities, preferably at the site where the plates are fabricated. The cores should be straightened and machined to specified dimensions by the vendor.

The cores are prepared as follows: Rectangular ingots 10-1/2" X 4" X 38" weighing about 1100 pounds each are cast at FMPC, and are slabbed at FMPC to 10-1/2" X 1-1/2" X 103". They are then sent to Superior Steel Corporation where they are machined to obtain flat surfaces and to remove surface imperfections. The slabs are preheated at 1150°F for 30 minutes in a 35% Li_2CO_3 -65% K_2CO_3 bath, cooled for about 60 seconds, and rough-rolled at around 1075°F to reduce the thickness from about 1-1/4" to 0.35" in 5 passes. The strip so produced continues from the roughing mill to the finishing stands, where it is reduced in 3 more passes to the thickness range 0.180" to 0.190". After cropping and cutting to length, the sheets are pickled, rinsed, and dried with forced dry air.

The resulting sheets 15 feet long by 10 inches wide are then shipped to Atlas Steels, Ltd., Welland, Ontario, where they are beta heat-treated by heating for 2 minutes in a salt bath at 1320° to 1360°F, cooling in air to 600°F, and finish quenching in water. Immersing in water removes the salt from the heat treating.

The sheets are then returned to Superior Steel Corporation where they are slit and edge-machined to the required width. They are then packed and shipped to SRP.

The specifications for the required bare uranium cores, given in DPST-55-437, are summarized below:

<u>Density</u>	<u>18.82 grams/cc minimum</u>
<u>Chemical Composition</u>	<u>Nat'l. U. with following impurities</u>
<u>Element</u>	<u>Quantity, ppm</u>
Carbon	150 - 700
Boron	0.25 max.
Iron	150 max.
Nitrogen	100 max.
Manganese	25 max.
Chlorine	20 max.
Silicon (reported as SiO_2 equiv.)	58 max.
Chromium	65 max.
Nickel	65 max.

Dimensions (See Figures 12 and 13)

- Length172 inches $\pm$ 1/2 inch.
(as received)
- Width 2 widths required:
2.460 inches $\pm$ 0.005 inch for ribbed plate.
2.940 inches $\pm$ 0.005 inch for plain plate.
Sides are machined; edges are broken with file.
- Thickness0.185 inch $\pm$ 0.005 inch.
(as received)
- End Design . . .This has not yet been established, and awaits data from BMI. It is known that trailing end plugs can be integrally extruded with the several end designs shown in Figure 11, but there are still insufficient data on leading end plugs to decide on the best of these for a leading end design. For this feasibility test, "SAP" end plugs will probably be used.
- SurfaceThe plates are inspected visually and rejected for surface defects which would interfere with bonding. Surface is as-rolled.
- StructureAn equiaxed beta-transformed structure is required.
- Straightness
- Camber0.030 inch/2 feet max. Max. of 0.060 inch
(saber curve) in 14 feet of length.
- Bow0.015 inch/foot max. Not more than one 0.015 inch bow for each foot of length. Max. of 0.060 inch in 14 feet of length. Straightness of plates is important to prevent excessive friction or jamming of the plates in the mandrel tip and die during extrusion cladding.
- Straightening . Plates that do not conform to the above requirements will be stretch-straightened.
- HandlingIn order to prevent bending and to maintain the plates as straight as possible at all times when being transferred from one operation to another, they will be placed in channels of aluminum or other suitable material. When not being transferred, the plates should be laid on tables.

Aluminum Sheaths

Each plate will be sheathed with aluminum by extrusion cladding. One billet of 1100 or of M-329 aluminum, about 6-5/8 inches in diameter by 9 inches long, is required to clad and to furnish bonded end plugs to each plate. Since in the extrusion-cladding process the sheath will be formed over the core, there are no dimensions for the sheath as such. The desired dimensional tolerances on the two different clad plates are shown in Figures 1 and 4.

2. Nickel Plating of Cores

The core is coated with nickel in an electroplating process that includes five main steps: (1) degrease, (2) acid pickle, (3) anodic etch, (4) acid etch, and (5) electroplate. Cores are placed in stainless steel racks for handling during cleaning and plating, and the rack serves as a "thief" during plating to minimize build-up of the nickel at edges and corners. Two or three cores may be plated in a single rack as long as each core is encircled by a thieving frame. Rack design must permit movement of the contact points at least once during the plating cycle, to prevent bare spots at the points of contact.

Adherence of the nickel plate to the core, and the subsequent diffusion during bonding are dependent upon obtaining a clean uranium surface for plating. The racked core is degreased to remove any oil remaining from the machining operation (to obtain metallographic samples, for end design, etc.), and is pickled in hot nitric acid to remove rolling scale. An anodized layer is then produced on the uranium surface by electrolytic treatment, and is subsequently removed by etching in a nitric acid solution.

Experimental results have shown that roughening the uranium surface before plating is an important step in achieving reproducibly good bond strength. The roughening procedures most successfully employed have been (a) dry grit blasting, and (b) anodizing. Recovery of uranium is simpler following the anodizing process, so this is preferred. Anodization and subsequent acid removal of the uranium oxide layer result in a removal of about 0.0015 inch of uranium from each surface of the plate. This treatment insures that electroplating is conducted on a fresh uranium surface. The surface layer of uranium that is removed often contains a high concentration of hydrogen. The total surface layer of uranium that is removed by pickling, followed by anodizing, followed in turn by acid removal of the oxide formed corresponds to a reduction of about 0.003 to 0.004 inch in the core thickness from the as-received condition (0.184 ± 0.004 inch to 0.180 ± 0.004 inch).

A layer of nickel about 0.0004 inch + 0.0001 inch thick is then deposited on the core from a high sulfate bath. With the present rack design the build-up of nickel at the edges is approximately twice the thickness of the layer over the surfaces, and this build-up extends about 1/8 inch from each edge and corner. Since the deposited nickel is relatively porous, the plated cores are dried in hot air to minimize the amount of retained moisture. The temperature and the time of the drying operation must be controlled to prevent oxidation of either the nickel or the uranium. The high sulfate bath was originally used as a "strike" bath, and the bulk of the nickel was deposited from a modified Watts bath. The Watts bath was discontinued because rinsing the plates in the process water available in the laboratory resulted in contaminated nickel plate. This contamination was caused by the high calcium content of the process rinse water, and can be eliminated by using deionized water.

Thorough rinsing of the electroplated cores is required to remove acids and salts, and to eliminate contamination of the electroplate.

3. Preparation of Components

The extrusion billets of 1100 aluminum or M-329 aluminum, about 6-5/8 inches in diameter by 9 inches long, must be lightly surfaced by machining dry in order to remove impurities and contaminants embedded in the surface. Since the billets are completely upset during extrusion, and therefore present oxide-free metal continuously to the core to be clad, no chemical cleaning is required.

4. Extrusion Cladding

The ground rules agreed upon for using the Watson-Stillman extrusion press in the 320 Building for this extrusion cladding program are (a) that the press shall not be changed or modified in any way that will prevent return to its original condition upon demand; (b) that this extrusion cladding program shall not in any way interfere with production requirements; and (c) that coated (electroplated) uranium cores be delivered to the extrusion press to avoid contaminating the 320 Building with uranium.

No modification of the Watson-Stillman press is required that would be in conflict with the preceding paragraph. This press does not have an opening extending from the hollow ram back through the cylinder to the outside of the press, so it is impossible to employ the Battelle method of making a fully coaxial extrusion.

There is, however, no difficulty in employing a modification of the Battelle approach with the Watson-Stillman press, in which the billet is forced to make a right-angled turn. This involves the manufacture of a container to fit the present container holder in the 320 Building press. This new container will direct the extruding billet of aluminum through a turn at right angles to the direction of ram movement, to meet and envelope the core which will travel also at right angles to the direction of ram movement. The new container will consequently be roughly L-shaped, with the die attached to the right-hand bottom end of the L, the core entering at the left bottom end of the L and exiting through the die, and the aluminum billet entering the top of the L, as viewed from the back of the press looking toward the die abutment. This is shown schematically in Figure 14.

As the billet is making effectively a horizontal right-angled turn, it is divided into two streams of aluminum by two portholes and a divider in the bore of the container. Each of the two streams of aluminum is thereby directed into a corresponding annulus formed by the container walls and an internally positioned mandrel. At this stage, there are two streams of aluminum flowing at right angles to the ram movement, and flowing parallel to the core, which is moving also at right angles to the ram movement inside the hollow mandrel which acts both as a core guide and as a separator to prevent the aluminum from making contact with the core at this stage.

The two streams of aluminum now are forced through additional portholes to fan out and distribute the metal as symmetrically as possible around the tip of the hollow mandrel, so that a uniformly advancing sheath of aluminum will be available to envelope and bond onto the nickel-plated core as the latter emerges from the mandrel tip.

Fastened to the exit-end of the container, and spaced 0.040 to 0.100 inch beyond the mandrel tip is the extrusion die. The pressure-temperature-time relationships necessary to weld the portholed streams of aluminum integrally together, and to bond the aluminum to the nickel-plated core, are developed in this 0.040 to 0.100 inch welding chamber in front of the die. The die then acts as a sizing and shaping guide for the extrusion-clad core. A separate die and mandrel tip combination is required for each different core size; a different die is required for each change in rib height.

Although extrusion is a commercial process of many years standing, the relationships between the pressure applied to the ram, and the pressure exerted by the extruding metal on the die, mandrel, or core have not been sufficiently investigated to be thoroughly understood. From data at hand,

it is expected that 30,000 to 60,000 psi will be applied on the billet in the Watson-Stillman press to extrusion-clad a core; this is a small fraction of the 2750-ton capacity of the press. From a few experiments at BMI and at Moczik Tool and Die Co., it can be rationalized that the corresponding pressure on the nickel-plated core in the welding chamber is 5000 to 7000 psi, and that the bulk of the applied pressure is required to overcome the friction of the flowing aluminum against itself, against the container walls, and through the porthole orifices.

In order to extrude a trailing end plug integrally bonded to the core and sheath, one simply continues to extrude aluminum after the clad core has emerged from the die. It is not difficult to determine empirically how much billet is required to clad a core, and how much longer the billet must be to provide the required end plugs. In practice, it is easy to see where the clad core ends and the end plug begins, because the coefficient of thermal expansion of aluminum (24×10^{-6} in/ $^{\circ}$ C) is greater than that of uranium (17×10^{-6} in/ $^{\circ}$ C), so the all-aluminum end plug upon cooling shrinks more than the thinly clad core. Experience indicates that on an extrusion-clad core 3.220 inches wide by 0.240 inch thick, an integrally extruded end plug will be about 3.212 inches wide by 0.235 inch thick, with no deterioration of the bond between end plug and core or sheath.

In order to extrude a leading end plug, one begins to extrude aluminum before forcing the nickel-plated core into the flow of aluminum. Once the aluminum has come into contact with the core, the extruding aluminum draws the core continuously with it when the Battelle design of mandrel tip and die is employed; this type of extrusion cladding has been called the "self-propelling core method" as distinguished from the "pushed core method" employed less successfully by Battelle, in which design it is required that the core be pushed continuously during the cladding operation. For several reasons, particularly to avoid complications in synchronizing independent pushing mechanisms, it is desirable to have self-propulsion of the core. This seems best realizable by using inserts of steel or of an aluminum alloy dovetailed into the leading end of the core, so that these will protrude sufficiently from the mandrel tip to become clad by the aluminum and thereby to ensure self-propulsion of the core. Battelle is presently working on several configurations of inserts and core-ends to determine the most satisfactory of the presently planned approaches. The two most interesting plans are sketched in Figure 11.

It is planned initially to extrusion-clad one core, complete with end plugs, per billet of aluminum. With experience, however, this plan may be changed to produce two or more clad cores per billet. The extrusion cladding

rate is planned initially to be between four and ten feet per minute. The cladding rate being used at Battelle at this writing is one-half foot per minute, and will continue to be held at this rate during studies of the leading end plug design. It is not considered desirable to change the rate during this study. It is expected, however, that data will be available from Battelle by July 30 on the relationship between bond strength and cladding rate for the same die. The only other experience that is presently available to rely on is that of Chalk River, who found bond strengths of 2000 psi to 5000 psi at an extrusion cladding rate of 22 feet per minute, versus strengths of 8000 psi to 12,000 psi for a cladding rate of 8 to 10 feet per minute. Their die design, however, was sufficiently different from Battelle's that one cannot extrapolate the present Battelle 27,000 psi at one-half foot per minute to a low figure at a higher cladding rate. It should be possible to increase considerably the cladding rate with a relatively small change in average bond strength.

In order to use the Watson-Stillman press without modifying the existing hydraulic cylinders at approximately ram level between the container and die-head, and since these cylinders may interfere with extruding at a right angle within the horizontal plane, it may be necessary to tilt the extrusion downwards about 15° from the horizontal, so that the incoming core on its run-in table will pass over one of these cylinders, and the clad core on its run-out table will pass under the cylinder on the other side of the press. This would involve twisting the L-shaped container about 15° on its up-and-down axis (as L is typed on paper) in order correspondingly to depress the tip at the lower right. Such an arrangement would in no way affect extrusion cladding, but might be aesthetically undesirable. The ground rules reasonably exclude modification of these cylinders; in a production line, the position of the cylinders on a new press would be specified to provide against any interference, and a different type of press would be used.

5. Extrusion Cladding

Process

The extrusion tools, namely, the container, die block, die and mandrel tip, are heated in position by embedded Calrods to $1025-1050^\circ\text{F}$ ($552-566^\circ\text{C}$). The billet is preheated in a separate furnace to 1025°F (552°C).

The die housing and core preheat furnace are purged with argon. A flow of argon is maintained through the system during extrusion. The flow necessary to prevent oxidation of the core will be determined experimentally when the equipment is in use.

The billet is inserted in the container, and the ram, with attached dummy block, is advanced. Aluminum is extruded until the portholes of the mandrel tip are filled, but no aluminum is in the die.

The core is placed on the entrance transfer table, moved into the preheat furnace and die block, and positioned in the mandrel tip. When no aluminum is in the die, a steel plate inserted through the exit side of the die will serve as a stop in positioning the core. The core pusher is then engaged to grip the plate and hold it flush with the mandrel tip slot.

The core is allowed to preheat for about 3 minutes prior to extrusion to attain a temperature of 975°F (525°C). The preheat time will be dependent upon the heating equipment used and will be determined when the equipment is available.

Pressure is applied to the billet using experimentally determined ram speeds corresponding to plate speeds of 4 to 10 feet/minute. The optimum plate speed will be dependent upon the length of plate which is preheated. With the core in the mandrel slot a solid aluminum end plug is extruded; the core pusher holds the plate against the back extrusion pressure. When the desired length of end plug has been extruded the core pusher forces the plate into the die where it is enveloped by the flowing aluminum. A bond is formed between the nickel-plated core and the aluminum at the die opening, and the clad piece is propelled through the die with the extruding aluminum. Shaping of the core end may facilitate pick-up of the core by the extruding aluminum.

The pusher mechanism releases the core as the latter enters the die.

As the first core passes through the die block a second core is held lightly against the trailing end of the first, and is stopped in the mandrel slot by the extruding aluminum. As the second core stops it is immediately gripped by the core pusher to prevent back extrusion into the mandrel slot.

When the trailing end of the first core has passed through the die and an end plug has been extruded, the ram is stopped and the extruded aluminum is cut with a saw so that the clad plate may be removed with handling equipment.

While the clad plate is being removed, the second core, which has been gripped in the mandrel slot, is being preheated. This plate is then clad in the same manner as was the first.

It may be found necessary to use a dummy steel follower after each core rather than using consecutive cores. This would be a short length of plate used to plug the mandrel slot until the following core is preheated. It would then be clad as a core, with a trailing end plug. When the extrusion is stopped it could be removed and the following core clad in the above manner.

It is not known at this time if the force required to hold the plate in the mandrel tip against the back extrusion, and to push it into the die, will cause buckling of the soft preheated core; however, precautions have been taken to support the core between the pusher and the mandrel slot so as to minimize buckling.

Since an attached dummy block is used, billets may be fed into the container continuously. As each billet is extruded the ram and dummy block are retracted, and a fresh billet is inserted. This operation is conducted while a clad plate is being removed and the following plate is being preheated.

When it is necessary to remove the die housing after a run, a small steel dummy is used to plug the mandrel slot; the gate lock is released and the aluminum butt and die block are pushed out with the ram. When these have been freed from the container they are carried out through the platen with the die head, and an electric saw or a shear cuts the butt flush with the die block, leaving no gap for entrapped air. The aluminum may be left in the die housing, to be extruded out or used for cladding during the next run.

No lubricants are to be used where they might come in contact with the core or the aluminum. These areas include the I.D. of the container, the dummy block, billet, ports, mandrel slot and working faces of the dies.

An alternate method to extruding integral end plugs is that of cladding attached end plugs. This method has proven satisfactory using machined steel end plugs, but as yet SAP (Al + 19 v/o Al_2O_3) is the only aluminum alloy found which has sufficient strength at 1000°F (537°C) to withstand the pressures at the die tending to "pinch off" the end plug.

The core, with attached end plugs (Figure 11) is placed on the entrance transfer table, moved into the preheat furnace and die block, and positioned in the mandrel tip. The leading end plug extends through the die opening approximately one-half inch to provide a means of starting the core. When the core has been heated, aluminum is extruded through the die, cladding the end plug and the core which are propelled through the tools.

As the first plate is being clad the second, with attached end plugs, is placed on the transfer table and manually pushed to butt against the trailing end of the first. With only a light pressure maintained on the trailing plate it will be stopped in the mandrel tip, preventing back extrusion as the extruding aluminum forces the first plate through the die. The pushing mechanism is immediately engaged to grip the entering plate, and the extrusion is stopped so that the clad plate may be removed.

When the second plate has been preheated to the desired temperature the extrusion is continued and the plate is pushed into the flowing aluminum to be clad. A short steel dummy may be used in place of the following plate to plug the mandrel slot while the following plate is being preheated or a billet is being inserted into the container. The steel dummy is extruded out with a following plate as is the normal procedure.

6. Tool Clean-Out

Tool clean-out is not anticipated after each run nor after each shift. It should be possible to reheat the tools and extrude out the remaining aluminum after periods of shutdown.

For the tools to be used with the 2750-ton press in the 320-M Building, the die block and butt will be freed by pushing the ram through the heated container. They can then be carried out by the die head. The outer shell of the die block is in two sections which fit over the tapered inner shell. Removing this outer shell permits the split inner shell to be placed in caustic to remove the aluminum from the ports and die. When this section is clean it may be opened, and the die and mandrel tip removed. These sections are to be thoroughly cleaned and inspected before reassembly.

7. Equipment

The description of equipment for this process will cover only one particular installation. It is that proposed for cladding plates using the extrusion press in the 320-M Building. This method is not the most desirable for production use, but is an expediency in adapting a workable method to existing equipment in order to obtain extrusion clad plates in the shortest possible time.

a. Assembly

Plates are to be clad in the 320-M Building at SRP using the 2750-ton extrusion press. The plate being clad will travel in a nearly horizontal plane at right angles to the center line of the ram and container of the press. A large circular die block, consisting of two concentric split shells designed for easy disassembly, will contain

the mandrel tip and die, which are an adaptation of the coaxial extrusion cladding experiment which has been developed at Battelle for short lengths of plate.

Auxiliary equipment includes an entrance transfer table with a preheat furnace and an argon atmosphere to prevent oxidation of the core, a core pushing mechanism, and a run-out table and special handling racks to carry the finished plates from the press.

b. Die Housing

The die housing is a cylinder of approximately 25-inch diameter by 18 inches thick, positioned between the container and die abutment of the extrusion press, as shown in Figure 14. Since a maximum of 5-1/4" clearance is available between the container and the platen, the die housing will be recessed into each. These provide additional strength to resist the high bursting pressures anticipated with the tools. To facilitate cleaning and disassembly the housing will be constructed of four sections, as shown in Figure 15. Two of these form the outer shell and two the inner shell.

(1) Outer Shell

The outer shell consists of two cylinders, A and B, of about 25-inch O.D. with tapered internal diameters. Keyways position the unit so that it may be passed through the die abutment with the sliding die head. Pressure from the container and ram compresses the two sections against the bolster, providing the means of sealing the tapered inner shell, C and D.

The cylinders are machined from Braeburn PD-2 die steel to provide the required hot hardness and toughness at temperatures up to 1100°F. The sections must be maintained at a hardness of $R_c 44$.

(2) Inner Shell

The inner shell consists of a tapered cylindrical section (C and D). The taper, matched to that of the outer shell, provides a means of sealing against the internal pressures developed during the extrusion. A tapered seal seats against the container. The mandrel tip (G), extension (F), and die (E) fit into the cavity of the split shell.

As the billet is extruded from the container it passes through a single port of 3-1/2-inch diameter which is then split into two 2-inch ports designed to feed the

aluminum at the two flat faces of the plate. These ports turn a 90° angle from the center line of the container so that the aluminum is flowing in the direction in which the plate will be moving. Each of the two ports feeds into a kidney-shaped mixing chamber which in turn opens into three of the six ports of the mandrel tip.

The inner shell is machined from Braeburn T Alloy tool steel, as is the outer shell, and must be maintained at a hardness of $R_c 44$.

(3) Mandrel Tip and Guide Unit

The mandrel tip (G) and guide (F) are shown in Figure 15. This unit, with the die, is placed in the inner shell of the die housing such that each of the two mixing chambers of the inner shell feeds into three ports of the mandrel tip. This porting system is designed so as to feed aluminum around the core with a uniform flow and pressure at all surfaces.

The aluminum leaves the ports and flows over the tip of the mandrel into the final mixing chamber between the tip and the die. Here the aluminum is in contact with the core and forms a bond with the nickel under the proper time, temperature, and pressure conditions. As the bond is formed the flow of aluminum through the die carries the plate forward.

The mandrel tip is the most critical part of the extrusion tools. The six ports must provide uniform pressures and aluminum flow to the core in order that the latter will be centered in the die and subsequently in the sheath. The shape of the tip is important in directing the flow of the aluminum to induce "self propulsion" of the core. A tip that is not streamlined leads to high extrusion pressures and excessive forces normal to the surface of the core; these tend to grip the core and prevent propulsion. Severe streamlining of the tip leads to a weak member which is subject to excessive deflection at extrusion pressures, with resultant pinching or restriction of the core in the slot.

Sufficient clearance must be allowed in the mandrel slot to compensate both for the deflection of the tip and for variations in the core cross-section. If the clearance is too great, back extrusion of aluminum around the core, and restriction of the core, may result. This clearance is dependent upon the degree of streamlining of the tip, the die used, and the extrusion pressures used; Figure 16 illustrates one design which has proved satisfactory in early developments.

It can be seen that the clearance increases from the edge to the center of the slot as does the deflection.

The plate is guided into the mandrel tip slot through a hollow cylinder (F in Figure 15) which extends through the outer shell to the preheat area. This extension is pinned for alignment of the back guide with the mandrel slot.

The mandrel and guide are made from Braeburn T alloy steel hardened to $R_c 44-46$. This alloy has very desirable high temperature properties.

(4) Die

The die, E in Figure 15, used to form the aluminum sheath on the core, is pinned for alignment with the mandrel slot. A swage bearing seems, from the data available, to be optimum for good bonding and for filling at the ends of a plate when extruding integral aluminum end plugs. Shear bearings require somewhat lower extrusion pressures but tend to produce poorer bonds and poorer extruded end plugs than do the swage bearings. Severe swage bearings (90° included entrance angle) are excellent in these respects but require higher pressures and show a greater tendency for back extrusion of aluminum in the mandrel slot. The slight swage bearing is a compromise of these two types. More evaluation on the effects of shear, swage, and radius bearings may be advisable at a later date.

The bearing length of a die varies as the cross-section of the sheath varies, and is determined by the die maker. Minor corrections may be required of each new die after initial extrusions.

The die is made of Braeburn T alloy steel hardened to $R_c 44-46$.

(5) Heating of the Die Block

The die block is heated by means of 24 cartridge-type heaters spaced around the outer shell. The total output of the heating elements is 40 KW at 440 volts. The temperature of the block is regulated by controllers with thermocouples placed close to the die and billet areas.

The elements are removable so that the outer shell (A and B) may be separated to disassemble the tools.

c. Auxiliary Equipment

The run-in table, preheat furnace, core pusher, and run-out table are in the design stage; however, a general description of these items is included in this document.

(1) Transfer Tables

The design of entrance and exit transfer tables for use with this equipment is not yet complete; however, the general characteristics which are desired will be discussed.

The entrance transfer table will be enclosed, in part, by the preheat furnace. It should have, in addition to the bottom rollers, side and top rollers at intervals of about 2 feet to maintain alignment of the plate as it enters the die. If possible, the side and top rollers should be hinged, as a unit, to the bottom roll section to facilitate removal of a jammed or buckled plate from the die.

The rolls of the lower section should be spaced at close intervals of 3 to 4 inches to prevent sagging of the core, when it is stationary and at temperature.

The end of the transfer table nearest the die should fasten to the pusher mechanism which in turn will be fastened to container, or some section of the press, for rigidity.

The run-out tables need only to supply support and a guide for the plate as it leaves the die.

(2) Preheat Furnace

The preheat furnace will serve to heat the core and to contain the inert gas atmosphere. Calrod-type heating elements will be interspersed with, or around, the rollers of the run-in table. The furnace is to be in sections so that the length of core which is preheated may be varied. Initially, the entire core will be heated; as the program continues it is hoped that the furnace may be shortened so that the core will be heated as it passes through a section adjacent to the die housing. The core pusher will also be inclosed by the furnace in this area. Inlets for the inert gas should be provided on each section of the furnace.

(3) Core Pusher Mechanism

This unit will be essentially two flat shoes which will be driven so as to grip the plate on the wide faces to hold it positioned in the mandrel tip. A forward

The shoes will be of sufficient area to prevent deformation of the plate. Although the shoes will be in the heated zone, the drive mechanism may be located outside of the furnace. The shoes will be placed as close to the die housing as is possible in order to minimize the tendency for buckling of the heated core.

on Clad Cores

The specifications for the extrusion-clad plates follow:

a. Outer Ribbed Plate (Figure 1)

Overall length of clad 172 inches + 1/2 inch max.
core and end plugs.

Thickness (away from ribs) 0.240 inch $\pm$ 0.008"

Overall thickness Min. 0.587"; max. 0.593"

Length of clad core 162 inches + 1/2".
Length of end plugs Not firmed up; min. 2"; max. 5"

Width (bevel) 3.160 inches + .010"
- .005"

[REDACTED]

9. Testing and Straightening

The finished plates are inspected for dimensional tolerances, and tested nondestructively for bond continuity, sheath quality, and soundness of end closure. Bond continuity is measured by means of ultrasonics. The soundness of the end closure and the location of the ends of the core are revealed by fluoroscopy or X-radiography. The quality of the sheath is determined by visual inspection for surface defects, spot tests for contamination and residual cladding thickness, and by autoclaving the plates at 175°C for 48 hours in saturated steam at 125 psi. It is recommended that the plates be autoclaved in the vertical position.

Straightness specifications are as follows: (1) camber: less than 1/2 inch in 15 feet; (2) bow: less than 1 inch over 15 feet or less than 1/4 inch over any 1 foot length. The plates should be straightened, if necessary, by gag pressing before autoclaving. Then when the plates are transferred to the vertical position for autoclaving, the straightness can be remeasured.

A final visual inspection of the surface of the plate should be made after autoclaving.

10. Reject Plate Recovery

Aluminum is removed from reject plates by etching in a solution of NaOH and NaNO_3 . The nickel electroplate is then removed with HNO_3 . The stripped plate is either recycled to the plating operation or is scrapped, depending on dimensional tolerances and surface quality. With the extrusion cladding process, it will be possible to use plates with 10 mils thinner cladding than has been considered safe or practical for the other processes. Consequently, rejection will be for other causes than thinness of cladding.

11. Waste Solutions

Waste solutions that contain uranium are neutralized and filtered to recover the uranium. These operations are similar to those in use in 313-M Building, except that phosphoric and hydrochloric acids are present, and the anodic etch solution must be oxidized with H_2O_2 before neutralizing, in order to prevent formation of an unfilterable precipitate.

B. Process Data

The operations required for extrusion cladding plates are given in the following flow sheet. Based on experience with step-press-clad plates, and on judgment about the probable performance of extrusion cladding, rejects should be limited to 10% of

as-received cores. Half of this, or 5%, should be reclaimable because 2 widths are required, so excessively wide plates can be machined to the tolerances of one or the other of the two widths.

An additional 2% of the cores may be rejected for nickel electroplating defects, of which half should be reclaimable by stripping. This brings the cumulative total of rejects to 6%.

A further 3% rejection of extrusion clad plates for a variety of causes (voids at end plugs, uncentered cores, bowing during cladding) may be experienced, of which half should be salvageable by stripping and reprocessing.

The maximum rejection of fuel plates through fabrication should therefore be limited to 7-1/2% for all causes and the yield should correspondingly be 92-1/2%.

WJOL/jss

FLOW SHEET
FABRICATION OF PLATE FUEL ELEMENTS BY
EXTRUSION CLADDING

DPW-56-276

17. Cold process H_2O , 1 minute.
18. Cold deionized H_2O .
19. Forced dry air, 70° - $80^{\circ}C$ to remove moisture, 1 minute.
20. SAP plug machined to fit dovetail slots in core (shape and dimensions dependent on data for forthcoming from BMI)
21. Inspect for dimensions.
22. Trichlorethylene, 2 minutes
23. Chemical make-up lb/100 gal.

CuCN	...	33
NaCN	...	41
Na_2CO_3	...	24
Rocheile salt	...	48

 40° - $45^{\circ}C$, 30 amp/ft², 1 min.
 This is to deposit about 0.01 mil of copper in order to facilitate later nickel plating for bonding.
24. Cold process H_2O , 1 min.
25. Nickel flash. Use solution of Item 31 at $35^{\circ}C$, 5 min. at 16 amp/ft². This is to deposit about 0.05 mil nickel over the copper, to prevent a copper-uranium interface at the dovetail joint.
26. Cold process H_2O , 1 min.
27. Cold deionized H_2O
28. Inspect for complete coverage of copper on dovetail by nick. Do not store over 2 days before cladding.
29. Handle with clean dry gloves. Use cloth padded arbor press assemble dovetailed joint at both ends of core.
30. Inspect for fit of dovetail, concentricity of core and end plugs

31. Chemical make-up lbs/100 gal.
 $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$ 58.
 $\text{Na}_2\text{O}_4 \cdot 7\text{H}_2\text{O}$ 133
 (or $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$)
 NH_4Cl 12.5
 H_3BO_3 12.5
 Activated carbon 5
 H_2O_2 30% 1 pin
 35°C, 40 min. at 16 amps/ft²
 or 20 min. at 32 amps/ft².
 This will deposit 0.4 mil
 nickel for bonding.

32. Cold process H_2O , 1 minute.

33. Cold deionized H_2O , 1 minute.

34. Hot deionized H_2O , 70-80°C.

35. Forced dry air, 70-80°C., 1 min

36. Inspect for plating defects.

37. Use polythene wrap and metal channel to avoid bending and damage to electroplate. Do not store more than 2 days after plating. If obliged to store over 5 days, Canadians rub with steel wool before cladding.

38. 2S or M-329 aluminum, furnished to size.

39. Skin cut by dry machining to remove possible surface contaminants.

40. Inspect for dimensions, cleanliness, gross inclusions,

41. 1000°F (538°C) in billet furnace, 10 minutes.

42. From Moczik Tool and Die Works

43. Initial preheat to 1000°-1050° (538°-566°C).

44. Tank gas.

45. Continuous flush of preheat furnace on run-in table.

46. 2750-ton horizontal press in 320 Bldg. Initial push to fill portholes.
47. Preheat 2 minutes with argon flush.
48. 4 to 10 ft/min., 30,000 to 60,000 psi at 1000° to 1050°F (538° to 565°C).
49. Traveling saws to cut off excess leading and trailing end plug sections.
50. Surface condition, wrinkling, straightness.
51. For voids at end plugs.
52. Ultrasonic test.
53. Eddy current test.
54. Critical dimensions, concentricity of cladding.
55. Dry machine to remove Al bevels on sides, until IIIA Process Tubes are ready.
56. Gag press to remove bow and camber.
57. Vertically at 170°C, 125 psi steam, 40 to 48 hours.
58. For stained surface, gouges, general appearance.
59. All clad rejects.
60. 15% to 20% NaOH, 20% NaNO₃, 40° to 90°C, 2-1/2 hours
61. Cold water, 2 minutes
62. 40% to 50% HNO₃, 70°C, 3 to 5 minutes.

63. Cold water, 2 minutes.

64. Hot water, 55° to 65°C,
1 minute.

65. Forced dry air.

66. "B" Process Tubes, aluminum
shims, top and bottom fittings

FIGURE 1**CROSS SECTION** **MATERIAL:**

SHEATHS - 1100 ALUMINUM

TOLERANCES

FRACTIONAL ± 1/64"
CAMBER 1/32" PER FOOT OF LENGTH
BOW 1/32" PER 2 FEET OF LENGTH

OUTER PLATE

MDXI-437

FIGURE 2

ASSEMBLY
MARK III-A PLATES IN
MARK III PROCESS TUBE

SCALE: 2" = 1"

FIGURE 3

CROSS SECTION

MATERIAL:

SHEATH - 1100 ALUMINUM

TOLERANCES

FRACTIONAL ± 1/64"
CAMBER 1/32" PER FOOT OF LENGTH
BOW 1/32" PER 2 FEET OF LENGTH

CENTER
PLAIN PLATE

MDXI - 439

FIGURE 4CROSS SECTION MATERIAL:

SHEATH - 1100 ALUMINUM

TOLERANCESFRACTIONAL $\pm \frac{1}{64}$ "CAMBER $\frac{1}{32}$ " PER FOOT OF LENGTHBOW $\frac{1}{32}$ " PER 2 FEET OF LENGTHCENTER PLATE

MODIFIED TO FIT INTO

MARK III B PROCESS TUBE

FIGURE 5

MAT'L: 6063 AL.

REFERENCE DRAWING NO. E26830 (DUPONT ENGINEERING SKETCH)

"B" PROCESS TUBE

FIGURE 6

**SHIMS FOR
MARK III PROCESS TUBE**

SCALE: 2" = 1"

B" PROCESS TUBE WITH END PLUGS

FIGURE 8

MAT'L: 63S-T6 ALUMINUM
 125 FINISH ALL OVER

TOLERANCES

ON ALL DIMENSIONS
 FROM FINISHED SURFACES
 EXCEPT AS NOTED.

TO BE
 DECIMAL $\pm .005$ "
 FRACTIONAL $\pm 1/64$

"D"-PLUG (BOTTOM)

MDXI-193

FIGURE 9

TOLERANCES
ON ALL DIMENSIONS
FROM FINISHED SURFACES
EXCEPT AS NOTED.

TO BE
DECIMAL $\pm \frac{1}{64}$ "
FRACTIONAL $\pm \frac{1}{64}$ "

MATERIAL: $\frac{1}{2}$ " O.D. x $\frac{1}{16}$ " WALL 304 S.S. TUBING

RE-ENTRANT TUBE

FIGURE 10

MATERIAL: 63S-T6 ALUMINUM
¹²⁵ FINISH ALL OVER

TOLERANCES

ON ALL DIMENSIONS
 FROM FINISHED SURFACES
 EXCEPT AS NOTED.

TO BE
 DECIMAL $\pm .005^{\circ}$
 FRACTIONAL $\pm \frac{1}{64}^{\circ}$

'D'-PLUG (TOP)

MDXI-199

FIGURE 11 **CORES & END PLUG DESIGNS**

FIGURE 12**CROSS SECTION
AND
LENGTH** **CORE OF MDX1-437**

FIGURE 13

CROSS SECTION
AND
LENGTH

CORE OF MDXI-439

FIGURE 14

FIGURE 15.

DPW

FIGURE 16

MANDREL TIP SLOT
FOR BMI TOOLS