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DEVELOPMENT OF TECHNIQUES FOR FABRICATION OF
SMALL-DIAMETER THIN-WALL TUNGSTEN TUBING

Interim Progress Report covering the period from
July 1, 1963 through December 31, 1963

by

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FOREWORD

This interim progress report on tungsten-tubing fabrication development is limited to progress, believed to be of technical significance, that has occurred during the reporting period. Since the intent is to report only items of significant progress, not all work completed during the period is reported. Since this is an informal report, the results and data presented are preliminary and subject to change unless otherwise stated.

The issuance of this report is not intended to constitute final publication in any sense of the word. Final results will be submitted for publication in professional journals or will be published as an ANL topical report.

This is the first report on this program. Future progress reports will contain a listing of preceding reports to ensure continuity.

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ABSTRACT

Tungsten tubes suitable for secondary fabrication have been extruded from various starting materials. Pressed and sintered sleeves, vapor-deposited tubes, and pre-extruded tubes have been successfully extruded. In addition, consolidation and extrusion of high-purity tungsten powder in a single extrusion show promise. Various starting materials are being evaluated on the basis of obtaining good fabricability and properties, as well as providing a more economical means of producing high-quality tungsten tubing.

Secondary fabrication will start after hot-swaging dies and other warm-working equipment have been received. Warm-working is necessary because tungsten's ductile/brittle transition temperature is above room temperature.

Equipment, extrusion techniques, and results are described, along with plans for future work.

INTRODUCTION

The primary purpose of this program is to devise and develop techniques for the fabrication of high-quality, small-diameter, thin-wall tubing of tungsten and tungsten alloys. The small-diameter, thin-wall, tubing classification includes tubing with outer diameters of 0.32 cm (0.125 in.) or less and wall thicknesses approximately 10% of the OD. While a great deal of literature is available on the fabrication of tungsten into bars, wires, and sheet stock, relatively little information is available on fabricating tungsten tubing. Further, fabrication of tubing 0.32 cm (0.125 in.) OD or smaller of any high-strength refractory metal poses problems not always found when manufacturing tubes with diameters of 1.25 cm (0.500 in.) or thereabouts.

A corollary purpose of the program is to devise techniques that will provide an economical means of fabricating small-diameter, thin-wall, tungsten tubing, thereby possibly opening new fields for the application of such material, or reducing costs for existing applications.

The general fabrication procedure will consist of selection of proper starting materials, extrusion into small-diameter tube blanks, and secondary fabrication into final tubing. Several potential materials are available for selection of the starting material. The purpose of this program is to study the following starting materials either for ingot or for extrusion billet preparation: pressed and sintered tungsten powder sleeves, electron-beam or arc-melted ingots, pre-extruded tungsten tube blanks, large-diameter tungsten single crystals, rolled and welded tungsten sheet cylinders, and vapor-deposited tungsten tubes. Direct consolidation and extrusion of tungsten powder into tubing will also be studied. All of these starting materials will be evaluated in optimizing fabricability, and in improving the quality and properties of the final product.

Primary fabrication of the various starting materials will be by extrusion. The techniques employed will be more fully described in the body of this report, but emphasis will be placed on extruding tungsten sleeves together with a deformable core as in coextrusion, rather than on extruding over a nondeformable mandrel. This eliminates the problem of adequate mandrel performance in extruding small-diameter tubing. Also eliminated is the problem of mandrel lubrication and subsequent ID conditioning of the extruded tubes.

One objective of extrusion will be to extrude the tungsten sleeves at temperatures below the recrystallization temperature. If extrusion temperatures can be lowered, obtaining adequate die performance and lubrication become less of a problem than at higher temperatures.

Extruding tungsten tubing directly to final diameters of 0.32 cm (0.125 in.) or less will be difficult, if not impossible. Secondary fabrication is therefore needed to impart final dimensions and adequate properties to the tungsten tubing. The secondary fabrication of small-diameter, thin-wall, tungsten tubing is expected to be quite difficult, for the material must be worked above the ductile-brittle transition temperature. Care must be exercised to ensure that the small-diameter material retains sufficient heat during the working operation to remain above this temperature. Two main methods of secondary fabrication - swaging and drawing - will be used. Other subsidiary fabrication steps such as straightening will be necessary, but these will only be reported in detail if they require specialized techniques other than those currently available or employed in conventional tube fabrication.

Destructive and nondestructive testing will be carried out at all stages of fabrication to ensure selection of proper starting materials, to optimize fabrication parameters, and to obtain the maximum properties and qualities of the final product. The economics of the various techniques employed will be kept in mind in order to minimize the cost of the final material consistent with the objectives of quality and maximum properties.

In this initial report, progress on extrusion of various starting materials will be described and discussed. As yet, secondary fabrication of extruded tube blanks is too embryonic to be included and will be covered in later publications. No melting of tungsten or tungsten alloys has been done to date, since billet starting materials have been procured from commercial sources.

EQUIPMENT

Complete integrated facilities for processing materials from ingots to final products are available in the Foundry and Fabrication Group at Argonne National Laboratory. Available for use are an electron-beam furnace, an arc furnace, three extrusion presses, three rolling mills, two drawbenches, and three swaging machines. The furnaces and extrusion presses will be described in this report. The drawbenches and swaging machines will be described in subsequent progress reports that will cover secondary fabrication in more detail. The rolling mills will not be described unless they become part of the fabrication procedure.

The electron-beam furnace is a 60-kW unit designed for melting, purification, and casting of refractory metals and alloys and was manufactured by the National Research Corporation. The furnace can use either a powder feed from a vibratory hopper, or rod feeding. The electron gun has a separate evacuating system to protect it from pressure bursts occurring during melting. The furnace can produce ingots from 3.8 to 12.2 cm (1.5 to 4.8 in.) in diameter, and 61 cm (24 in.) maximum length, depending on material and on power limitations. A photograph of the furnace is shown in Figure 1, and a sketch of the various components in Figure 2.

The National Research Corporation cold-mold arc furnace has a maximum capacity of 4,500 amperes. Mold sizes range from 2.8 cm (1.1 in.) to 14.5 cm (5.7 in.) in diameter, the maximum ingot length being 45.7 cm (18 in.). The furnace is capable of maintaining a vacuum of 10 microns or less during melting. The furnace is capable of either consumable or non-consumable operation. Consumable melting is done under vacuum, while nonconsumable melting is done under approximately 250 mm (one-third atmosphere) of argon to sustain the arc. A magnetic stirring device is available to promote homogeneity and quality of the arc-cast ingot. A photograph of the arc melting furnace is shown in Figure 3.

Three extrusion presses are available for program work. They include a 150-ton, modified, Lake Erie vertical press; a 350-ton, Lombard vertical press; and a 1250-ton, Lake Erie horizontal press. The 150-ton press is an oil, hydraulic-powered unit, while the two larger presses are powered from a single water-accumulator system.

The 150-ton hydraulic press was modified by adding the container shift shown in Figure 4. The press is capable of extruding 2.5- and 3.2-cm- (1- and 1.250-in.)-diameter billets. Maximum ram speed of the press is limited to 2.5 cm/sec (1 in./sec). This is rather slow for extrusion of refractory metals at high temperatures, which require high-speed extrusion to avoid softening of the hardened tooling. In addition to conventional, resistance-heating furnaces, a small induction heater is available. The coil

106-7335

Figure 1. Photograph of 60-kW Electron-beam Melting Furnace

106-7362

Figure 2. Sketch Showing Components of Electron-beam Melting Furnace

Figure 3
Photograph of
Arc Melting
Furnace

106-7045

Figure 4

Photograph of Stem and Container
Shift on 150-ton Vertical Lake Erie
Extrusion Press

106-7041

is positioned directly above the furnace so that after heating and soaking long enough to ensure a uniform billet temperature, the billet is dropped

directly into the container. Extrusion begins immediately after the coil is moved away from the advancing ram. The time from the end of heating to initiation of extrusion is less than 5 seconds. The press is most useful for small-scale productive efforts and is used to evaluate tooling arrangements, die materials, and extrusion techniques of potential merit for use in the larger presses. The tooling arrangement for the press is shown in Figure 5.

106-7050

Figure 5. Tooling Arrangement for 150-ton Lake Erie Vertical Extrusion Press

is used for general extrusion work as well as for ingot breakdown of refractory metals and alloys to provide feed stock for the 350-ton, vertical, extrusion press.

The 1250-ton, Lake Erie, horizontal extrusion press shown in Figure 6 is designed to extrude 10.1- and 15.2-cm- (4- and 6-in.)-diameter billets, and is capable of delivering a 908-metric-ton (1,000-ton) load at an extrusion speed of 25.4 cm/sec (10 in./sec). The tooling arrangement is shown in Figure 7. Billet heating equipment consists of a large furnace heated with silicon carbide resistors and capable of operation up to 1500°C. Transfer equipment between the furnace and the press minimizes manual billet handling and provides rapid transfer of hot billets to the container. In the design stage is an induction-heated furnace (vacuum or inert gas) capable of heating refractory metal billets to high temperatures. A 7.6-cm- (3-in.)-diameter container and associated tooling were recently received. This will enable extrusion of billets more consistent with the mold sizes of the arc and electron-beam furnaces. The 1250-ton press

106-7046

Figure 6. Photograph of 1250-ton Lake Erie Horizontal Extrusion Press

106-7049

Figure 7. Tooling Arrangement for 1250-ton Extrusion Press

The 350-ton, vertical, Lombard, extrusion press shown in Figure 8 is a high-speed press intended primarily for extrusion of tubing. The press is capable of delivering 270 metric tons (300 tons) at a 38.1-cm/sec (15-in./sec) ram speed and handles 5.1-cm- (2-in.)- and 6.4-cm- (2.50-in.)- diameter billets. The tooling arrangement is shown in Figure 9. In addition

106-7043

Figure 8. Photograph of 350-ton Lombard Vertical Extrusion Press

106-7048

Figure 9. Tooling Arrangement for 350-ton Extrusion Press

to the die shown in the tooling arrangement drawings, current practice includes the use of a container die located inside the container liner. This design materially reduces die cost and fabrication time and permits the container liner to absorb some of the high radial stresses imposed on the die during extrusion.

A small induction-heated furnace (using either a vacuum or an inert atmosphere) is located over the hydraulic billet loader and is powered by a 30-kW, portable, Tocco MG unit. In addition, a small, open-air, induction coil is located in the rear of the press for heating billets that do not require inert atmospheres or vacuums. With this arrangement, the billets are manually transferred to the press in transfer times of 10 seconds or less. The press is capable of both direct or indirect extrusion and can use a free-moving mandrel through a hollow stem, since the main ram has a 5.1-cm- (2-in.)-diameter hole extending the length of the ram. Extrusions made on the press can be run either into a vertical well hole in the pit beneath the press, or over a curved runout section onto a horizontal table.

Hot extrusions can be rough-straightened immediately after extruding by using straightening bars located on the runout table. This technique ensures sufficient straightness to later permit loading into a conventional Medart rod straightener.

To date, extrusion temperatures have been kept below 1250°C on the two large presses, thus enabling the use of molybdenum disulfide-graphite-heavy oil lubricants rather than high-temperature glasses. In a similar vein, the use of relatively low extrusion temperatures has allowed the use of conventional, hot-work tool steel dies without ceramic coatings. Adequate die life has been achieved with minimum die wash because of the high extrusion speeds available. Facilities for ceramic coating of dies and applying glass lubrication to hot extrusion billets are available, however, and these techniques will be used should the need arise.

TECHNICAL PROGRESS

Preliminary Work

Before a formal program was developed and initiated, attempts were made to draw vapor-deposited tungsten tubes to a final target size of approximately 0.317 cm OD x 0.03 cm wall thickness (0.125 in. OD x 0.012 in. wall thickness). A few Kovar tubes with tungsten vapor-deposited on the ID were purchased from Wheaton Industries, Addison, Illinois. The deposited tungsten was very coarse-grained and oriented in a radial direction, as seen in Figure 10a. (The microstructure of the tungsten deposited on the ID of a copper tube is shown in Figure 10b. The improved ID surface of the deposit is evident. These tubes were procured at a later date and used in work described in a later section.) Measurements of the hardness of the deposited tungsten averaged 498 DPH. Attempts were made to reduce these tubes by drawing, both at room temperature and at approximately 1000°C. Neither attempt was successful, since the deposited tungsten broke into short rings. The results were not entirely unexpected because of the brittle nature of tungsten, the radial grain orientation, and the application of a tensile stress in drawing that is perpendicular to the direction of grain orientation. Further work on drawing tungsten that has been vapor-deposited inside a tube has been abandoned for the time being. The abandonment is due to the problems mentioned and also to the very irregular and rough ID profile of the deposited tungsten tube. After more is learned about warm-drawing of tungsten tubing from extruded tube blanks, attempts to draw vapor-deposited tungsten may be tried again. Progress in obtaining better deposits of tungsten, and in eliminating the radial growth of individual grains across the complete wall thickness, may make it possible to supply a vapor-deposited product with sufficient strength and randomness of grain orientation for direct hot drawing.

In an effort to determine the hot-working temperatures of tungsten consolidated by vapor-deposition techniques, small specimens of tungsten strip were jacketed in a molybdenum can and pressed under static loads at 1250°C with about 10% reductions per pass. The microstructure of a deposited flat tungsten strip is shown in Figure 11. (NOTE: Although no work was done with vapor-deposited, tungsten strip that had been sintered, the microstructure of a vapor-deposited, tungsten strip sintered at 1765-1780°C is shown in Figure 11. No apparent change in the transverse microstructure is evident, but the longitudinal microstructure has been changed by sintering. The columnar grains no longer traverse the total strip thickness as in the as-deposited strip. Hardness readings on an as-deposited strip measured 450 DPH, while on the deposited-and-sintered strip the transverse hardness was 383 DPH and the longitudinal hardness was 370 DPH.)

(a) Deposited on ID
of Kovar Tube

Micro 36279

498 DPH

165X

(b) Deposited on ID
of Copper Tube

Micro 36280

360 DPH

165X

Etchants: 10% $K_3Fe(CN)_6$, 10% KOH, 80% H_2O

Figure 10. Microstructure of Transverse Section of Tungsten Tubing Made by Vapor Deposition

Figure 11. Vapor-deposited Tungsten Strip: Microstructure of Deposited Strip and of Deposited and Sintered (1765-1780°C) Strip

One vapor-deposited, tungsten strip, 0.023 cm (0.009 in.) thick in the middle of its width, was jacketed with approximately 1.27 cm (0.500 in.) of molybdenum on one side, and approximately 0.95 cm (0.375 in.) of molybdenum on the other side. The tungsten specimen was examined after about 40% total reduction on the overall jacketed thickness after hot pressing. The edges of the tungsten strip were cracked, and the strip surface facing the jacket side with the thinner molybdenum was full of cracks. The surface facing the jacket side with the thicker molybdenum did not show these surface cracks. This may be attributed to the faster cooling of the jacket side, with the thinner molybdenum chilling the mating surface of the tungsten strip with sufficient rapidity to result in surface cracking. The tungsten strip received only about 16-1/2% reduction in thickness, contrasted

to the overall 40% reduction of the compact. The dimensions of the components of the jacketed assembly before and after pressing were as follows:

<u>Thickness</u>	<u>Before Pressing</u>	<u>After Pressing</u>
Mo jacket, thick side	1.27 cm (0.5 in.)	0.76 cm (0.298 in.)
Mo jacket, thin side	0.95 cm (0.375 in.)	0.50 cm (0.196 in.)
W strip thickness	0.023 cm (0.009 in.)	0.019 cm (0.0075 in.)

Although a molybdenum jacket is used to contain the tungsten strip, the fabrication of thin sections of vapor-deposited tungsten remains a difficult operation. Deformation must be done hot and must be done rapidly to minimize heat loss during fabrication.

Following this initial work on drawing and hot-pressing vapor-deposited tungsten, the program scope was increased. Hereafter, the initial deformation in the fabrication of tungsten tubing has been done by hot extrusion.

The starting materials and the extrusion results for these various approaches will be described in the following sections.

Starting Materials

Of the various materials mentioned earlier, work to date has been carried out on the following starting materials: 1) vapor-deposited tungsten sleeves, 2) pre-extruded tungsten tubing, 3) pressed-and-sintered tungsten powder sleeves, and 4) high-purity tungsten granules. Typical analyses for carbon, hydrogen, nitrogen, and oxygen, together with analyses for certain metallic minor elements, are given in Table I for the various starting materials.

Vapor-deposited tungsten tubing procured from Wheaton Industries, Inc., was deposited from a WF_6 gas onto the inside of a tube of Kovar or copper. After removal of the base tubing, the finish of the outside-diameter surface of the tungsten tubing was a smooth matte, while the finish of the internal-diameter surface varied from a matte for thin-wall tubing, to one having a nodular appearance for thicker walls. The tubing was very coarse-grained and characterized by oriented grain growth in a radial direction, as seen in Figures 10a and 10b. Sizes of the vapor-deposited tungsten tubes used in the extrusion experiments ranged from 0.64 cm (0.250 in.) OD x 0.46 cm (0.180 in.) ID, to 1.27 cm (0.500 in.) OD x 1.17 cm (0.460 in.) ID. In some cases, the tubing was characterized by a tapered wall thickness. In deposition, the tungsten deposit thins down near the ends of the tube, thus accounting for the tapering wall thickness. The quality of vapor-deposited tungsten tubing has recently been improved. The roughness of the internal surface can be decreased, and tubing is now available whose cross-sections

show a series of more or less equiaxed grains rather than a single-oriented grain characteristic of the tubing used in these initial studies. Tubing with the improved microstructure is being procured and will be fabricated into tubing by hot extrusion. Results will be compared to that obtained with vapor-deposited tungsten characterized by large oriented grains that have grown across the total wall thickness.

Table I

TYPICAL ANALYSES OF TUNGSTEN STARTING MATERIALS

Element	Typical Analysis, ppm		
	Vapor-deposited ⁽¹⁾ Tungsten Tubing	Pressed-and-sintered ⁽²⁾ Tungsten and Pre-extruded Tungsten Tubing	High-purity ⁽³⁾ Tungsten Powder
C	N.A. ⁽⁴⁾	50 max	<10
O ₂	35-100	100 max	7
N ₂	10-20	50 max	<1
H ₂	~1	10 max	1
Al	N.A.	<6	<10
Si	<6	<7	<10
Fe	<2	15	<10
Cr	<2	4	N.A.
Ni	<2	6	<10
Cu	<2	5	<5
Mo	<2	35	<20
Mn	<2	<6	N.A.
Mg	<6	7	<3
Sn	<2	<6	N.A.

(1) Supplied by Wheaton Industries, Inc., Addison, Illinois.

(2) Supplied by General Electric, Lamp Metals & Components Dept., Cleveland, Ohio.

NOTE: The C, O₂, N₂, and H₂ analyses are maximums allowed by GE specifications. Pre-extruded tungsten tubing obtained from Nuclear Metals, Inc., West Concord, Mass. NMI used pressed and sintered tungsten sleeve in primary extrusion.

(3) Supplied by Allied Chemical Company, General Chemical Div., Morristown, New Jersey,

(4) N.A. = Not available

Pre-extruded tungsten tubing was obtained from Nuclear Metals Company, West Concord, Mass. Details of the fabrication technique for producing this tungsten tubing are described elsewhere.⁽¹⁾ The original tungsten used in their extrusions consists of a pressed and sintered tungsten sleeve as described below. A typical microstructure of the extruded tubing is shown in Figure 12.

Pressed and sintered tungsten sleeves, 3.16 cm OD x 2.54 cm ID x 10.2 cm long (1.250 in. OD x 1 in. ID x 4 in. long), were procured from the

General Electric Company. The powder sleeves were hydrostatically pressed and hydrogen-furnace-sintered at a temperature above 1800°C. Sintered densities were approximately 93%, based on a theoretical density of 19.3 gm/cc. All sleeves were inspected by the vendor, using dye-penetrant and ultrasonic techniques, and were judged to be free of defects. A typical sleeve had a Rockwell hardness of 32 R_C (about 320 DPH).

Longitudinal

Micro 36775

250X

Transverse

Micro 36774

250X

Etchant: 10% K₃Fe(CN)₆, 10% KOH, 80% H₂O

Figure 12. Microstructure of Tungsten Tube
Extruded by Nuclear Metals, Inc.

High-purity tungsten granules, procured from the Allied Chemical Company, were used in direct conversion of tungsten powder to tubing by hot extrusion. The purity of this material with respect to interstitial elements is indicated in Table I. The granules are produced by reducing WF_6 with hydrogen. The granules, shown in Figure 13, tend to be spherical, the average granule diameter being about 475 microns, and approximately 80% of the granules produced being between 420 and 590 microns. Hardness of this granular material is approximately 1000 KHN as reported by the vendor.

Micro 37334

100X

Etchant: 10% $K_3Fe(CN)_6$, 10% KOH, 80% H_2O

Figure 13. Microstructure of High-purity Tungsten Granules from Allied Chemical Company

Melting

No work on arc or electron-beam melting of tungsten or tungsten-base alloys has been done as all starting materials to date have been commercially available. Melting will be done if the desired starting material or special alloys are not otherwise available.

Extrusion

An overall compilation of data on starting materials and extrusion parameters is given in Table II. In all cases, billet assembly and enclosure welding were done in an argon atmosphere glovebox. The following discussion of extrusion will be presented on the basis of starting materials.

a) Extrusion of Vapor Deposited Tungsten Sleeves

A small specimen of a vapor-deposited tungsten sleeve, 0.635 cm OD x 0.521 cm ID x 1.9 cm long (0.250 in. OD x 0.205 in. ID x 0.750 in. long), was assembled with an internal molybdenum core and jacketed in 304 stainless steel. The composite billet was extruded (extrusion No. 71) at 1250°C through a 1.232-cm (0.485-in.) die corresponding to an extrusion ratio of 4.2:1. The extrusion was done on the 150-ton vertical press with a fixed ram speed of 2.54 cm/sec (1 in./sec). Radiography of the extruded composite rod showed a "dog-bone" effect at the lead end of the tungsten tube, but the rest of it was of a uniform diameter. Two radial cracks were observed in the radiograph. The microstructure of the vapor-deposited tungsten sleeve is shown in Figure 10b; the microstructure of the extruded tungsten is shown in Figure 14. A typical worked structure is evident.

The 304 stainless steel jacket was removed by dissolution in aqua regia, and the molybdenum core by dissolution in a 30-60% nitric acid solution. The extruded tungsten tube surface showed very fine longitudinal striations. Also visible were some circumferential striations (not cracks) with depths approximately 0.0025 cm (0.001 in.) or less. The two radial cracks seen in radiography were evident. The dimensions of the extruded tube were 0.315/0.325 cm OD x 0.028/0.030 cm wall thickness (0.124/0.128 in. OD x 0.011/0.012 in. wall thickness). The variance in diameters and wall thicknesses of the extruded tungsten tube resulted from a carry-through of a tapered wall section existent in the original, vapor-deposited, tungsten sleeve. The tungsten tube reduced slightly less than the overall extrusion due to the relative softness of the 304 stainless steel jacket at the extrusion temperature.

Further extrusions of vapor-deposited tungsten sleeves with billets of the same design (304 SS jacket and Mo core) and extrusion temperature (1250°C) were tried on the 150-ton press. Composite billets

Table II
DATA ON EXTRUSION OF TUNGSTEN TUBING

Extrusion No.	Press and Nominal Billet Diameter	Tubing Material		Jacket Material	Annulus Material	Core Material	Die Size, cm (in.)	Extrusion Ratio ? : 1	Avg. Ext. Speed, cm/sec (in./sec)	Lubricant	Induction Billet Heating				Transfer Time, sec	Extrusion Pressures		"K" 1000 kg/cm ² (1000 psi)	Remarks
		Composition	Size, cm (in.)								% Rated Power	Heat Time, min, sec	Soak Time, min, sec	Billet Temp, °C		Breakthrough 1000 kg/cm ² (1000 psi)	Running 1000 kg/cm ² (1000 psi)		
71	150-ton 2.54 cm (1 in.)	Vapor-deposited W sleeve	0.635 OD x 0.521 ID (0.250 OD x 0.205 ID)	304 SS	-	Mo	1.228 (0.484)	4.2	2.5 (1)	MoS ₂ and graphite (50:50) in synthetic oil	20	2-30	-	1250	5	10.8 (153)	10.8 (153)	7.5 (107)	Radiograph shows tube belled on lead end, but balance looked good.
106	"	W granules (Allied)	2.142 OD x 1.778 ID annulus (0.844 OD x 0.700 ID annulus)	304 SS	-	304 SS	1.270 (0.500)	4.0	2.5 (1)	MoS ₂ and graphite (90:10) in synthetic oil	25	1-50	-	1250	5	8.9 (127)	8.1 (115)	5.8 (83)	Jacket tore in 20-30 places over length of extrusion. Metallography shows W granules in discontinuous network and surrounded by 304 SS.
107	"	W granules (Allied)	2.142 OD x 1.778 ID annulus (0.844 OD x 0.700 ID annulus)	304 SS	-	304 SS	1.270 (0.500)	4.0	2.5 (1)	"	25	1-45	1-0	1250	5	8.9 (127)	8.9 (127)	6.4 (91.6)	Same as No. 106, but tearing not quite so severe.
142	350-ton 5.08 cm (2 in.)	NMI pre-extruded W sleeve	1.167/1.182 OD x 0.981/0.998 ID (0.459/0.466 OD x 0.386/0.393 ID)	304 SS	-	Mo	2.250 (0.887)	5.3	12.9 (5.1)	MoS ₂ and graphite (95:5) in synthetic oil	15	6-0	5-0	1250	10	10.3 (147)	8.4 (119)	5.0 (71.3)	Extruded section of W and Mo core broken in 3 sections with "teardrop" design indicating ductile fracture.
156	150-ton 2.54 cm (1 in.)	W granules (Allied)	2.142 OD x 1.778 ID annulus (0.844 OD x 0.700 ID annulus)	304 SS	-	304 SS	1.270 (0.500)	4.0	2.5 (1)	"	25	1-15	5-0	1250	7	6.3 (89)	6.3 (89)	4.5 (64.2)	304 jacket torn off and rewelded to other sections of extrusion. Metallography shows W granules in discontinuous network and surrounded by 304 SS. 304 jacket too soft and thin to contain and compact the W granules.
168	"	Vapor-deposited W sleeve	0.635 OD x 0.447/0.472 ID x 4.28 L (0.250 OD x 0.176/0.186 ID x 1-11/16 L)	304 SS	-	Mo	1.270 (0.500)	4.0	2.5 (1)	"	20	2-15	4-30	1250	~17	?	8.9 (127)	6.5 (92)	Ten-second delay in transfer via misunderstanding. Extruded OK. No cracks visible in radiograph, but visible on surface of decanned sleeve.
169	"	Vapor-deposited W sleeve	1.265/1.270 OD x 1.167/1.184 ID x 5.1 L (0.498/0.500 OD x 0.459/0.467 ID x 2 L)	304 SS	-	Mo	0.953 (0.375)	7.0	2.5 (1)	"	20	2-0	5-0	1250	7.5	13.4 (191)	10.8 (153)	5.5 (78.8)	Extruded OK. Radiography shows extruded tube with belled ends. Uniform diameter over about 95% of length. Indications of radial cracks in radiograph.
170	"	Vapor-deposited W sleeve	1.015/1.023 OD x 0.882/0.898 ID x 4.6 L (0.400/0.403 OD x 0.347/0.354 ID x 1-13/16 L)	304 SS	-	Mo	0.635 (0.250)	16.0	2.5 (1)	"	20	2-15	7-0	1270	8	-	-	-	Stalled; only 1.9 cm (3/4 in.) extruded.
171	"	NMI pre-extruded sleeve	1.184/1.205 OD x 0.980/0.998 ID x 3.96 L (0.467/0.475 OD x 0.386/0.393 ID x 1-9/16 L)	Mo	-	Mo	0.953 (0.375)	7.0	2.5 (1)	"	20	3-15	3-0	1400	7	-	-	-	Stalled; only 1.27 cm (1/2 in.) extruded.
172	"	Vapor-deposited W sleeve	Re-extrusion of No. 170	304 SS	-	Mo	0.873 (0.344)	8.5	2.5 (1)	"	20	2-0	5-0	1250	5	-	-	-	Re-extrusion of No. 170. Stalled again.
173	"	NMI pre-extruded sleeve	Re-extrusion of No. 171	Mo	-	Mo	1.258 (0.495)	4.0	2.5 (1)	"	20	2-30	5-0	(1400)	-	-	-	-	Stalled, only 2.54 cm (1 in.) nose extruded. Billet temperature estimated due to heavy MoO ₃ smoke.
174	"	NMI pre-extruded sleeve	1.160/1.203 OD x 0.985/1.003 ID x 2.54 L (0.457/0.474 OD x 0.388/0.395 ID x 1 L)	Mo	-	Mo	1.368 (0.538)	3.5	2.5 (1)	"	25	3-15	3-0	1475	5	14.3 (204)	11.7 (166)	9.3 (132)	Extruded OK. Radiograph shows uniform W tube with slight bellling on ends and no apparent cracking.
175	"	W granules (Allied)	1.270 OD x 0.635 ID x 3.49 L (1/2 OD x 1/4 ID x 1-3/8 L)	Mo	-	Mo	1.361 (0.536)	3.5	2.5 (1)	"	25	2-45	3-0	1500	5	11.6 (165)	11.6 (165)	9.3 (132)	Extruded OK. Mo end plug designed to precompact W granules before extruding. Radiograph shows W granules to be fully densified into a sound tube with no evidence of cracking. Metallography indicates full compaction and welding of granules but circular crack near W ID. Probably due to contraction of Mo core.
176	"	"	"	"	-	"	1.270 (0.500)	4.0	2.5 (1)	"	25	2-30	3-0	1525	?	14.3 (204)	10.8 (153)	7.7 (110)	Same as No. 175.
177	"	"	"	"	-	"	"	4.0	2.5 (1)	"	25	2-30	3-30	1660	5	11.6 (165)	11.6 (165)	8.4 (119)	Same as No. 175.
187	350-ton 5.08 cm (2 in.)	GE Press & sintered sleeve	3.17/3.19 OD x 2.52/2.54 ID x 10.5 L (1.249/1.258 OD x 0.991/0.998 ID x 4-1/8 L)	304 SS	-	Mo	2.252 (0.887)	5.3	9.1 (3.6)	"	55-60	5-30	5-0	(1250)	45	9.9 (140)	9.0 (128)	5.4 (76.8)	Billet heated to 1250°C and soaked. Billet delayed in transfer until surface measured 1100°C. Extruded OK. Radiograph shows sound, uniform tube.
188	"	"	"	304 SS	-	Mo	1.870 (0.737)	7.7	11.7 (4.6)	"	55-60	4-30	5-0	1270	12	11.7 (166)	-	-	No delay in billet transfer. Extruded OK. Radiograph shows severely rippled W tube and Mo core and extrusion OD. Obviously the 304 outer jacket too hot to have sufficient strength to contain the stiffer W and Mo during extrusion.
202	"	"	3.17/3.18 OD x 2.52/2.53 ID x 10.7 L (1.249/1.253 OD x 0.993/0.996 ID x 4-3/16 L)	304 SS	-	Mo	1.780 (0.700)	8.4	8.9 (3.5)	MoS ₂ and graphite in synthetic oil	50	6-0	5-0	(1195)	31	11.4 (161)	10.7 (152)	5.1 (71.5)	Billet cooled until jacket measured 1100°C. Extruded satisfactorily. Slight end effects on both ends. Radiograph indicates W tube free from defects.
203	"	"	3.17/3.18 OD x 2.53/2.54 ID x 10.7 L (1.249/1.254 OD x 0.995/0.999 ID x 4-3/16 L)	"	-	"	1.715 (0.675)	9.1	11.2 (4.4)	"	40	6-30	5-0	1125	10	9.5 (134)	9.3 (132)	4.2 (59.8)	Extruded satisfactorily. Slight end effects on both ends. Radiograph indicates W tube free from defects.
204	"	"	3.18/3.20 OD x 2.53/2.54 ID x 10.7 L (1.254/1.258 OD x 0.995/0.998 ID x 4-3/16 L)	"	Al ₂ O ₃	"	1.630 (0.642)	10.0	13.0 (5.1)	"	50	5-45	5-0	1125	11	9.2 (130)	8.8 (124)	3.8 (53.8)	Extruded satisfactorily. Slight rippling at nose end probably due to impact of rod against stopping wall. About 2/3 of W tube uniform and free from defects in radiography.

Transverse

304 SS Jacket

W Tube

Mo Core

Micro 36893

165X

Longitudinal

304 SS Jacket

W Tube

Mo Core

Micro 36894

165X

Etchant: 10% $K_3Fe(CN)_6$, 10% KOH, 80% H_2O

Figure 14. Microstructure of Vapor-deposited Tungsten Tube after Extrusion (No. 71) at 1250°C and 4:1 Reduction Ratio

could not be extruded at 16:1 (extrusion No. 170) and 8.5:1 (extrusion No. 172) ratios with an 80-ton load representing a limiting stem stress of 14,100 kg/cm² (200,000 psi). A billet successfully extruded at a 7:1 ratio (extrusion No. 169) showed possible radial cracks or striations in the tungsten tube in radiography. A billet extruded at a 4:1 ratio (extrusion No. 168) appeared very uniform, with no evidence of radial cracks when radiographed. After the stainless steel jacket was removed from the extruded tubes, both showed circumferential surface striations which did not penetrate deeper than 0.0025 cm (0.001 in.). No definite radial cracks were observed. The microstructure of the tungsten sleeve extruded at a 7:1 ratio (extrusion No. 169) is shown in Figure 15; the typical surface appearance of extruded vapor-deposited tungsten tubes is shown in Figure 16 (extrusion Nos. 168 and 169).

The difficulties in extruding billets at ratios greater than 7:1 stem from the slow 2.54-cm/sec (1-in./sec) ram speed of the 150-ton press. The relatively rapid cooling of the small-diameter, 2.54-cm (1-in.), billet makes it difficult to maintain sufficient plasticity in the billet for extrusion at the higher reduction ratios. Further extrusion of vapor-deposited tungsten tubing will be scaled up to 5.08-cm- (2-in.)-diameter billets for extrusion on the 350-ton vertical press, where rapid ram speeds are obtainable and rapid chilling of the billet becomes less of a problem.

b) Re-extrusion of Extruded Tungsten Tubes

Two small sections of tungsten tubing extruded by Nuclear Metals, Inc., were available for re-extrusion. The tubes measured 1.167/1.182 cm OD x 0.981/0.998 cm ID (0.459/0.466 in. OD x 0.386/0.393 in. ID). The microstructure of these tubes is shown in Figure 12. Half of one piece of tubing was jacketed in a 304 stainless steel billet, with a molybdenum core inside the tungsten tube. The billet was extruded on the 350-ton vertical press at 1250°C through a 2.250-cm (0.887-in.) die to give a 5.3:1 reduction ratio (extrusion No. 142). While the billet extruded satisfactorily, radiography showed the tungsten tube and molybdenum core to be broken into three sections with a "tear-drop" design indicating a ductile fracture. It is reasoned that the 304 stainless steel at the extrusion temperature of 1250°C was so soft, relative to the tungsten, that the stainless steel did not provide sufficient uniform constraint during extrusion. This lack of restraint resulted in the periodic fracturing of the tungsten tube and molybdenum core when the billet passed through the die.

The second section of this tungsten tube was jacketed in a 2.54-cm- (1-in.)-diameter molybdenum can with a molybdenum core. Attempts to extrude this small-diameter billet on the slow-moving, 150-ton, vertical press at an extrusion temperature of approximately 1400°C, and at reduction ratios of 7:1 (extrusion No. 171) and 4:1 (extrusion No. 173), resulted in stalling the press after less than 1.2 cm (0.500 in.) of the

Longitudinal

304 SS Jacket

W Tube

Mo Core

Micro 37316

100X

Transverse

304 SS Jacket

W Tube

Mo Core

Micro 37315

100X

Etchant: 10% $\text{K}_3\text{Fe}(\text{CN})_6$, 10% KOH, 80% H_2O

Figure 15. Microstructure of Vapor-deposited Tungsten Sleeve Extruded (No. 169) at 1250°C at 7:1 Reduction Ratio

Figure 16. As-extruded Surface of Extruded Tungsten Tubes

billets had been extruded. Here again, as with the vapor-deposited tungsten extrusions, the rapid chilling of the small-diameter billet probably resulted in insufficient plasticity for the billet.

A third attempt to extrude a pre-extruded tungsten sleeve canned in a molybdenum jacket with a molybdenum core resulted in a successful extrusion on the 150-ton press at an extrusion temperature of 1475°C with a 3.5:1 reduction ratio (extrusion No. 174). The billet extruded satisfactorily, and radiography showed the tungsten tube to be sound and free of cracks with only slight "dog-boning" on the lead and tail ends. The extruded tungsten tube measured about 0.63 cm OD x 0.05 cm wall thickness (0.250 in. OD x 0.020 in. wall thickness). Hardness measurements showed the cross section of the extruded tungsten sleeve to be 519 DPH (50 R_C); the molybdenum core and jacket measured 274 DPH (99 R_B). The microstructure of the extruded

composite rod is shown in Figure 17. The surface quality of the extruded tungsten tube after removal of the cladding is shown in Figure 16 (extrusion No. 174).

Longitudinal

Mo Jacket

W Tube

Mo Core

Micro 37318

100X

Transverse

Mo Jacket
247 DPH

W Tube
519 DPH

Mo Core
247 DPH

Micro 37317

100X

Etchant: 10% $K_3F_3(CN)_6$, 10% KOH, 80% H_2O

Figure 17. Microstructure of Nuclear Metals, Inc., Extruded Tube after Re-extrusion (No. 174) at ANL at 1475°C at 3.5:1 Reduction Ratio

c) Extrusion of Pressed and Sintered Tungsten Powder Sleeves

Tungsten sleeves, 3.16 cm OD x 2.54 cm ID x 10.2 cm long (1.250 in. OD x 1.000 in. ID x 4 in. long), were procured from the General Electric Company. Molybdenum cores were placed inside the sleeves, and these components were placed inside 304 stainless steel cans to make up composite extrusion billets. The first billet was extruded at an extrusion ratio of 5.3:1 on the 350-ton vertical extrusion press (extrusion No. 187). The billet was induction-heated to 1250°C and soaked at temperature for 5 minutes. Transfer of the hot billet to the press was deliberately delayed until the surface temperature of the 304 stainless steel jacket had dropped to 1100°C and the strength of the stainless steel had correspondingly increased. The extrusion was uniform in diameter, with only a slight break in the 304 stainless steel jacket at the point where the tungsten sleeve began to extrude. Radiography showed a uniform tungsten tube with "dog-bone" effects at both ends. No cracks were observed in the decanned tungsten tube measuring approximately 1.47-cm OD x 0.14-cm wall thickness (0.55-in. OD x 0.055-in. wall thickness). The tungsten tube surface is shown in Figure 16 (extrusion No. 187) and shows slight circumferential striations less than 0.0025 cm (0.001 in.) in depth. The as-extruded tungsten microstructure is similar to that shown in Figure 12. Hardness measurements on a transverse section showed the tungsten tube to be 536 DPH (51 R_C); the 304 stainless steel jacket was 157 DPH (81 R_B), and the molybdenum core was 227 DPH (96 R_B).

A second pressed-and-sintered tungsten sleeve was assembled into an identical billet and extruded at a 7.7:1 ratio at 1250°C (extrusion No. 188). After being soaked at temperature, the billet was directly extruded with no delay in transfer to cool the 304 stainless steel jacket. Although the billet extruded, the resulting rod was severely rippled along the length containing the tungsten and molybdenum components. Radiography revealed a wavy pattern in the tungsten tube and molybdenum core, as seen in Figure 18. The pattern is characteristic of a coextruded composite billet where the jacket material is relatively soft compared to the core material. In this case, the steel jacket at 1250°C had insufficient strength to provide uniform constraint on the tungsten and molybdenum during extrusion.

Three additional tungsten sleeves have been extruded. Two sleeves were assembled into a composite billet in the manner described previously. The first billet was heated to 1195°C and delayed in transfer to the press until the stainless steel jacket had cooled to 1100°C. The billet was pushed at an 8.4:1 reduction ratio. The radiograph of the extruded rod showed the tungsten tube to be uniform and free of defects. A second sleeve was extruded at a 9.1:1 reduction ratio at an extrusion temperature of 1125°C with no cooling of the stainless steel jacket between

Micro 37386 1X

Figure 18. Print from Section of Radiograph of Extrusion No. 188: Pressed and Sintered Tungsten Sleeve with Molybdenum Core and 304 Stainless Steel Jacket Extruded at 1250°C at 7.7:1 Reduction Ratio

billet heating and extrusion (extrusion No. 203). Here again, radiography revealed a uniform tungsten tube. A third tungsten sleeve was extruded using the DPM technique. This technique has been described elsewhere⁽²⁾ and basically consists of extruding a metal sleeve with an internal deformable core. A thin annulus between the core and sleeve is filled with a disposable particulate matter (DPM). This technique permits removal of the central core material from the extruded product by mechanical means rather than by acid dissolution. In this case, the tungsten sleeve was placed in a 304 stainless steel jacket with a molybdenum core in a manner similar to the previous extrusions. However, a thin annulus filled with -140 +170 mesh Al_2O_3 separated the tungsten sleeve from the molybdenum core. The annulus thickness was 0.084 cm (0.029 in.). The billet was heated to 1125°C and immediately transferred to the press and extruded to a 10:1 reduction ratio (extrusion No. 204). Again, radiography indicated the tungsten tube to be uniform in diameter along its length, except for lead and tail end defects, and to be free of radial cracks. The microstruc-

ture of these later extrusions is similar to that of an earlier extrusion (Figure 12) except that a higher degree of cold work is evident due to the higher reductions during the extrusion.

d) Direct Hot Consolidation and Extrusion of Tungsten Tubing from High-purity Tungsten Granules

Initial work has been done on direct conversion of tungsten powder to tubing by hot consolidation and extrusion in a single operation. Material used for this work was high-purity tungsten granules procured from the Allied Chemical Company and described earlier in this report. The first two extrusion billets were fabricated from 304 stainless steel. The billets were 2.42 cm (0.950 in.) in diameter, with an annular space 2.14 cm OD x 1.78 cm ID (0.844 in. OD x 0.700 in. ID). This annular space

was filled with tungsten granules that had been outgassed at 1000°C. The granules were poured into the annulus and lightly tapped so that the resultant fill density was approximately 50% of the theoretical density. Two of these billets were extruded on the 150-ton vertical press at 1250°C at a 4:1 reduction ratio (extrusion Nos. 106 and 107). In both cases, the 304 stainless steel jacket tore in 20 to 30 places along its length, exposing the tungsten powder. The stainless steel jacket and core were too soft at the extrusion temperature to act as a suitable container for compacting and extruding the tungsten granules. However, evidence of deformation in the tungsten granules indicated that the technique might be feasible. A third stainless steel billet was assembled, and the outer stainless steel jacket thickness was greatly increased. This billet was also extruded at 1250°C at a 4:1 ratio (extrusion No. 156), and although the jacket held together and did not tear, the stainless steel again was too soft and the tungsten granules were only partially consolidated. The soft stainless steel tended to flow between the tungsten granules and prevented complete consolidation of a uniform tungsten sleeve. The partial tungsten granule consolidation and stainless steel penetration can be seen in Figure 19.

Additional billets were assembled using molybdenum in place of 304 stainless steel to provide a stronger container for transmitting more force for consolidation and extrusion of the tungsten granules, and to eliminate jacket material extruding around the granules and preventing complete consolidation. As shown in Figure 20, the billet design incorporated a thin collapsible shell behind the main body of the billet. At the beginning of the applied extrusion force, the thin wall collapsed allowing the end plug with its protruding ring as a punch to enter the billet annulus and compress the tungsten granules before actual extrusion started. This also prevented the billet can from extruding between granules before complete compaction was achieved.

Three billets were assembled according to this billet design and were extruded on the 150-ton vertical press at temperatures of 1500-1660°C and extrusion ratios of 3.5:1 to 4:1 (extrusion Nos. 175, 176, and 177). All billets extruded satisfactorily although the molybdenum surface showed moderate galling due to inadequate lubrication at the high extrusion temperatures. The microstructure of all three extrusions were identical to that of extrusion No. 177, which is shown in Figure 21. All the tungsten granules were consolidated into a dense tungsten tube with fine grain size. A typical worked structure is evident by the elongated grains visible in the longitudinal section. The molybdenum core and jacket appear metallurgically bonded to the tungsten tube. The tungsten surface profile, both on the inner and outer surfaces, is "scalloped" because of the shape of the tungsten granules. Hardness measurements on the extruded cross section showed the tungsten tube to be 554 DPH (53 R_C), and the molybdenum core and jacket to be 242 DPH (98 R_B). After the tungsten tubes were decanned by acid dissolution of the molybdenum jacket and core, the tungsten tube OD

Micro 37330

100X

Etchant: 10% $\text{K}_3\text{Fe}(\text{CN})_6$, 10% KOH, 80% H_2O

Figure 19. Transverse Microstructure of Tungsten Granules Extruded (No. 156) in 304 Stainless Steel Can at 1250°C at 4:1 Reduction Ratio

Figure 20. Billet Design for Compacting and Extruding Tungsten Granules Directly into a Tube

Transverse

Mo Jacket
242 DPHW Tube
554 DPH

Micro 37325

100X

W Tube

Mo Core

Micro 37324

100X

Longitudinal

W Tube

Mo Core

Micro 37326

100X

Etchant: 10% $K_3Fe(CN)_6$, 10% KOH, 80% H_2O

Figure 21. Tungsten Granules Extruded into a Tube by 4:1 Reduction Ratio at 1660°C

and ID surfaces showed a "snake-skin" texture as seen in Figure 16 (extrusion Nos. 175 and 176). This is due to the elongation of individual tungsten grains. Greater deformation of the tungsten granules by higher extrusion ratios may minimize this surface texture. All three extrusions of the tungsten powder possess the circumferential crack shown in Figure 21. This peculiar crack gives rise to the possibilities of whether: (a) the higher coefficient of expansion of molybdenum results in the molybdenum core, bonded to the ID of the tungsten tube, pulling a layer of tungsten away from the original tube upon cooling; (b) a layer of tungsten bonded to the molybdenum core shears away from the body of the tungsten in extrusion, because of different rates of deformation between the tungsten and the softer molybdenum core; or (c) the presence of argon gas in the tungsten-powder-filled annulus plays a part in the formation of the crack.

Larger billets are being prepared for extrusion of tungsten powder on the 350-ton vertical press where the higher reduction ratios can be used. Also, extrusion temperatures will be lowered consistent with obtaining sound metallurgical bonding between the tungsten granules.

Secondary Fabrication

Since tungsten possesses a ductile-to-brittle transition temperature above room temperature, secondary fabrication must be done warm. Hot-swaging dies and suitable heating furnaces for hot swaging and drawing are on order and should be received shortly. In the absence of this equipment, secondary fabrication of extruded tungsten tubes has not yet been attempted. Subsequent progress reports will cover equipment modification for hot secondary fabrication and progress on actual secondary fabrication of tungsten tubes.

Product Evaluation

To date, product evaluation has consisted of radiography of as-extruded bars and tungsten tubes that have been dejacketed. All indications to date show that the tubes are sound and free of defects, except for the directly consolidated tungsten powder tubes possessing the circumferential cracks discussed earlier. Samples of tubing have been submitted for non-destructive testing by ultrasonic and eddy-current techniques, but the high attenuation factor of tungsten and the small diameter of the tubing have limited results. The development of suitable test techniques is underway.

As tungsten tubing is processed through various stages, and as sufficient amounts become available, mechanical property tests will be run in order to: 1) determine the properties produced by various fabrication schedules, 2) determine the reproducibility of such properties, and 3) determine the effect of various starting materials on obtainable properties.

Testing will be done at room temperature and at elevated temperatures above the ductile/brittle transition temperature. Planned tests call for measurements of hardness, ultimate tensile strength, and yield strength. Tubing should be hot-pressure tested to determine the burst strength and radial expansion capability. This latter measurement is oriented toward end-product usage and is necessary for selection of optimum processing and design of the final complex.

DISCUSSION OF PROGRESS AND FUTURE WORK

An analysis of the methods used to produce tungsten tubing in the reporting period shows that all methods have produced encouraging results and merit further work. Re-extrusion of extruded tungsten tubing and extrusion of pressed-and-sintered tungsten sleeves have been relatively straightforward. Work in this area will consist of refining billet materials, establishing extrusion temperatures, and increasing reduction ratios. By careful selection of extrusion temperatures and techniques for billet heating, it is hoped that the molybdenum core currently used in extruding tungsten tubes can be replaced by a less costly material such as stainless steel. Further work using the DPM extrusion technique will be done to provide easier removal of the core material from the extruded rod.

Additional work is planned in extruding vapor-deposited tungsten sleeves. Efforts will be directed toward selecting extrusion conditions that will allow higher reduction ratios without resulting in radial cracking of the deposited tungsten sleeve. Better control over the initial quality of the vapor deposited sleeve, and advances made in vapor deposition of tungsten tubing in providing a more equiaxed, finer-grained tube, may prove beneficial.

Work on direct compaction and extrusion of tungsten tubing from powder will continue. The reasons for the circumferential cracking must be determined and the problem eliminated. Billets will be scaled up in size to allow extrusion on the 350-ton press to afford better control over billet heat loss and to allow higher reduction ratios. The effect of the peculiar "snake-skin" surface of these extrusions on secondary fabrication and final tube quality and properties will be evaluated.

Plans also call for extrusion of tungsten sleeves made by other techniques. Sleeves of drilled tungsten single crystals, rolled and welded tungsten sheet, and arc- or electron-beam melted ingots will be extruded into tube blanks for secondary fabrication. Materials that appear to offer no fabrication advantage or improvement in final properties and that prove to be uneconomical will be phased out in favor of the more promising methods.

Upon receipt of equipment for hot secondary fabrication, considerable effort will be placed on techniques and methods for secondary fabrication of extruded tungsten tubes.

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