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IMPROVED FABRICATION TECHNIQUES FOR LITHIUM-6 FLUORIDE-TEFLON AND LEAD SHIELDS FOR GAMMA DOSIMETRY

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UNION CARBIDE CORPORATION
NUCLEAR DIVISION
OAK RIDGE GASEOUS DIFFUSION PLANT

operated for the **ATOMIC ENERGY COMMISSION** *under* **U. S. GOVERNMENT** **Contract W-7405 eng 26**

**UNION
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Printed in the United States of America. Available from Clearinghouse for Federal
Scientific and Technical Information, National Bureau of Standards,
U.S. Department of Commerce, Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.65

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Date of Issue: December 22, 1969

Report Number: K-1779

Subject Category: HEALTH AND SAFETY

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FLUORIDE-TEFLON AND LEAD SHIELDS FOR GAMMA DOSIMETRY

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UNION CARBIDE CORPORATION
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*Presently located in the Stellite Division, Union Carbide Corporation, Kokomo, Indiana.

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ABSTRACT

This report reviews the development of fabricating lithium-6 fluoride-Teflon (Li^6F -Teflon) and lead shield assemblies to provide inexpensive dosimeters for gamma radiation. The newly developed techniques include molding, in one pressing, the complete Li^6F -Teflon shield with a center hole for silver-activated phosphor glass rod detectors; lead foil serves as the lead source for the shield assembly. A description of the equipment, as well as the automation portion of the pressing procedures, is also presented in this study.

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CONTENTS

	<u>Page</u>
INTRODUCTION	7
SUMMARY.	9
FABRICATION OF Li^6F -TEFLON SHIELDS	9
Preparing the Li^6F -Teflon Mixture	9
Prepressing the Li^6F -Teflon Mixture	13
Ram and Die Design.	13
Loading the Die	15
Pressing the Shields.	15
Automation.	20
Removing the Shield From the Die.	20
Cutting the Double Half-Shield Into Half-Shields.	24
Control Tests	24
FABRICATING THE LEAD SHIELDS	28
Preparing the Blanks.	28
Die and Rams.	33
Loading the Lead Blank for Pressing	33
Pressing the Shields.	33
Punching the Shield Caps.	35
Control Tests	35
PRODUCTION AND COSTS	35
Production and Costs of the Li^6F -Teflon Shields	36
Production Costs of the Lead Shields.	36
Combined Cost of Shield Assembly and Materials.	37
ACKNOWLEDGMENTS.	37
REFERENCES	38

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FLUORIDE-TEFLON AND LEAD SHIELDS FOR GAMMA DOSIMETRY

INTRODUCTION

The handling and processing of large quantities of highly enriched uranium at the United States Atomic Energy Commission (USAEC) installations require monitoring these areas for a possible accidental nuclear excursion. The detector system described by Hurst and Ritchie (1) was designed for measuring radiation from such an incident. In that design, two silver-activated phosphor glass rods, which provide duplicate measurements of gamma radiation, were encased in a metallic lithium shield or container. This resulted in a bulky and relatively expensive system. A more practical approach was needed.

More recently, Bailey (2) explored the possibility of developing a less expensive detector system, and designed a new shield for the phosphor glass dosimeter. The newly designed shield was less costly than the metallic lithium shield, and, in addition, would fit the dosimeter insert of personnel film badges currently in use. In the Bailey design, a Li^6F -Teflon shield protects the silver-activated phosphor glass rods from thermal neutrons; and a lead shield, which slips over the Li^6F -Teflon shield, provides protection from low-energy gamma radiation. The Li^6F -Teflon shield was fabricated by hot-pressing a mixture of Li^6F and Teflon, and the lead shield was cold-pressed from lead powder. Contained in these shields, the silver-activated phosphor glass rods would show only the intensity of the higher-energy gamma rays. Since these rays are the more damaging, it is especially important that they be measured selectively.

The attractive characteristics of the Bailey shield system resulted in continued effort at the Oak Ridge Gaseous Diffusion Plant (ORGDP) toward practical production of the shields. Foley and White (3) showed that hot-pressing a mixture of Li^6F and fluorocarbon resin powders into suitable shields for the glass rods was feasible. Bailey continued the development work and initiated production by assembling equipment, including a degree of automation, and formulating tentative procedures for pressing both the Li^6F -Teflon and the lead shields. Lee (4) established the economical feasibility of the pressing method on a production basis, and also improved equipment and techniques, including automation, for pressing the Li^6F -Teflon and lead shields. He fabricated 200 Li^6F -Teflon shields: 100 for Edgewood Arsenal, Edgewood, Maryland; and 100 for testing and development work at ORGDP. The brief production effort was combined with development in a program designed to meet precision dimensions and mechanical strength, and to progressively reduce unit costs.

Continuing with the development of production methods initiated by Lee, improved and more economical techniques for fabricating the Li^6F -Teflon and lead shield assemblies were achieved. Twenty-four hundred shield assemblies were fabricated. An enlarged view of a complete dosimeter, including two silver-activated phosphor glass rods, is shown in figure 1. This report details the development of practical techniques for producing the Li^6F -Teflon and lead shields, and discusses the economics of production.

Figure 1
DOSIMETER ASSEMBLY, INCLUDING PHOSPHOR GLASS RODS

SUMMARY

Twenty-four hundred dosimeter shield assemblies were fabricated. New techniques were developed to improve the quality and reduce the cost of the assemblies. The development resulted in reducing the number of pressings required for a Li^6F -Teflon shield from 2 to 1, molding the center hole for the silver-activated phosphor glass rods, improving the die design, and automating the pressing cycle. Techniques were developed to use lead foil for fabricating the lead shields instead of lead powder, used in previous assemblies. The lead foil provided a superior shield at greatly reduced cost. The newly developed techniques reduced the effort required to fabricate a complete shield assembly from 74 to 16½ min, which represents a 78% reduction in fabrication time of previously used techniques. The economics involved are discussed and suggestions for further cost reductions are made.

FABRICATION OF Li^6F -TEFLON SHIELDS

Fabricating the Li^6F -Teflon shields involved preparing the Li^6F -Teflon powder mixture and forming the shields. The powder mixture was prepared by mixing Li^6F with Teflon powder and prepressing the mixture to improve the molding properties. The shields were formed by hot-pressing the prepared powder mixture into a cylindrical rod having molded holes and male and female ends, as shown in figure 2. The cylindrical rod, which is referred to as a double half-shield, was cut into male and female half-shields, shown in figure 3. Figure 3 also shows the dimensions of the half-shields. The male and female half-shields were assembled, as shown in figure 4, to form the completed Li^6F -Teflon shield. The molded hole in the center will contain the two silver-activated phosphor glass rods.

The procedures for preparing the powder mixture and for fabricating the shields, with a discussion of those procedures and a description of the equipment, are given in the following sections.

PREPARING THE Li^6F -TEFLON MIXTURE

The Li^6F -Teflon shields were fabricated from a mixture of 87 wt % Li^6F * and 13 wt % Teflon** powders. The lithium contained 95.5 mole % of the Li-6 isotope. The Teflon powder was virgin TFE with a nominal particle size of 500 μ . The two powders were blended with a mortar and pestle. During the blending, sufficient acetone was added to form a paste. After blending, the powder mixture was dried at 200°C for 1 hr.

*The Li^6F was precipitated from a Li^6OH solution, obtained from the Y-12 Plant, Oak Ridge, Tennessee.

**The Teflon powder was obtained from Liquid Nitrogen Processing Company, Malvern, Pennsylvania.

Figure 2
 Li^6F -TEFLON DOUBLE HALF-SHIELD

Figure 3
Li⁶F-TEFLON HALF-SHIELDS AND DIMENSIONS

Figure 4
ASSEMBLED MALE AND FEMALE HALF-SHIELDS,
SHOWING MOLDED HOLE FOR
SILVER-ACTIVATED PHOSPHOR GLASS RODS

PREPRESSING THE Li^6F -TEFLON MIXTURE

The pressing properties of the powder mixture were greatly improved by prepressing the powder prior to molding the shields. The mixture, in 75-g batches (set by the size of the prepressing ram and die), was pressed to 50,000 psi and heated to 340°C . After 10 to 15 min, the mixture was cooled to approximately 100°C , and the pressure was released. Applying the pressure before heating, and cooling before releasing the pressure prevented charring of the Teflon by excluding air from the mixture. The pressed mixture was then crushed with a mortar and pestle, and ground in a ball mill to pass a 30-mesh screen. The prepressing increased the density, and the grinding and ball milling improved the flow characteristics.

The improved flow characteristics and increased density eliminated fabrication problems associated with molding the center hole in the shield (see figures 1, 2, 3, and 4). Prior to the development of this technique, the holes were drilled. Drilling the holes was expensive and time-consuming, because the LiF is very hard, and the Teflon clogged the drill flutes. Attempts made to mold the hole without prepressing the powder mixture were not successful. The large amount of compacting caused the ram pin (see figure 5) to veer, resulting in bent or broken pins and shields with holes out of specifications. With prepressed powder, the holes were generally molded within specifications and without pin damage.

RAM AND DIE DESIGN

The die and rams, which were designed to press the Li^6F -Teflon prepressed powder mixtures into the double half-shield (figure 1), are shown in figure 5. The long (moving) ram was fabricated with a male form on the end and a pin insert in the center for molding approximately half the center hole. The short (stationary) ram, which fits in the bottom of the die, was fabricated with a female form on the end, and a pin was inserted for molding the remaining portion of the center hole. The die is a thick-walled cylinder with a well in one end for a thermocouple. (The thermocouple monitored the molding temperature of the powder and controlled the automatic pressing cycle, described in a later section.) Both the die and the rams were made from Huron Tool Steel, and hardened to 57 - 60 Rockwell C.

The pin inserts, which were press-fitted into the ends of the rams, have advantages over pins machined as part of the rams. Press-fitted pins have less tendency to break, and usually can be replaced when they do break. A 0.001-in. taper along the exposed part of the pin facilitated removing the pressed shields from the ram and pin. (See figure 5; hole dimensions are shown in figure 3.)

The replaceable pin design permitted evaluating conveniently a number of tool steels: Huron, Graph-Air, Momax High Speed (type H-41), Morris Orbit IV (type H-41), and Rex AAA (type T-4). Pins made of the last three steels were the most resistant to bending and breakage. In all cases, the pins were hardened to 57 - 60 Rockwell C.

Figure 5
DIE AND RAMS FOR Li^6F -TEFLON SHIELDS

Seating the pin in the ram is important. Poor seating, usually due to trapped air, could result in pin creepage, and consequent variation in the depth of the molded hole. In the long ram, this problem was eliminated by machining a blunt taper at the end of the pin fitting into the ram, as shown in figure 5. The blunt taper provided a cavity for the trapped air, allowing the pin to fully seat.

In the short ram, a set screw with a vent hole (see figure 5) was used for proper seating. Positioning the set screw, which served as a base for the pin, fixed the length of the molded hole in the shield. The set screw design, which was not practical in the long ram because of its length, also served as an aid in pin replacement in the short ram; removing the set screw permitted pressing the damaged pin from the ram.

LOADING THE DIE

An electromagnetic vibrator*, assembled as shown in figure 6, was used to pack the Li^6F -Teflon powder mixture uniformly in the die prior to pressing. The vibrator was attached to a heavy lead base. A rubber pad between the lead base and vibrator permitted the latter to operate efficiently. A spring-loaded funnel, which directed the powder mixture into the die, held the die against the vibrator. The intensity of the vibrations was controlled with a variable transformer in the vibrator circuit.

Prior to loading, the die and rams were lubricated with a light film of silicone oil. The short ram was inserted into the bottom of the die, and the die assembly was placed on the vibrator (figure 6). Using a small dipper which held slightly more than the 1 g of prepressed powder mixture required for a shield, the powder was added slowly to the funnel, allowing time for the vibrator to compact the mixture in the die. After loading, the long ram was inserted into the top of the die, making the assembly ready for pressing.

PRESSING THE SHIELDS

The steps involved in pressing the shields were as follows:

1. The loaded die and ram assembly was positioned on the press (see figure 7), and the thermocouple was inserted into the die well.
2. The pressure was carefully applied until the molding pressure of 85,000 psi was reached.
3. Air in the powder mixture was removed by releasing and reapplying the pressure three times. Unless removed, the compressed air would char the Teflon when heated.

*Syntron Electric Vibrator, Model V-4, Syntron Company, Homer City, Pennsylvania.

Figure 6
DIE LOADING ASSEMBLY

- SAFETY SHIELD —————→
- UPPER TRANSITE BOARD —————→
- INDUCTION HEATING COIL —————→
- DIE ASSEMBLY (TYPE USED FOR LEAD) —————→
- AIR COOLING JET (TWO USED) —————→
- TRANSITE PEDESTAL —————→
- LOWER TRANSITE BOARD —————→

Figure 7
HYDRAULIC PRESS IN RETRACTED POSITION

4. With the pressure applied, the die assembly was heated to 340°C, which was the molding temperature.
5. The molding temperature was maintained for 35 sec. While maintaining the molding temperature, the pressure was released (to about 5 psi) and reapplied three times. This compacted the softened mixture into a dense shield.
6. Without releasing the pressure, the die assembly was cooled with a directed stream of air. Unless the pressure were maintained during cooling, the greater coefficient of contraction of the shield compared to the steel die, and the friction between the shield and die walls caused the shield to cleave. This cleavage occurred in planes at right angles to the longitudinal axis of the shield (4).
7. When the temperature fell to 50°C or less, the pressure was released, and the die assembly with the formed shield was removed from the press.

For economical production of the shields, two die assemblies were employed and steps 4 through 6 were automated. While the powder mixture in one die assembly was being molded, the molded shield in the second die assembly was removed, and the die was loaded for the next pressing. During this automated pressing program, the removed shield was cut into half-shields and checked for length and hole eccentricity. Since the automated steps (steps 4 through 6) involved heating and cooling the die assembly, which required several minutes, ample time was available for the other operations. Those operations will be described in more detail in the sections to follow.

Steps 1, 2, 3, and 7 were not automated, since those steps did not involve heating or cooling, and were rapidly made. In addition, steps 1 and 7 required the operator to place the die assembly in the press and remove it. Step 2 required the operator to monitor the alignment of the die assembly with the press platens during the long travel of the ram. It was in step 2 that the powder was initially compacted under pressure.

Shown in figures 7 and 8 is the hydraulic press in the retracted and pressing positions. Also shown in the figures are the induction heating coil, air cooling jets, and safety shield. The hydraulic press was set for a molding pressure of 85,000 psi. The oil flow to and from the hydraulic cylinder, controlled by a system of solenoid valves, raised and lowered the lower platen for die pressing and removal. Transite boards protected the metal platens from the heated die assembly, and a Transite pedestal raised the die assembly for convenient positioning inside the lowered induction heating coil.

An induction heater with a remote induction coil was used to heat the die assembly during the pressing cycle. The coil, 2½ in. in diameter, made of ¼-in. copper tubing, was cooled with water, flowing through the tubing. A pneumatic cylinder moved the coil out of the way (see positions of coil, figures 7 and 8) at the end of the heating cycle. The two cooling jets, connected to a source of compressed air (controlled with a solenoid valve), directed the air to rapidly cool the die assembly.

SAFETY SHIELD
UPPER TRANSITE BOARD
INDUCTION HEATING COIL
DIE ASSEMBLY (TYPE USED FOR LEAD)
AIR COOLING IFT (TWO USED)
TRANSITE PEDESTAL
LOWER TRANSITE BOARD

Figure 8
HYDRAULIC PRESS IN PRESSING POSITION

The safety shield, constructed of 1-in. Plexiglas, was designed and installed to protect the operator from flying fragments in the event of a broken ram or die. Although no such breakage occurred, this safety precaution is strongly recommended, and was used throughout the development and fabrication of over 4000 experimental and production shields. The safety shield also served to protect the operator from inadvertently coming in contact with the energized induction coil or the hot die. For safety and operating convenience, the shield was automatically raised and lowered with a pneumatic cylinder activated by the position of the lower platen. The shield came up only when the lower platen was completely retracted (figures 7 and 8).

AUTOMATION

The automation for steps 4 through 6 involved a two-part system designed to control the molding temperature, and to program the pressing cycle. The molding temperature was controlled with the thermocouple which sensed the temperature at the die, and a bridge circuit with an appropriate electronic amplifier, set to maintain the molding temperature by controlling the power of the induction heater. The second part of the system, which controlled the pressing cycle, consisted of: an initiating relay activated by the vacuum-tube plate current of the induction heater circuit; a heating-cycle timer which controlled the total time the die remained at the molding temperature; a cycling timer which released and reapplied the molding pressure; and an override timer which limited the cycling timer to three cycles. The delay timer, indicated in figures 9 and 10, used only in fabricating the lead shields, will be discussed under that section. A photograph and a diagram of the automation system are shown in figures 9 and 10.

The sequence of events occurring during automation was as follows: Pressing the start button (see figure 10) lowered the heating coil around the die (see figure 8) and turned on the induction heater. When the molding temperature was reached, the power to the induction heater was reduced by the proportional amplifier, deenergizing the initiating relay in the plate circuit. Back contacts on the initiating relay started the heating-cycle timer (see figures 9 and 10), which, in turn, started the cycling and override timers. After the cycling timer had gone through three cycles of releasing and reapplying the press pressure, the override timer terminated the cycling. The termination was phased to occur with the molding pressure applied. At the end of the heating cycle, determined by the setting of the heating-cycle timer, the induction heater was turned off, the induction coil was raised (see figure 7), and the compressed air was turned on to cool the die.

REMOVING THE SHIELD FROM THE DIE

A small hydraulic hand press with a bridge-type support, as shown in figure 11, was used to remove the Li^6F -Teflon shield from the die. The die was positioned on the support, with the long ram at the top and the base of the short ram through a hole in the support. The hole was large enough to pass the ram base, but not the die body. Since the top ram was

Figure 9
AUTOMATIC PRESSING AND TEMPERATURE CONTROL

Figure 10
AUTOMATED SYSTEM FOR PRESSING LITHIUM-6 FLUORIDE AND LEAD SHIELDS

Figure 11
HYDRAULIC HAND PRESS FOR REMOVING SHIELDS FROM DIE ASSEMBLY

longer than the die body, the exerted hydraulic force pushed the shield, along with the short ram, out of the die under the bridge.

CUTTING THE DOUBLE HALF-SHIELD INTO HALF-SHIELDS

The shield, removed from the die, was a double half-shield, with mating shapes at the ends (see figure 2). One half-shield was cut exactly to length, and then the other was cut to length (see figure 3). The small remaining piece from the center was crushed, ground, and added to the prepressed mixture for reuse. Matching the male and female ends, as shown in figures 1 and 4, formed the completed Li^6F -Teflon shield.

The double half-shields were cut with a modified gem cutting saw using a 4-in. abrasive (fine, A-100) wheel blade. An aluminum platform riding on ball bearing slides, and a shield holder with a screw stop, precisely positioned the shield for cutting to the desired length (see figures 12, 13, and 14). A groove in the base of the shield holder and a spring-loaded gripper held the shield in place while cutting.

Both the male and female half-shields were the same length when measured from the shoulder (see figure 3). To accommodate both shield forms, the end of the screw stop was shaped, that is, hollowed out so that the periphery of the screw rested against the shoulder of the male half-shield, as shown in figure 14. The shaping of the screw stop permitted interchangeable cutting of both male and female half-shields without readjusting the stop.

A stream of compressed air directed at the end of the half-shield through a small hole in the housing and through the length of the set screw (see figure 14) ejected the completed half-shield into the cupped hand of the operator, held near the edge of the platform.

CONTROL TESTS

Each half-shield was measured for length and for eccentricity of the center hole. The other specifications were fixed by the dimensions of the die and ram assembly (figures 3 and 5). The specification for the shield length, which was 0.354 ± 0.002 in., was measured from the shoulder to the bottom of the shield (see figure 3) with a micrometer. The eccentricity of the center hole was measured with a dial test indicator. For this test, the shield was slipped over a close-fitting, slowly rotating shaft, and the test dial indicator, bearing against the outside wall of the rotating shield, indicated the eccentricity. An eccentricity of ± 0.008 in., or less, was accepted.

Those shields which did not meet specifications were crushed and ground, and added to the prepressed powder mixture for reuse. Those rejects amounted to about 5% of production. Although a reject rate of 5% was not excessive, and was economically acceptable (see discussion under Economics), it was constructive to evaluate the causes of the rejects. As previously indicated, the shield length must be cut to ± 0.002 in., and the eccentricity of the molded hole must be within ± 0.008 in. Rejects not meeting

Figure 12
SAW FOR CUTTING HALF-SHIELDS

Figure 13
CLOSE-UP OF ASSEMBLY FOR CUTTING HALF-SHIELDS

Figure 14
 DETAILS OF SHAPED SCREW WITH AIR HOLE (ISOMETRIC VIEW)

length specifications were caused by a dull saw blade, or by deflection of the blade while cutting the shield. The former, which was evidenced by the production of shields consistently not meeting specifications, was avoided by regularly replacing the blade after each 8-hr period of shield production. Blade deflection while cutting was caused by too much force against the blade edge. Careful feeding of the shield minimized the reject rate from this source. The problem might be further minimized with large metal backing or reinforcing washers on each side of the blade. Such washers, which were not used in the current production, are recommended for future evaluation.

Rejects due to eccentricity of the molded hole were caused by a fatigued or bent molding pin, which in turn was caused by the powder mixture having low density and poor flow properties. As indicated earlier, the large amount of compacting required with low-density powders caused veering of the pin. Poor flow properties aggravated this condition. Further improvement in those properties by adequate prepressing should minimize, if not eliminate, pin damage and consequent shield rejects from this cause.

FABRICATING THE LEAD SHIELDS

The lead shields, shown with dimensions in figure 15, were fabricated from lead foil. Involved in the fabrication were: cutting the foil into blanks (rectangular pieces 0.7×1 in.), pressing the blanks into shields, and punching caps for the shields. Those operations are described in the following sections.

PREPARING THE BLANKS

The lead foil*, obtained in 5-ft rolls $2\frac{1}{2}$ in. wide, had a nominal thickness of 0.0185 in. Measurements indicated that the actual thickness varied from the nominal thickness by several thousandths of an inch. The specifications for the wall and bottom thickness of the shields was 0.020 ± 0.001 in. The wall thickness was fixed by the diameter dimensions of the die and ram. The bottom thickness, however, was dependent upon the amount of lead in the blank, as is seen in the following discussion. To meet the thickness specifications of the bottom, the blanks had to be precisely cut, and variance in foil thickness had to be taken into account. The latter was done by adjusting the length of the blank, depending upon the foil thickness.

The $2\frac{1}{2}$ -in.-wide lead foil roll was cut into 9-in. lengths, and after trimming and squaring the edges, each length was cut across the width into strips 0.700 in. wide. The strips were sorted into groups according to thickness, to the nearest 0.001 in., and cut into blanks with lengths (nominally 1 in.) depending upon the thickness of the strip.

*Obtained from National Lead Company, Cincinnati, Ohio.

Figure 15
LEAD SHIELD

The trimming and cutting was done with a modified paper cutter, shown in figure 16. The steel blade had been refinished and polished, to assure that no steel particles would become dislodged from the blade and become imbedded in the lead foil. Such particles would cause binding and destruction of the die and ram set. A micrometer on the side and a straight-edge perpendicular to the cutting edge of the cutter assured the accurate cuttings required to meet the thickness specifications. Figure 16 shows a 9-in. length of foil, which had been trimmed and squared, being cut into 0.700-in. strips, and figure 17 shows a strip being cut into blanks.

The relationship between the thickness and the length of the blank was derived, as follows:

$$V_b = V_s \quad (1)$$

where

V_b = volume of lead in the blank, and
 V_s = volume of lead in the shield.

Expressing the volume of the blank in terms of length, width, and thickness, and the volume of the lead in the shield in terms of radius and height:

$$\ell \cdot w \cdot t = \pi h(r_o^2 - r_1^2) + \pi t_1 r_o^2 \quad (2)$$

where

ℓ and t = length and thickness of the blank,
 w = width of the blank = 0.700 in.,
 r_o = outside radius of the shield = 0.122 in.,
 r_1 = inside radius of the shield = 0.102 in.,
 t_1 = base thickness of the shield = 0.020 in., and
 h = inside height of the shield = 0.778 in.

Rearranging:

$$\ell \cdot t = \frac{\pi h(r_o^2 - r_1^2) + \pi t_1 r_o^2}{w} = 0.0170. \quad (3)$$

A table was prepared in which ℓ was listed as a function of t . In the table, ℓ was expressed directly in micrometer readings of the paper cutter (see figure 17).

A similar relationship based on weight had been developed using the density of lead. This relationship was used for shield fabrication with lead powder, and during the initial fabrication with lead foil. The weight relationship was replaced by the dimensional relationship, because cutting the lead blank to length was more practical than cutting the blank to a specific weight.

PHOTO NO. PH-66-1751

Figure 16
CUTTER FOR LEAD FOIL

Figure 17
SETTING THE BLANK FOR CUTTING TO SPECIFIC LENGTH

DIE AND RAMS

The die and rams used to press the blanks into shields are shown in figure 18. A 0.001-in. taper (see figure 18 and ID of lead shield, figure 15) along the end of the ram around which the lead blank was wrapped (see next section, Loading the Lead Blank for Pressing) facilitated removing the shield from the ram. The set of die and rams was fabricated from Huron Steel, and hardened to 57 - 60 Rockwell C.

LOADING THE LEAD BLANK FOR PRESSING

After lubricating the rams and die by wiping the surfaces with a cloth impregnated with silicone oil, the 0.700-in.-wide lead blank was wrapped around the shield-forming long ram. This brought the edges to within 0.01 in. of touching, and the foil extending past the end of the ram provided lead for forming the wall and bottom of the specified thickness. Inserting the ram with the blank into the top of the die, and the short ram into the bottom of the die, made the assembly ready for pressing.

PRESSING THE SHIELDS

Pressing the lead shields was, in many respects, similar to pressing the Li^6F -Teflon shields, previously described. The equipment, which included the press, safety shields, induction heater and air cooler, and automation were the same. Only the programming was different. The specific steps in forming the lead shields were as follows:

1. The loaded lead die assembly was positioned in the press; the thermocouple was placed in the thermocouple well of the die; and pressure was carefully applied. A forming pressure of 85,000 psi was used. The pressure was released, reapplied, and again released. This step, which shapes the shield from the blank, was carried out without heat.
2. With the pressure released, the die assembly was heated to 300°C, and maintained for 5 sec to fuse the shield seams. At the end of the 5-sec period, the heater was turned off, and cooling air was applied.
3. When the die temperature dropped to 50°C or less, pressure was twice applied and released to remove deformities in the shield caused by the heating. If the pressure were applied before the die cooled to 50°C or less, the lead in the die would be extruded. The delay timer (see figures 9 and 10) provided the necessary cooling time by delaying the application of the pressure.

Step 1 was performed manually; steps 2 and 3 were automated. As with the Li^6F pressing, two die and ram assemblies were used. While the shield in one die assembly was being formed automatically (steps 2 and 3), the lead shield formed during the previous pressing was removed from the second die, and a blank was inserted for the next pressing. The formed shield was removed from the die assembly in the same manner that the Li^6F -Teflon shields were removed (see figure 11). Also carried out during the automated period were the control tests for shield strength and bottom thickness. These tests are described in the following section.

Figure 18
DIE AND RAMS FOR LEAD SHIELDS

PUNCHING THE SHIELD CAPS

Caps for the shields were punched from lead foil selected to have a thickness of 0.020 ± 0.001 in. A long ram similar to that used for pressing the Li^6F -Teflon shields, but with a flat end and without the hole-forming pin, was attached to the upper platen of a manual press. A matching die was positioned directly below the ram. With the lead foil placed on the die, discs with the same diameter as the Li^6F -Teflon shields were punched out. These were used to cap the lead shields (figures 1 and 15).

CONTROL TESTS

All shields were tested for seam strength and bottom thickness. The strength test was made by forcing a tapered rod (pencil) into the open end of the lead shield until the lip of the shield formed a very slight flare. If the shield did not crack, it was considered acceptable for strength.

The bottom thickness was checked with a dial test indicator by slipping the shield over the end of a rod in a vertical position. The thickness was read from the dial test indicator, which had been zeroed against the rod without the shield in place. A reading of 0.020 ± 0.001 in. was acceptable.

A 10% rejection rate was experienced in the production of the lead shields. Although acceptable, the rejection rate could be reduced with more refined control of the lead temperature during the heating step. To meet the seam strength and bottom thickness requirements, the lead must be softened but not melted. The sharp melting point of lead makes this requirement critical. The optimum temperature for softening the lead without melting, which is empirically set, must be precisely maintained. In addition, the rate of heating must be precisely reproduced, since some temperature lag will prevail between the thermocouple and lead sites, especially during rapid heating of the die assembly. Locating the thermocouple well as close to the die cavity as possible, precisely positioning the induction heating coil relative to the die assembly, and using a precise temperature controller and induction heater should significantly reduce the rejection rate.

It may be possible to use a low-melting alloy with acceptable shielding properties, but with a broad melting point. This idea has been considered but not evaluated.

PRODUCTION AND COSTS

Twenty-four hundred shield assemblies have been fabricated. Since the production was combined with development, not all the shields were fabricated using the same techniques. As techniques for making better shields more economically were developed, they were applied. The latest and most economical techniques, which are described in this report, were applied toward the end of the production. In the following paragraphs are described the economics based on the latest techniques, and a comparison is

made with the cost using the techniques available prior to this improvement program. The cost of materials, which was relatively small, is also discussed.

PRODUCTION AND COSTS OF THE Li^6F -TEFLON SHIELDS

The final production rate for the Li^6F -Teflon shields was 80 acceptable shields (160 half-shields) per 8-hr period. This is equivalent to 6 min per shield (3 min per half-shield).

To the production time for the Li^6F -Teflon shield must be added the time to prepare the prepressed powder mixture. The prepressed powder mixture, in 75-g batches, required 3 hr per batch preparation. Since 75 shields (150 half-shields) were produced from each batch, the powder preparation time was $2\frac{1}{2}$ min per shield. Adding the $2\frac{1}{2}$ min for preparing the powder to the 6-min production time resulted in a total of $8\frac{1}{2}$ min per shield. Included in this production rate was the time lost due to rejected shields (about 5%, or 0.3 min per acceptable shield). The $8\frac{1}{2}$ -min production rate, obtained with automation and newly developed techniques, represents an 80% cost reduction over the 44-min rate obtained with previously used techniques (4).

Prior to these improvements, the Li^6F -Teflon shields were pressed manually, requiring two operators. One operator loaded and unloaded the dies, while the other operated the press. At that time, the shields were pressed full length, using a Li^6F -Teflon cap over the open end of the shield. Two pressings were required, one for the shield and one for the cap. This double pressing would be equivalent to pressing each half-shield separately. Eliminating the double pressing time by pressing the two mating half-shields at the same time, and eliminating the need for a second operator by automating the press, reduced the effort from 44 min to 26 min. An additional saving of $17\frac{1}{2}$ min per shield (20 min saved by eliminating the drilling, less $2\frac{1}{2}$ min for preparing the prepressed powder) achieved by molding the center hole instead of drilling the hole, resulted in the $8\frac{1}{2}$ -min/shield production rate, or a saving of 80%.

PRODUCTION COSTS OF THE LEAD SHIELDS

Similar savings were realized with the lead shields. The final production rate for the lead shields was 65 shields per 8-hr period, equivalent to $7\frac{1}{2}$ min per shield. An additional $\frac{1}{2}$ min for cutting the lead blanks and punching the lead caps brought the total to 8 min per shield. The 8-min production rate for the lead shields included 0.7 min per shield lost to rejects amounting to approximately 10% of production.

The production rate obtained with the newly developed techniques represents a 73% cost reduction compared to the 30 min per shield required using the earlier techniques (4). Prior to developing the techniques for using lead foil to form the lead shields, lead powder had been cold-pressed to form the shields. Although several hundred acceptable shields had been fabricated using the powder, the reject rate was 50 to 75%. This high reject

rate was due to poor particle bonding and poor flow of the lead powder in the die cavity. The use of lead foil in place of lead powder, which lowered the reject rate to 10%, reduced the cost in terms of effort from 30 to less than 15 min per shield. An additional cost reduction was realized by automating the press. Similar to the case for the Li^6F -Teflon shields, the automation permitted reducing the production effort to less than 8 min per lead shield, including the time required to cut the lead blanks.

COMBINED COST OF SHIELD ASSEMBLY AND MATERIALS

Combining the above savings for the Li^6F -Teflon and lead shields, the fabrication effort for a complete shield assembly was reduced from 74 to $16\frac{1}{2}$ min, which represents a cost reduction in fabrication time of 78%.

Material costs were relatively small, amounting to less than 20 cents per shield. This figure was the sum of the lithium isotope enhancement cost of 14.4 cents per shield, 4 cents per shield for converting the Li^6Cl or Li^6OH to Li^6F , 0.1 cent per shield for the Teflon powder, and 1 cent per shield for the lead foil. This brought the total cost per shield assembly to $16\frac{1}{2}$ man-min for labor and 20 cents for material.

ACKNOWLEDGMENTS

The authors gratefully acknowledge contributions to this program by the following people, who are listed with their organizational affiliations when the work was performed:

K. T. Ziehlke and C. E. Weaver, Metallurgy Department, Laboratory Division, for aid in selecting, treating, and testing the steels used in the rams and dies.

C. L. Keller, C. F. Moon, and J. W. Stapp, Fabrication and Maintenance Division, for suggestions on fabricating the rams and dies.

B. E. Martin, Isotopic Analysis Department, for help in modifying the gem-cutting saw.

C. Sulfridge, Isotopic Analysis Department, for aid in automating the system.

S. T. Benton, Chemical Development Department, for converting the Li^6OH to Li^6F .

J. C. Bailey, Physics Department, for continual encouragement in this program.

Trade names and sources of material are not meant to be limiting. Other brands of equal specifications could serve equally well.

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