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PLUTONIUM AND URANIUM AS ENGINEERING MATERIALS*

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Abstract

This is a review of current design possibilities using plutonium and uranium and their principal alloys as materials in engineering design. Mechanical and physical properties are summarized. Fabrication and joining techniques are presented, including forging, plating, machining, and welding. Also discussed are the peculiar difficulties and hazards of packaging and handling assemblies containing these materials.

Introduction

Plutonium and uranium have been used as structural materials in nuclear warheads and reactors for several years. These materials and their principal alloys are in their infancy of potential growth in use as energy sources for public utility power, earth moving, and vehicle propulsion. Many of these applications will soon be exploited by our private industrial economy in addition to AEC contract laboratories. It is the intent of this paper to summarize the important engineering properties of these materials and to discuss the current fabrication, joining, and packaging processes.

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Plutonium

Summary

Plutonium is prolific in its crystallography. Five solid-to-solid transformations occur between the melting point and room temperature. However, there are only two forms of plutonium in general use today. They are unalloyed alpha-phase plutonium, and delta-phase plutonium stabilized with 1.0 w/o gallium. Both types of plutonium have been used as fission components in nuclear explosives. They are relatively weak structural materials having ultimate tensile strengths of 22,000 psi and 14% elongation for gallium alloy; [1][1] 51,000 psi and 0.1% elongation for unalloyed plutonium. [2] The physical and mechanical properties vary widely between the two materials but in an engineering design sense these features are complementary.

Fabrication

Unalloyed plutonium is cast in either an inert atmosphere or a vacuum. It is normally worked in the beta phase at approximately 200 C. At this temperature the material is very ductile; elongations greater than 200% are obtained. Alpha material is hard and brittle at room temperature. Its machining characteristics are similar to cast iron. Unalloyed plutonium can be machined to a 20-μin. AA (Arithmetic Average) finish by a single-point tool. Machining is done in an inert atmosphere with a coolant to reduce fire hazards.

Gallium-alloyed plutonium is cast in the same environment as unalloyed plutonium but due to its great ductility it may be worked at room temperature.

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[1]Numbers in brackets refer to similarly numbered References in bibliography at end of paper.

The alloy is a soft material similar to aluminum. Consequently it is somewhat difficult to machine as its surface is easily damaged. A 32-μin. AA finish is considered good with a single-point tool. Machining is done with the same precautions and procedures as used for unalloyed plutonium.

Joining

It is not possible at present to weld unalloyed plutonium due principally to the great change in volume that takes place when the material transforms from a liquid to a room-temperature solid. Joining is limited to riveting, threading, interlocking, or cylindrical shrink fits that take advantage of the unusually high linear coefficient of expansion. The gallium alloy, however, may be "resistance" or TIG (tungsten-inert-gas) fusion-welded with no appreciable loss in tensile strength.

Packaging

Plutonium has some unusual properties that affect both the need for, and the method of packaging. Plutonium is chemically reactive and radiologically toxic, and therefore requires total atmospheric and body contact shielding. This is a problem throughout the life of the Pu part and particularly during the fabrication, gaging, and packaging cycles (Figs. 1-6). By employing materials-handling equipment such as conveyor belts and tape-controlled lathes, and visual aids such as closed circuit TV, most of the processes are carried out rather efficiently and without any real loss in precision. Whenever close contact is absolutely necessary such as shrink fitting two parts together, then a negative pressure air screen is used rather than a plastic shield to protect the operator.

For permanent packaging the most common methods are (1) plating the entire surface area of the individual parts with a material like nickel, or (2) welding a shielding envelope of, say, steel, around each component or subassembly. Another consideration in packaging is the heat generated by spontaneous fissioning of the plutonium. This amounts to 2 watts/kg, and it is necessary to provide a heat sink outlet to prevent damage to the protective envelope or the plutonium pieces.

Properties

One of the unusual physical properties of plutonium is the linear coefficient of expansion (Table 1). At room temperature it is approximately 58×10^{-6} in./in.-°C [3] for unalloyed plutonium; about five times that of steel. By contrast the gallium alloy coefficient is almost zero at that temperature. Unalloyed plutonium undergoes significant changes in mechanical properties (Table 2) at 20 C and is completely different at 120 C (the beta-to-alpha transformation temperature). Although both types of plutonium are given heat treatment to enhance their properties the maximum yield strength for either material is 50,000 psi which is achieved by the unalloyed plutonium at -30 C. [2]

Table 1 Physical properties — wrought structure at 20 C

	Density (g/cc)	Coefficient of thermal expansion ($\times 10^{-6}$ in./in.-°C)	Thermal conductivity (cal/cm/sec-°C)
Unalloyed Pu	19.5-19.7 [4]	58 [3]	0.019 [5]
Gallium alloy [1]	15.8	3.9	0.015

Table 2 Mechanical properties – wrought structure at 20 C

	Ultimate tensile strength (10^3 psi)	Yield strength (10^3 psi)	Elong. in 1 in. (%)	Elastic modulus (psi)	Poisson's ratio
Unalloyed	50.9 [2]	32.1 [2]	0.1 [2]	14.7 [2]	0.18 [6]
Gallium alloy [1]	21.8	20.5	14.0	6.7	0.25

Uranium

Summary

Uranium and alloys of uranium are inherently much stronger structural materials than plutonium. Their principal uses are in nuclear warheads, reactors, and particle accelerators. In these applications the uranium materials are often designed to sustain stress levels of over 100,000 psi. They may be subjected to several thousand G loads or may be pulse-heated as in a reactor resulting in high thermally induced stresses. Because of its high density (18.9 g/cc) (Table 3) uranium is often utilized as an inertial mass or for radiation shielding. In addition to unalloyed uranium there are two alloys which will be reviewed in this paper. They are U-10 w/o molybdenum and U-7.5 w/o niobium 2.5 w/o zirconium. Both of these alloys have ultimate tensile strengths greater than 120,000 psi (Table 4).

Table 3 Physical properties – wrought structure at 25 C

	Density (g/cc)	Coefficient of thermal expansion ($\times 10^{-6}$ in./in.-°C)	Thermal conductivity (cal/cm/sec-°C)
Uranium	18.9 [7]	10.2-14.9[a] [8]	0.66 [9]
U-7.5 Nb 2.5 Zr [10]	16.6	14.8	--

[a]80% reduction rolled at 600 C, beta annealed, and final 10% reduction rolled.

Table 4 Mechanical properties – wrought structure at 20 C

	U.T.S. (10^3 psi)	Yield strength (10^3 psi)	Elong. %	Elastic modulus	Poisson's ratio
Uranium	125 [11]	48 [11]	35 [11]	26 [12]	0.22 [13]
U-10 Mo [11]	122	127	16	-	-
U-7.5 Nb 2.5 Zr [10]	205	230	6	-	-

Fabrication

Alloyed and unalloyed uranium are usually arc melted in vacuum or in an inert atmosphere such as argon. Unalloyed uranium may also be cast from vacuum induction melts or from induction melts under a flux cover. Forging and rolling operations are also performed in an inert atmosphere at 950 C. Press forming or spinning may be done at room temperature in a normal atmosphere.

Wrought uranium has machining properties similar to stainless steel. It is tough and abrasive but may be drilled and tapped easily. Single-point tooling can produce surface finishes of 16-μin. AA. Coolants are required to machine and to reduce the possibility of fire.

Joining

Uranium and the two alloys may be TIG or EB (electron beam) fusion welded. TIG welding is done in a helium or argon atmosphere and EB welding in vacuum. Table 5 shows the tensile properties of TIG welded U-Mo and U-NB-Zr alloys. Brazing is a more difficult operation. There has been some success brazing silver to uranium but this technique is avoided in favor of welding whenever possible.

Table 5. Tensile properties of uranium alloy TIG welds at 20 C [11]

Alloy composition w/o Mo	Nb	Zr	Heat treatment	Yield strength (10^3 psi)	U.T.S. (10^3 psi)	Elong. %
10	-	-	Postheat 275 C 1/2 hr	140	145	6
-	7.5	2.5	none	130	136	11
-	7.5	2.5	Postheat 275 C 1/2 hr	139	152	6

Packaging

Unalloyed uranium oxidizes readily in the normal atmosphere so it is usually canned in some manner if long-term use is desired. The Mo and Nb-Zr alloy have "stainless" qualities that do not normally require protective coatings. However, the U-10 Mo alloy suffers stress-cracking in the presence of oxygen. Parts made of this material that normally encounter high stress loads (of tens-of-minutes duration) in service are given protective coatings. Electroplated nickel is the most common canning material, although, gold and silver have also been used.

Properties

Many of the best mechanical properties of high alloy steel may be obtained in uranium alloys, particularly in the ternary U-7.5 Nb-2.5 Zr. As in steel, tailored effects such as toughness, high yield strength, or ductility, may be obtained by appropriate heat treatment. Vacuum annealing has been particularly effective in producing a ductile, high yield material. Yield strengths in the U 7.5 Nb-2.5 Zr alloy may be varied from 90,000 psi to 260,000 psi with elongations of 14% and 1% respectively. The physical metallurgy of this alloy is somewhat reminiscent of a maraging steel. That is, the high temperature solution treated allotrope transforms by a shear process to a rather soft room temperature allotrope which can be hardened by reheating at an intermediate temperature.

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13. Ibid. p. 123.

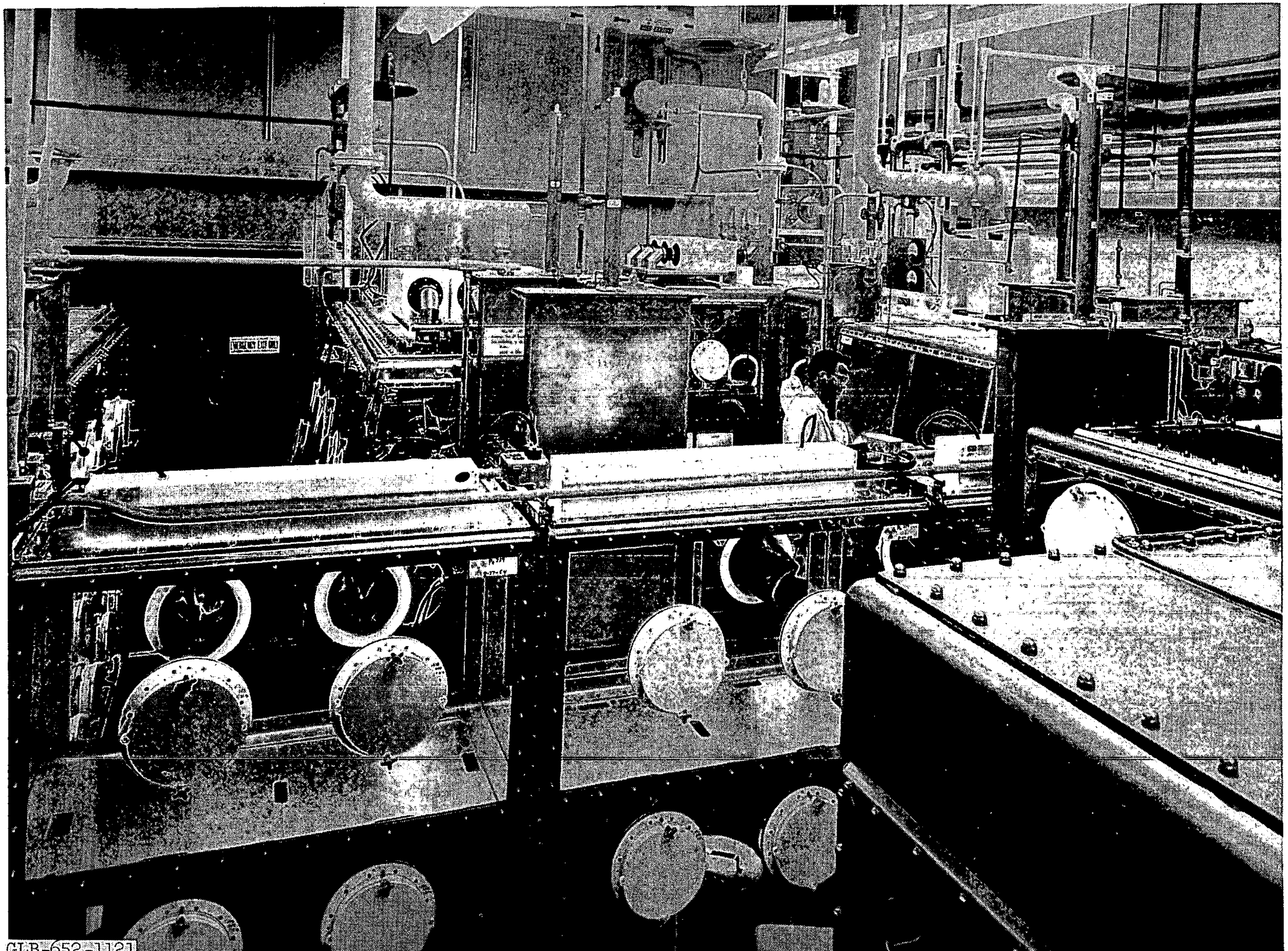

Fig. 1. Glove box assembly line.

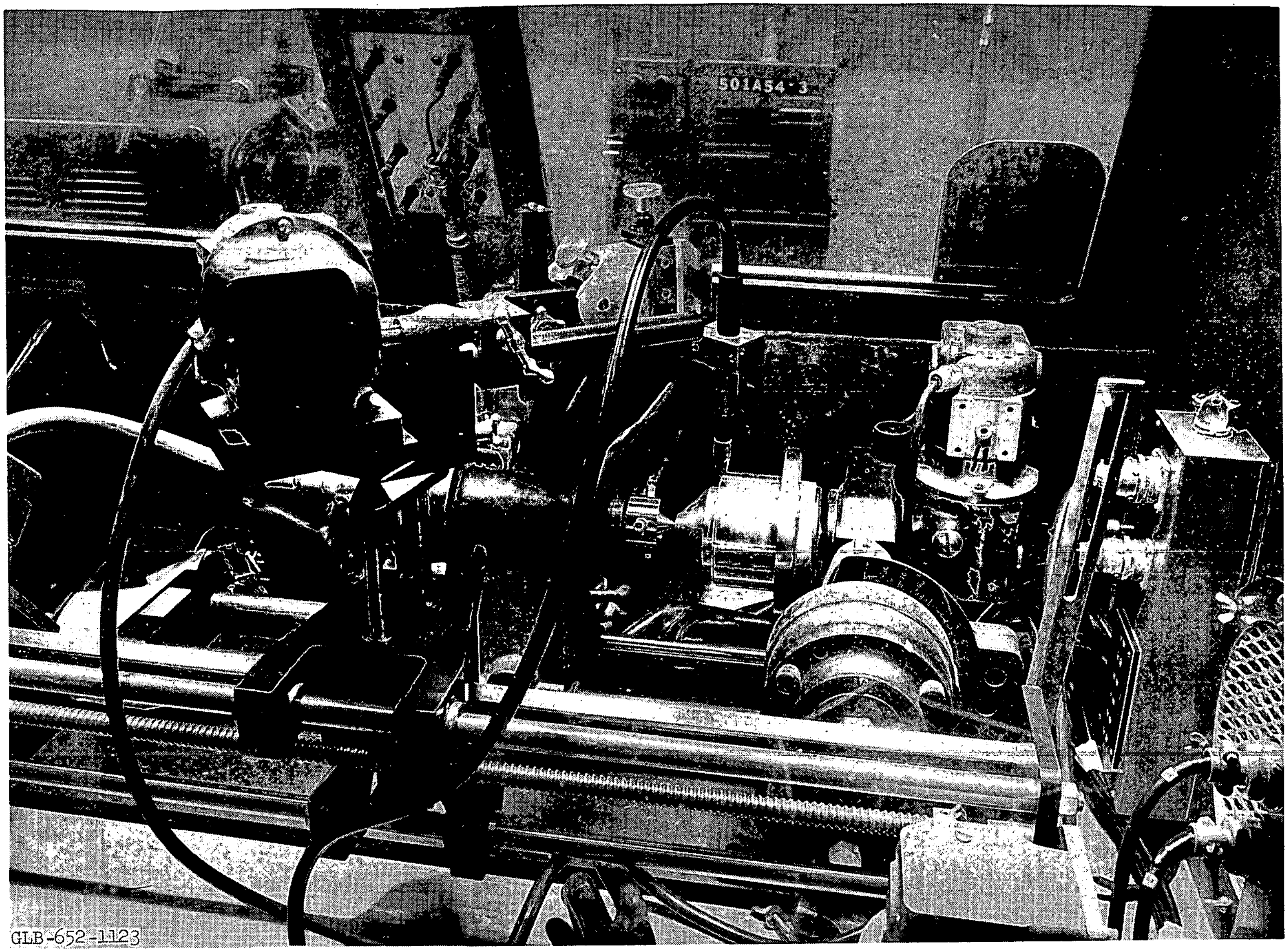

Fig. 2. TIG welder electrode positioned for welding.

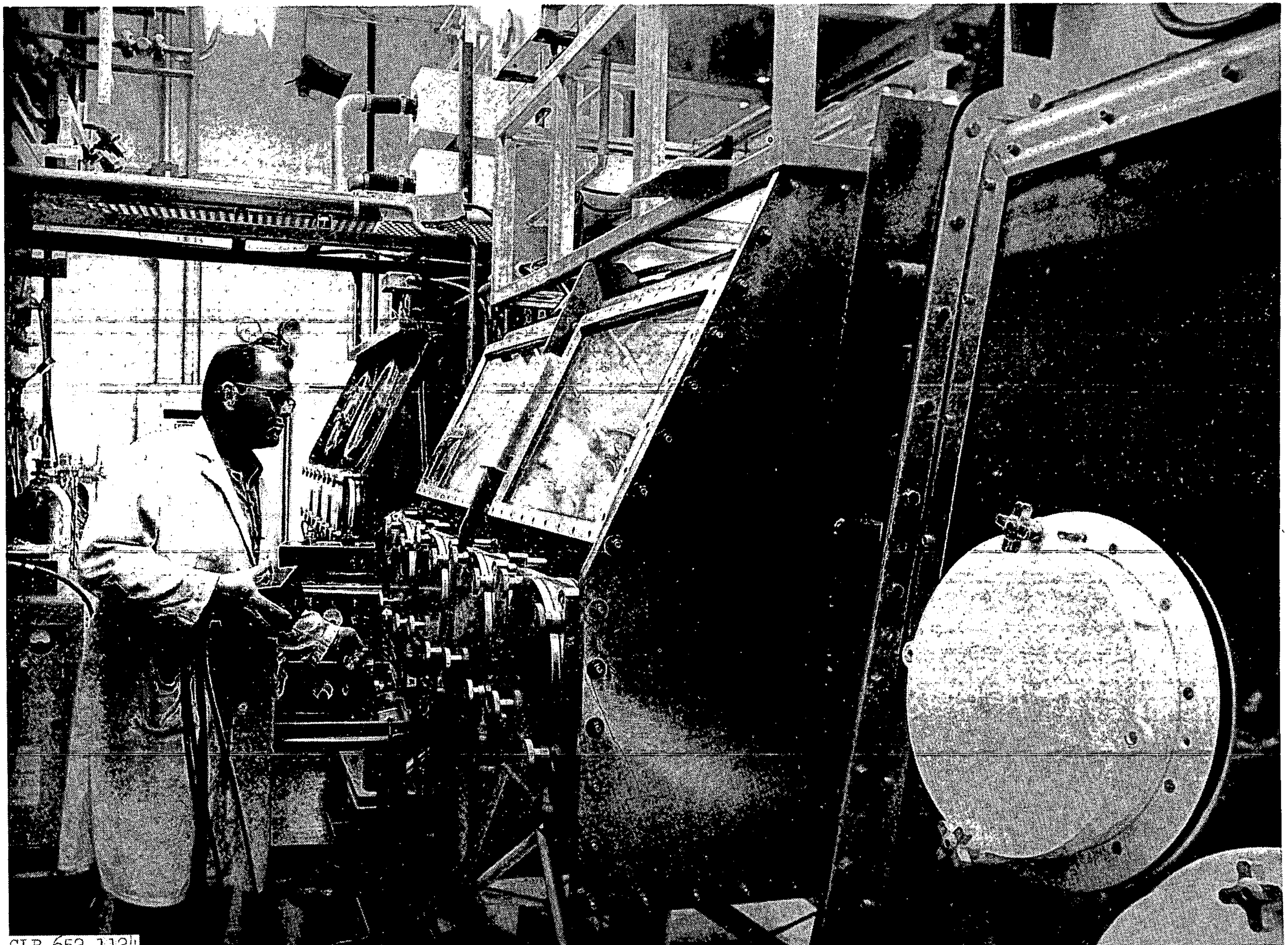

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Fig. 3. Remote control TIG welding operation.

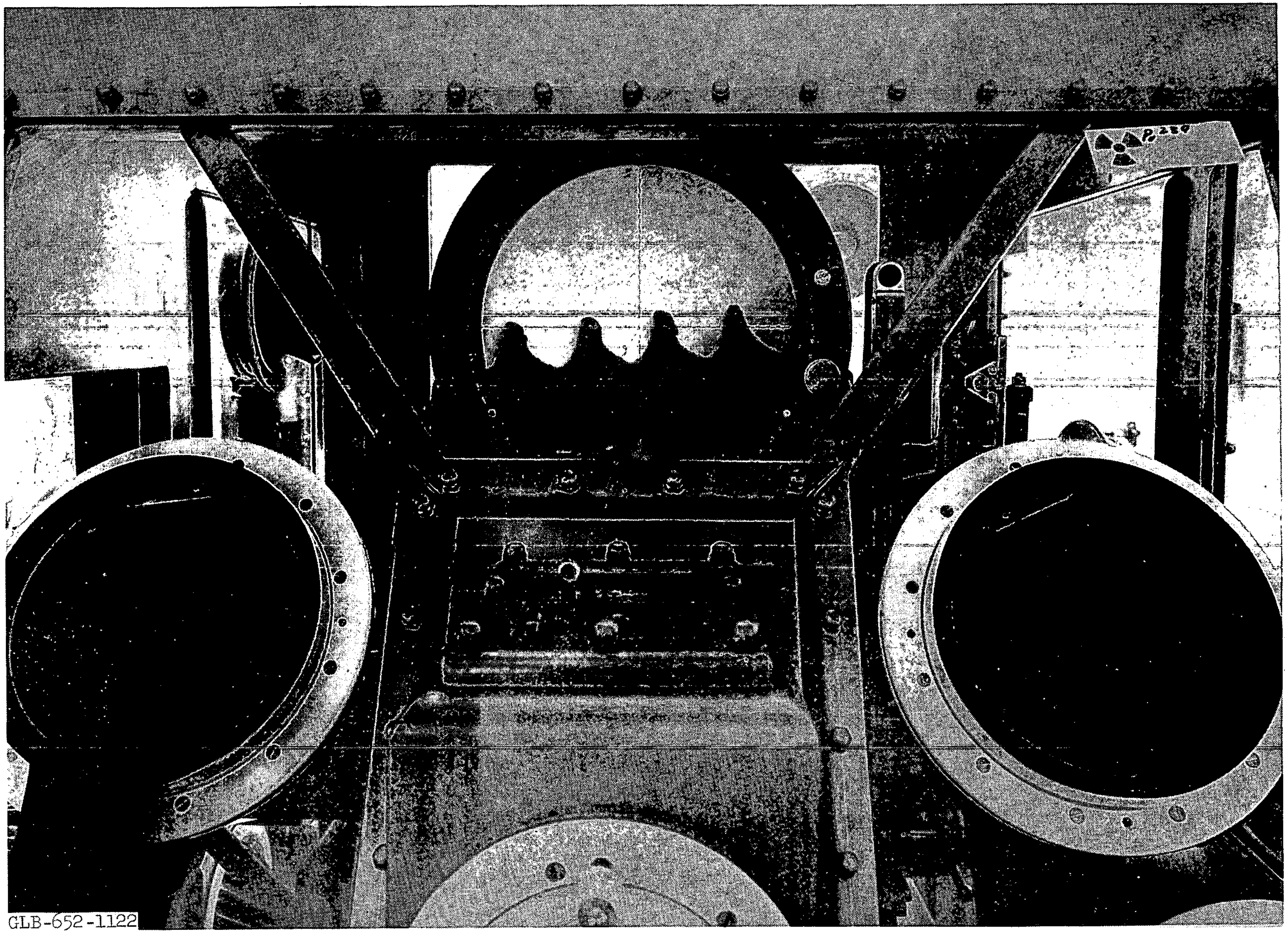

Fig. 4. Optical comparator checking thread form.

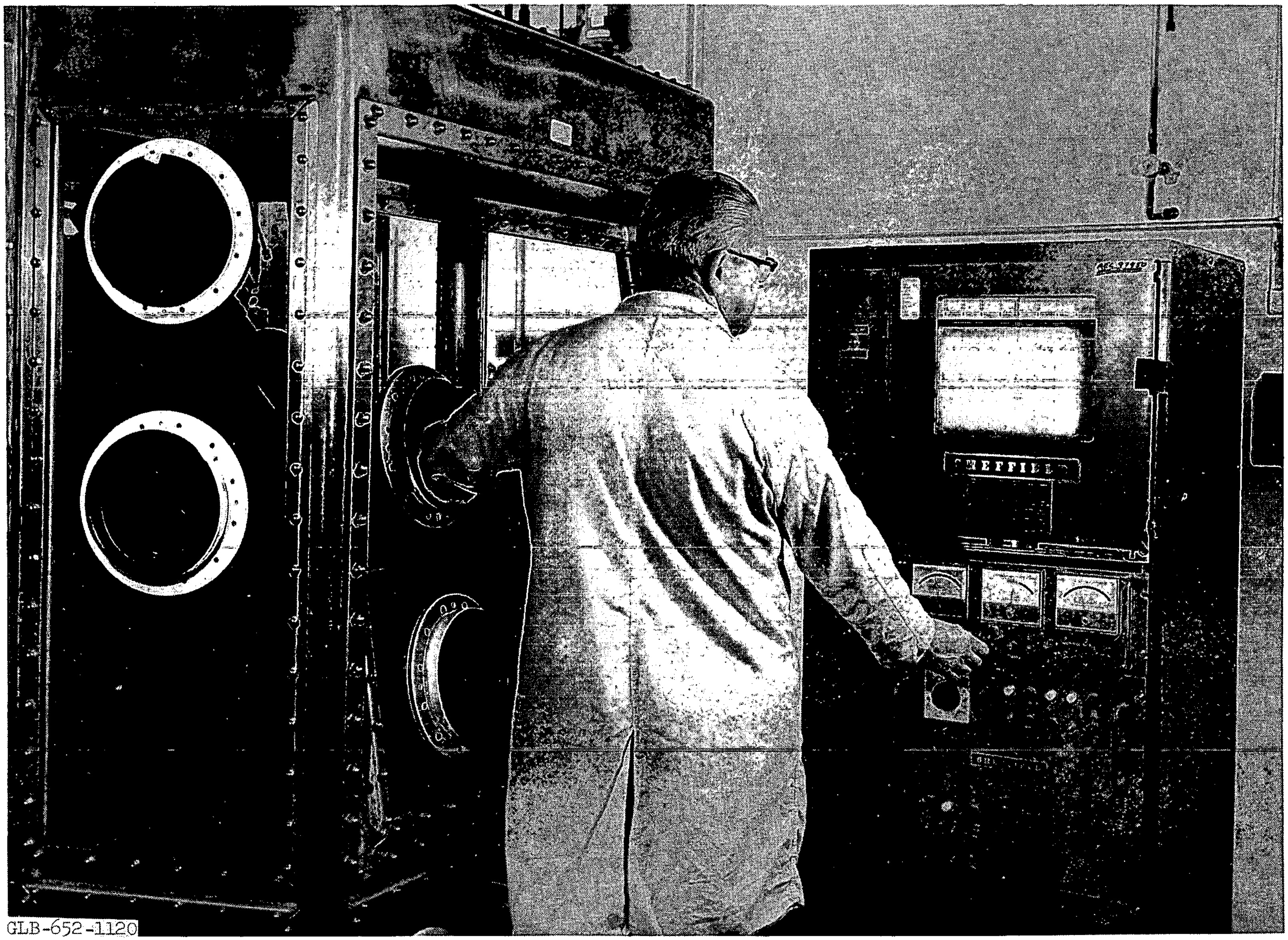

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Fig. 5. Operation of precision thickness gage.

Fig. 6. Contact assembly in negative pressure air screen room.