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HEAVY WATER ORGANIC COOLED REACTOR

SURFACE FINISH IMPROVEMENT IN CAST UC SLUGS

By

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ABSTRACT

Preliminary studies were conducted to develop an economical process for preparing UC fuel slugs as specified for HWO CR requirements. The principal deterrents to the use of as-cast slugs were:

- 1) Surface defects, including "cold shuts" and exterior protuberances
- 2) Excess "bow" (nonstraightness).

Techniques were investigated for improving the surfaces of as-cast slugs, either through modifications in the melting and casting operation or through machine-finishing operations.

Melting and casting studies have shown that UC slug surfaces are improved by:

- 1) Using outgassed molds ($\sim 2300^{\circ}\text{C}$)
- 2) Casting into preheated molds ($\sim 1000^{\circ}\text{C}$)
- 3) Casting with the melt at slight superheat
- 4) Casting with a reduced header (riser) thickness, which reduces slug bowing.

Centerless grinding techniques have been adapted to provide economical surface finishing of cast UC slugs with:

- 1) Dimensions and OD roundness controlled to ± 0.0005 in.
- 2) Total Indicator Reading (TIR) straightness controlled to 0.001 in.
- 3) Surface finishes of $< 200 \mu\text{in.}$

I. INTRODUCTION

In the past, fuel loadings have been made with hypostoichiometric (<4.8 wt % C) UC slugs, sodium bonded in Type 304 stainless steel cladding. The liquid metal bond (up to 0.025 in. annulus)⁽¹⁾ not only provided high heat transfer and diametric clearance for significant fuel swelling, but also permitted the loading of as-cast fuel slugs into the cladding. This design feature resulted in lower fuel fabrication costs and permitted the use of thin-walled stainless steel cladding, since cladding stresses under reactor operating conditions could be maintained at relatively low levels.

The HWO CR concept will use hyperstoichiometric (4.82 to 5.4 wt % C) UC slugs of low enrichment (1 to 1-1/2 wt % U^{235}). The fuel slugs (~ 0.470 or 0.270 in. in diameter) will be helium-bonded in thin-walled SAP cladding. As-cast fuel surfaces, while suitable for former reactor requirements such as the Large Sodium Graphite Reactor (LSGR),⁽¹⁾ would not be satisfactory for the HWO CR concept. Fuel defects, such as surface protuberances, out of roundness, or deviations from straightness, would cause localized stresses which might result in failure of the SAP cladding.

Surface finish requirements and dimensional tolerances (OD and TIR*) had not been established at the time this study was initiated. It was hoped that these criteria would evolve from the results of the study. Process capabilities had to be determined (and balanced against slug finishing costs and reactor requirements) to evaluate the extent of surface finishing which would be justified.

Two approaches were considered for obtaining the desired surface finish on the UC slugs:

- 1) Improvements in the current UC casting process
- 2) Development of an economical, postcasting, surface finishing treatment.

*TIR — Total Indicator Reading, a measure of the nonstraightness of fuel slugs.

II. GENERAL APPROACH AND DESCRIPTION OF PROBLEM AREAS

Ideally, it would be preferable to produce the desired product slugs directly from the casting operation or to at least minimize subsequent finishing operations. Mechanical finishing treatments were to be used, only if modifications to the casting process were unsuccessful in producing slugs with satisfactory surface finish.

The principal surface defects usually observed on cast slugs are:

- 1) Cold shuts
- 2) Rough, pitted, rippled exteriors.

Cold shuts (discontinuities or irregularities on the cast surface, where two liquid interfaces meet, but fail to fuse) are probably due to spatter or to poor fluidity of the poured liquid. Surface roughness may be caused by gas which is generated during pouring, and/or an interaction between the molten UC and the graphite mold. Typical cast slugs, demonstrating some of these surfaces defects, are shown in Figure 1.

At the start of this study, it was felt that cast slugs were relatively straight. However, subsequent experimental work indicated that maintaining slug straightness would be a major problem. This was especially true, when consideration was given to the various techniques for mechanical finishing.

Figure 1. Typical Surface Defects
on UC Castings

A. CASTING MODIFICATIONS TO IMPROVE SURFACE FINISHES

1. Examination of Slugs

Minor variables were examined for their effects on the surface finishes of as-cast slugs; they include:

- 1) Carbon content
- 2) Mold wall thickness
- 3) Slug length
- 4) Cooling time (from time melt was poured until furnace was opened and slug was removed from mold)

2. Direct Casting Into Preheated Molds

Previous reports have mentioned the use of preheated molds for casting UC; in one case,⁽²⁾ molds were heated to 1150°C; another⁽³⁾ implied that the optimum mold temperatures were 800 to 900°C. As part of this study, castings were made into molds which had been preheated to 900 to 1400°C; these were compared with castings made into molds at ambient temperature.

3. Use of Outgassed Molds

Outgassed molds have been used in casting UC,⁽³⁾ presumably to decrease the amount of gas evolved when the mold was heated to ~2500°C by the molten UC. Although outgassing temperatures of only 1200 to 1300°C were reported, higher temperatures were used during these studies, in view of the known outgassing behavior of graphites.

4. Melt Superheat to Increase Fluidity

Efforts were made to evaluate the effect of greater superheat on the fluidity of the melt. Since melt temperatures could not be determined in the presence of an arc, increases in the superheat were estimated empirically as slight increases were made in the power input. Assuming that no increase occurred in internal flaws ("piping") in the slug or greater interaction with the mold wall at the higher pouring temperature, the increased melt fluidity resulting from the higher temperature would produce castings of better quality.

5. Alternate Mold Materials

The reference mold material was ATJ graphite. A few other mold materials were tried to evaluate effect on slug surface finish. These materials were:

- 1) Vitreous (glassy) carbon
- 2) Pyrolytic graphite
- 3) TS-360 Grade graphite.

B. MECHANICAL SURFACE FINISHING TECHNIQUES

A slug grinding operation was considered to be the most practical means of obtaining good surface quality and dimensional tolerances. The principal problems anticipated in the use of such an operation were:

- 1) Integrity of the slugs, if they were too fragile to withstand the harsh working of a grinding wheel
- 2) Overheating of the slugs
- 3) Whether satisfactory costs and yields could be achieved.

Centerless grinding techniques are already standard practice with UO_2 pellet fuel, and have been reportedly used with UC at NuKem,⁽³⁾ and also with some success on UC for the CANEL Program.

Other finishing techniques, such as:

- 1) Airbrasive blasting
- 2) Shot peening
- 3) Barrel tumbling

were considered, but were rejected in favor of grinding. It was felt that these techniques could provide only minor polishing action, and would not remove the amount of material required to meet dimensional tolerances.

Previously, OD grinding had been the conventional method used at Atomics International for machining UC slugs required for special capsule tests. This operation utilizes a cylindrical grinder, where the slug is held and rotated by a chuck; a diamond wheel, rotating in a plane perpendicular to the slug axis, does the grinding. The operation is very slow (~ 5 to 6 min/slug), with grinding speeds restricted by:

- 1) Lack of backup support for the slug
- 2) Individual chucking operations required for each half of the slug.

From time to time, centerless grinding of UC slugs has been performed satisfactorily at AI on a modified Universal Grinder. This technique seemed to provide the most economical machining method; however, relatively straight slugs are required, in order to minimize the number of grinding passes.

In centerless grinding, no slug "fixturing" is necessary, a backup driving cylinder is available, and slugs can be fed through the unit and ground automatically. This process offers potentially greater grinding speeds than are attainable by the OD method. It was felt that two grinders might be used for production — one for "rough" grinding, and the second for finish grinding; the second used where less material is removed to obtain the required dimensions and surface finish. It was also believed that the grinding operation might be accomplished dry, so that subsequent (expensive) degreasing and cleaning treatments could be avoided. Some of the variables evaluated were:

- 1) Effect of slug straightness, diameter, length, and carbon composition
- 2) Evaluation of the heat problem [i.e., if dry grinding were possible or wet grinding was required, and whether or not (flowing) inert-atmosphere enclosures would be required]
- 3) Optimization of grinding wheel (i.e., diamond vs SiC, width of wheel, grit size of abrasive, and speed of wheel)
- 4) Amount of material removal per pass which would be feasible. The final finish required ($\sim 200 \mu\text{in.}$ appeared feasible), and the dimensional tolerances would determine the ultimate grinding costs.

There are four basic methods of centerless grinding:

- 1) Thrufeed
- 2) Endfeed
- 3) Infeed
- 4) Combination of infeed and thrufeed.

To cover the parameters involved in UC grinding, the thrufeed method was selected and tested to process the UC slugs. Thrufeed grinding, as its name implies, is done by passing the slug between the grinding and regulating wheels (Figure 2a and 2b). The slug enters the grinding area at one side of the wheels, and leaves at the other. Since all points of the work pass all points on the wheels, only straight surfaces (without interfering shoulders or varying diameters) should be worked by this method.

a. Photograph

b. Schematic

Figure 2. Thrufeed Grinding on Cincinnati Centerless Grinder

III. EXPERIMENTAL EQUIPMENT

A. MELTING AND CASTING

Most of the melting and casting tests were carried out in the small, tilt block, skull melting, nonconsumable arc furnace shown in Figure 3a. This furnace was built at AI to accommodate special fuel preparations (e.g., highly enriched fuels) in mold configurations or quantities too small to be handled conveniently by the large production furnaces. It is capable of casting $\sim 1\text{-}1/4$ kg of UC, from melts up to $\sim 1\text{-}1/2$ kg of material. As shown in Figure 3a, the bottom plate of the furnace vessel, which supports the graphite hearth, must be lowered to permit access to the furnace interior (charge loading and withdrawal of the slug from the mold). The hearth, a shallow, v-shaped rectangular block housed in a graphite trough, accommodates both the melting crucible and the mold, as shown in Figure 3b. This design permits the melt to be poured directly from the crucible into the mold, which is a convenient operation for relatively small castings. The hearth, which is counterweighted with lead to assist the pouring operation, is tilted by a foot operated, spring loaded, vertical pull rod, as demonstrated in Figures 3c and 3d. This technique permits hand operation of the water-cooled copper electrode (with graphite tip), but it can result in a relatively sluggish pouring operation (depending upon the friction of the rod, fit of the hearth, dexterity of the operator, etc.). Good castings are often dependent upon the technique of the operator. However, modification of the design was considered too costly for this program.

A helically-coiled heater, $\sim 1\text{-}7/8$ in. ID by $5\text{-}1/4$ in. long, machined at AI from a graphite cylinder, was used for the hot-mold tests. This insulated resistance heater (not shown in Figure 3a) was supported on the underside of the hearth (in the slot in the trough, shown in Figures 3c and 3d), so that it enclosed the mold. The slot in the trough accommodated the heater when the hearth was tilted. Power to the heater was supplied by a dc welder, and heater temperatures were measured with an optical pyrometer (or "power setting" on the welder, after appropriate calibrations).

Some melting and casting tests were conducted in the large, tilt pour, production furnaces, which have been described by others.⁽⁴⁾ These furnaces

a. Overall View

b. Graphite Hearth

c. Hearth in Melting Position
(Not Tilted)

d. Hearth in Pouring Position
(Tilted)

Figure 3. Small, Tilt Block, Arc-Melting Furnace

(Figures 4a and b) differ from the small furnace in several respects, so that direct comparisons of casting results cannot be made. The principal differences include:

- 1) The large furnace permits multiple-mold casting (up to 90 slugs at a time); the small unit permits only single-mold casting.
- 2) The massive mold block (used with or without mold liners) in the large furnace produces considerably different melt-cooling characteristics than those produced from the single, thin-wall mold used in the small furnace.
- 3) In the large furnace, the automatic electrode action is restricted to vertical adjustment in the center of the charge. The manual operation of the electrode in the small furnace permits vertical adjustment and also angular positioning of the electrode in any portion of the melt; this convenience permits an operator to "follow the melt" with the arc as the liquid UC is poured into the connected mold.
- 4) Through hand operation of an external trunnion, the melt crucible of the large furnace can be tilted $\sim 100^\circ$ for pouring. In the small furnace, the foot pedal operation permits tilting of the melt crucible of $< 35^\circ$.
- 5) The longer melting cycle ($\sim 1/2$ hr) in the large furnace requires higher power levels (from 3400 to 10,000 amp at ~ 30 v) to produce the superheat needed to maintain fluidity of the melt during the pour time; in comparison, the small furnace requires a melting cycle of only a few minutes at a power level of < 2500 amp at 30 v.
- 6) In the large furnace, melting is conducted in dynamic vacuum; in the small unit, it is conducted in a flowing inert atmosphere (He + A, at $1/3$ atm).

These differences reduce the effectiveness of using the small furnace to develop casting modifications that would be directly applicable to the large furnace. Some of these factors undoubtedly contribute to the production of superior castings (slugs of greater strength and integrity) in the small unit.

B. GRINDING

When this study was started, no centerless grinding equipment was available at AI. Preliminary feasibility tests were conducted with a centerless grinding attachment mounted on a Cresta Universal Grinder. A metal bonded (D60N50M21/8), 10-in. diameter by 1/2-in. wide, diamond wheel was used with a low-water-soluble oil (ACW 803) coolant, and the grinding was performed wet. This equipment was limited to grinding slugs $\leq 1/2$ in. in diameter and ≤ 3 in. in length.

After the feasibility of centerless grinding had been demonstrated, a unit of greater capacity (but relatively small, by centerless grinding standards) was

a. Outside

b. Inside

Figure 4. Electric Arc, Tilt Pour,
Vacuum-Melting Furnace

purchased for further evaluation tests. The unit selected was a Royal Master Preciso-Matic Centerless Grinder. This equipment, enclosed in a plastic box and connected to a ventilation exhaust for dust control, is shown in Figure 5.

Larger equipment, purchased for production evaluation, included a Cincinnati Centerless Grinder (Figure 6) and a Queen City Disc Grinder (Figure 7). These machines were used to establish:

- 1) Preliminary production rates for finishing large quantities of UC fuel slugs
- 2) Testing requirements
- 3) Finishing capabilities during large-scale production.

Both grinders (Figures 6 and 7) were connected to a sludge scrubber (Figure 6) for the recovery of UC. An output conveyor (Figure 8) was attached to the Cincinnati Centerless Grinder, thereby eliminating the need for a man at the output side of the grinder to catch the slugs as they were fed through. The test runs proved that this conveyor could handle any quantity of slugs that might be processed. Special handling trays and/or containers are being developed to add to this improvement. This system also eliminates breakage of the finished slugs, and permits random inspection of the slugs, as required.

3-6-67 UNC

00-18487A

Figure 5. Royal Master Centerless Grinder

3-6-67 UNC

7680-1817A

Figure 6. Cincinnati Centerless Grinder

3-6-67 UNC

7680-51165A

Figure 7. Queen City Disc Grinder

Figure 8. Output Conveyor

IV. EXPERIMENTAL RESULTS

A. MELTING AND CASTING TESTS FOR REDUCTION OF SURFACE DEFECTS

Many casting tests were made with 1/2-in. diameter slugs, to investigate the variables discussed previously. These experiments were generally performed in the small furnace, using previously prepared melt stock (sprues, headers, slugs, etc.) having carbon compositions of 4.8 to 5.3 wt %. The carbon contents of the resulting slugs were determined by metallographic examination.

1. Effect of Carbon Content

No significant differences were apparent in the surface finishes of slugs having carbon contents either in the 4.9 wt % range (4.82 to 5.10), or in the 5.2 wt % range (5.1 to 5.3), as is shown in Figure 9. Carbon compositions were varied concurrently with other parameters (i.e., slug length, mold thickness, preheated mold temperature, and cast slug cooling time).

2. Effect of Slug Length

The reference slug length was $\sim 6\text{-}1/2$ in., which was reduced to 6 in. by cropping. Tests were also made with castings $\sim 3\text{-}1/2$ in. long, which were cropped to produce 3-in. slugs. These shorter slugs were cast into the same molds as the longer ones; 3-in. graphite plugs were inserted in the molds to obtain the shorter castings.

As is shown in Figure 9, there were no significant differences between the surface finishes of the 3-in. and the 6-in. slugs. The shorter lengths were more difficult to cast; the smaller amount of material being poured required that the operator pour at a slower (undesirable) rate, to prevent overflowing the mold cavity.

3. Effect of Mold Wall Thickness

The reference mold material was ATJ Grade graphite, with a wall thickness of ~ 0.118 in. (OD = 0.750 in., ID = 0.515 in.), which produced a 0.50-in. diameter slug after shrinkage. While maintaining the same ID, tests were performed with molds of two other thicknesses (~ 0.093 and ~ 0.211 in.). Castings were made in each of the individual molds, concurrent with variations in the other parameters mentioned.

Figure 9. Castings of Varying Carbon Compositions and Varying Lengths

There were no significant improvements in the surface finishes of slugs prepared in these molds, or from molds having wall thicknesses of 0.055 and 0.125 in. (Figure 10) used in subsequent tests.

4. Effect of Slug Cooling Time

Cast slugs were usually cooled for ~15 to 20 min after pouring, prior to opening the furnace and removing the slugs from the molds. Under these conditions, the overall surface temperature of the slugs was ~280°C, a temperature

3-6-67 UNC

7660-51146A

Figure 10. Castings From Molds of Varying Wall Thicknesses

considered high enough for possible reaction of UC with air. A series of castings were made in which this cooling time was increased to 35 min, concurrent with variations in the other parameters. Although the surface temperature of the slugs was reduced from ~ 280 to $\sim 180^{\circ}\text{C}$, no significant improvements were noted in the surface finishes of the slugs as a result of the increased cooling time.

5. Effect of Greater Melt Superheat

The reference procedure was to melt the charge for ~ 3 min at a power level of ~ 2200 amp, which produced reasonably satisfactory UC fluidity. Since melt temperatures are difficult to measure in the presence of an arc, a series of tests were performed at three other power levels (2000, 2500, and 3000 amp) to evaluate potential benefits of greater melt fluidity.

Somewhat better surface finishes were obtained at 2500 amp than at the reference 2200 amp (Figure 11). This minor improvement offered no advantage to the overall program, since melts prepared in the large production furnace have fluidity at least equal to those produced at 2500 amp in the small furnace. However, this higher power level was used for subsequent castings in the small furnace. Castings from melts made at 3000 amp showed a marked increase in the amount of surface attack from the graphite mold.

6. Effect of Casting Into Preheated and/or Outgassed Molds

Melts were poured into molds heated to various temperatures, and the slugs were compared with those from cold (ambient) molds. The surfaces of slugs cast into (not outgassed) molds heated to $\sim 1000^{\circ}\text{C}$ were considerably improved, as suggested in Figure 12a; this improvement was even more pronounced when the molds had been outgassed (Figure 12b).

Photomicrographs were taken of three typical slugs which were cast into molds preheated to various temperatures. Table 1 shows that a more uniform grain size was obtained by using a mold preheated to $\sim 1000^{\circ}\text{C}$.

As a result of the slightly improved surfaces and more uniform grain size in slugs cast into molds preheated to $\sim 1000^{\circ}\text{C}$, this condition was adopted for the remaining tests.

Newly machined graphite molds were vacuum outgassed for 1 hr at $\sim 2300^{\circ}\text{C}$. Slugs cast into these molds were compared with those from molds which had not

SUPERHEATED

NORMAL

3-6-67 UNC

7680-51294

Figure 11. Improvement in Surface Condition of Slugs Produced With Increased Melt Superheat

3-6-67 UNC

7680-51295

a. From Molds — Not Outgassed

3-6-67 UNC

7660-5138A

b. From Molds — Outgassed

Figure 12. Improvement in Surface Condition of Slugs Produced With Preheated Molds

TABLE 1
EFFECT OF MOLD TEMPERATURE ON GRAIN SIZE OF
UC (~4.9 wt % C) CASTINGS

Slug Portion	Grain Size (μ)					
	Mold Temperature ($^{\circ}$ C)					
	Ambient		1000		1200	
	Edge	Mid-Radius	Edge	Mid-Radius	Edge	Mid-Radius
Top	254	305	215	215	254	178
Middle	215	215	254	215	254	178
Bottom	178	178	215	215	178	178

been outgassed. Figure 13a shows that slugs from outgassed molds had noticeably better surface finishes than those from molds that had not been outgassed (Figure 13b). Of all the parameters surveyed during the melting and casting investigation, the mold outgassing technique produced the greatest improvement in slug surface quality; this procedure has been adopted as a standard operation.

The slugs in both Figures 13a and 13b are arranged, from left to right, in their order of casting (from the same mold). These figures show a general deterioration in surface quality with increasing use of the mold. This effect was more pronounced when the mold had not been outgassed. Prior to these studies, the early reuse of a mold that had not been preheated or outgassed generally resulted in slightly improved slug surface finish (i.e., the second and third castings from the mold were better than the first). This indicated that some mold conditioning had occurred, and that smaller quantities of gas had evolved as the mold was gradually outgassed with reuse. Therefore, the improved surface quality of the first few slugs cast into outgassed molds (2300° C, under vacuum) can be attributed to a thorough outgassing of the molds before any castings were made. When outgassed molds are reused, there is very little change in the surface conditions of the slugs until about the third or fourth casting; then, surface defects begin appearing in subsequent castings. This would indicate that the benefits derived from the outgassing operation are no longer present. It has been speculated that some other mechanisms start prevailing at this point, producing deleterious gases from reactions on the interior of the mold, and thereby causing surface defects.

a. From Molds - Outgassed

b. From Molds - Not Outgassed

Figure 13. Improvement in Surface Condition Produced With Outgassed Molds - Not Preheated

It was not possible to determine the exact mechanism through which out-gassed and/or preheated molds improve the surface finishes of slugs. However, the change in surface finish with mold reuse appears to be related to a carbide coating which forms on the mold interior, and which increases as additional castings are made. This carbide apparently oxidizes (or hydrolyzes) to form uranium oxide; as additional castings are made, this oxide is chemically reduced to form undesirable gases (CO_2 and/or CO). These gases undoubtedly contributed to the roughness defects commonly observed on the surfaces of cast slugs. Indications of such phenomena were encountered during casting studies with the preheated molds. The normal procedure in hot-mold casting was to:

- 1) Clean the mold by brushing the interior to remove residual particles
- 2) Charge the furnace and evacuate it to a pressure of $\sim 50 \mu \text{Hg}$
- 3) Heat the mold to required temperature under dynamic vacuum
- 4) Switch to a dynamic flow of argon at a negative pressure of 20 in. Hg ($\sim 1/3$ atm, absolute) for the melting and casting cycle.

Typical slugs, obtained by this procedure from molds preheated to 1000°C , are shown in Figure 14. The symbols, OG or OGM, denote an outgassed mold, while X indicates the number of times the mold had been used previously. The good surface quality of Slugs 58 and 68, obtained from newly outgassed molds, is readily apparent; so are the surface defects in subsequent castings (Slugs 61 through 67) from the same mold used for Slug 58.

The mold used to cast Slug 67 (used 10 times) was sectioned longitudinally. Half of the mold was then heated to 1000°C in vacuum. Figure 15a shows metallic particles (golden-brown, probably UC_x) imbedded in the mold interior of the half that had not been heated. Figure 15b, of the half that had received the heat treatment, shows the mold interior covered with a soft, black, powdery film (probably U_3O_8) which could be brushed off. The mold used to cast Slug 68 (used only once) was sectioned in the same manner. Half of this mold was then heated to 1000°C in argon. The unheated section contained metallic particles similar to those in the previous mold, but there were not as many of them. The section of this mold that was heated in argon resembled the section that had not been heated; there was no evidence of conversion of the metallic particles to a U_3O_8 -like powder. It would appear that minor leakage (oxygen, water, etc., in the air), occurring during vacuum heating of the mold, is sufficient to oxidize

Figure 14. Slugs From Preheated, Outgassed Molds

3-6-67 UNC

6184-2

a. Half - No Additional Heating

3-6-67 UNC

6184-3

b. Half - Heated to 1000°C in Vacuum

Figure 15. Graphite Mold Used for Ten Castings

3-6-67 UNC

a. Cast Slugs in Their Molds

6184-4

3-6-67 UNC

b. Macrostructure of Outgassed Mold

6184-7

3-6-67 UNC

c. Macrostructure of Mold — Not Outgassed

6184-6

Figure 16. UC Slugs Cast in Large Furnace

the UC particles on the mold interior; as this oxide is not removed before pouring, it reacts with the molten UC or the crucible, creating gases which cause surface defects in the casting.

Since similar results can occur in the large furnaces (i.e., arc melting and pouring are carried out under dynamic vacuum into unheated molds, but the same reactions could occur when the molten UC heats the molds), similar confirmatory tests were conducted. Two mold liners were installed in the multi-cavity mold of a large furnace, and (simultaneous) castings were made according to production procedures. Figure 16a shows the two slugs and half of the mold in which each was cast. The mold on the left had been outgassed, and had only been used three times; the one on the right had not been outgassed, and had been used many times. The darker appearance of the interior of this latter mold and the poor quality of the surface of the slug cast in it coincided with the results of the previous tests. Figures 16b and 16c show the macrostructure of the two molds; the mold which had not been outgassed showed a rougher, more porous surface, with a large number of shiny, metallic particles imbedded in the mold wall. It would appear that mold outgassing not only minimizes gas evolution from the mold during the first few castings, but also helps retard degradation of the mold (i.e., to a porous, rough surface).

Figure 17 demonstrates the great improvement achieved in slug surface finishes, as a result of process modifications developed during these studies. The slugs on the right were cast into outgassed molds (1-hr vacuum treatment at 2300°C) which had been preheated to 1000°C in argon, prior to UC pouring; the slugs on the left were cast into molds which had not been outgassed, and which had been at ambient temperature at the time of pouring.

7. Effect of Alternate Mold Materials

As an extension of these casting studies, alternate mold materials (of lower porosity or greater chemical resistance) were investigated. It was felt that such materials might possibly provide further improvement in the surface finishes of the cast slugs. Three materials were selected for investigation.

a. Vitreous, "Glassy" Carbon

This material is available in two grades, V-10 and V-25, from The Carbone Corporation, Boonton, New Jersey. V-25 is the superior grade; the vendor

3-6-67 UNC

7660-5134 A

Figure 17. Improvement in Surface Finish of Castings Produced in Outgassed, Preheated Molds, Heated in Argon

reported that this grade was suitable for continuous use, and that it was resistant to thermal shock at temperatures up to 2500°C. This material has the characteristics of glass (hard, brittle, with an excellent surface), and reputedly has close microporosity, high impermeability to gas (zero porosity), and a resistance to oxidation and chemical corrosion that is superior to that of graphite. In tube form ($\sim 9/16$ in. ID by 0.090 in. wall), its high cost ($\sim \$100$ for a 10-in. length) and long delivery time (3 to 4 months) prevented our obtaining material suited to normal UC casting. The only V-25 material readily available was a crucible form (1-1/4 in. ID by 1-1/4 in. high by 0.090 in. thick wall), which was purchased and tested. While the crucible mold (not preheated, not outgassed) failed, as a result of thermal shock during the first casting, a solid ingot was produced. The ingot contained parallel ripples (like a washboard) about its periphery, but showed no signs of the rough pits or cold shuts commonly observed on UC castings. When the pieces of broken crucible were examined,

there were no indications of corrosive attack by the molten UC. The hard, glossy finish of the pieces was still intact, and one could wipe the surface without removing any loose material (i.e., negligible discoloration of Kimwipe).

The glassy carbon should not be completely disqualified as a potential mold material, since the crucible shape was not typical of that used in normal UC casting. The low-surface-area/unit-volume ratio of the crucible shape is not conducive to rapid dissipation of heat, and may have exaggerated heat conditions in the mold. This material is still considered promising; it might prove satisfactory, if a long tube with a bottom plug can be tested under normal UC casting conditions. This configuration would provide greater heat dissipation (lower mold bulk temperatures) and more uniform stress distribution.

b. Pyrolytic Graphite

A number of casting tests were made to evaluate the use of pyrolytic graphite as a mold material. The lower porosity and higher surface finish of this material offered promise of improved casting results. Molds were purchased from High Temperature Materials, Lowell, Mass., either machined from solid pyrolytic graphite or fabricated from ATJ Grade graphite and coated with 0.003 to 0.005 in. of pyrolytic graphite. However, the tests yielded no improvement in the surface quality of the slugs cast into either type of mold. Figure 18 shows slugs cast into molds machined from solid pyrolytic graphite. These molds showed a strong tendency to flake, as is indicated by the casting at the extreme right of Figure 18. Since pyrolytic graphite is more expensive than the reference ATJ Grade material, and because its use did not provide any improvement in the surface finishes of slugs, further study of this material was discontinued.

c. TS-360 Grade Graphite

A third mold material evaluated was TS-360 Grade graphite, available from the Carbon Products Division of Union Carbide Corp. When compared with ATJ Grade graphite, this material has a higher density (1.82 vs 1.73 g/cc), lower permeability (0.0015 vs 0.015 darcys), and better machinability; these properties gave promise of better surface finishes for slugs cast into such molds. A series of casting heats were made in ATJ Grade graphite molds and in TS-360 Grade molds; the molds were outgassed, but were not preheated. As is shown

3-6-67 UNC

7680-51145A

Figure 18. Castings From Molds Machined From Solid Pyrolytic Graphite

in Figures 19a and 19b, the first 3 or 4 slugs cast into the ATJ Grade mold had better surface finishes than the corresponding slugs cast into the TS-360 Grade mold. However, subsequent slugs from the ATJ Grade mold exhibited a greater increase in the number and severity of surface defects than did the subsequent slugs from the TS-360 Grade mold. With both molds, the diameters of the as-cast slugs varied only ~ 0.000 to 0.003 in., from the first casting to the twentieth. This suggested that, with proper mold cleaning, additional slugs could be cast into the molds. However, as is shown in Figures 19c and 19d, the surface quality of subsequent castings decreased markedly. Since the TS-360 Grade graphite offered only marginal improvement in slug surface quality (over that obtained from ATJ Grade), its appreciably higher cost prevented its being used as a replacement for ATJ Grade material.

B. MELTING AND CASTING TESTS FOR IMPROVING SLUG STRAIGHTNESS

The principal deterrents to the use of slugs in the as-cast condition include surface defects (protuberances, cold shuts, etc.) and excess bow (nonstraightness). Cast, or even machined, fuel slugs can be perfectly round and without surface defects (even highly polished), but still be unsuitable for reactor use because they deviate markedly from true straightness. When slug imperfections are being removed by grinding or other surface-finishing techniques, bowing is a greater problem than surface defects; stock removal per pass must be considerably less, when correcting bowing, to prevent slug breakage.

At the time this study started, the reasonable assumption was that the slugs were relatively straight, but during the early centerless grinding tests, non-straightness of slugs was creating another major problem, at least as significant as the one regarding surface quality. Typical measurements of slugs cast during the early part of this study are shown in Table 2.

It should be understood that these TIR measurements are only nominal indications of slug straightness, since the indicator readings are highly sensitive to minor irregularities (high or low spots) on the slug surface.

Part of the dimensional problem in cast slugs is related to the difficulty in machining a truly straight graphite mold. A typical unused graphite mold, $\sim 7\text{-}1/2$ in. tube length, was measured at ~ 1 in. intervals along its ID; the

a. First 20 Castings Made Into ATJ Grade Mold

Figure 19. Comparison of Castings Made to Test TS-360 Graphite Molds
(Molds Outgassed, but Not Preheated)
(Sheet 1 of 4)

3-6-67 UNC

7680 5153A

b. First 20 Castings Made Into TS-360 Grade Mold

Figure 19. Comparison of Castings Made to Test TS-360 Graphite Molds
(Molds Outgassed, but Not Preheated)
(Sheet 2 of 4)

3-6-67 UNC

7680 5180A

c. Subsequent Castings Made Into TS-360 Grade
and ATJ Grade Molds

Figure 19. Comparison of Castings Made to Test TS-360 Graphite Molds
(Molds Outgassed, but Not Preheated)
(Sheet 3 of 4)

3-6 67 UNC

7680 5185A

d. Final Castings Made Into TS-360 Grade and
ATJ Grade Molds

Figure 19. Comparison of Castings Made to Test TS-360 Graphite Molds
(Molds Outgassed, but Not Preheated)
(Sheet 4 of 4)

TABLE 2
TYPICAL NONSTRAIGHTNESS OBSERVED IN EARLY UC CASTINGS

Slug No.	Carbon (wt %)	Length After Cropping (in.)	Top OD (in.)	Bottom OD (in.)	Nonstraightness TIR* (in.)
3	4.9	6-1/8	0.495 - 0.502	0.501 - 0.502	0.009
4	4.9	6-1/8	0.496 - 0.501	0.499 - 0.501	0.005
5	4.9	3-1/8	0.494 - 0.498	0.497 - 0.498	0.006
6	5.0	3-3/8	0.495 - 0.497	0.497 - 0.499	0.004
7	5.2	3-1/4	0.496 - 0.499	0.497 - 0.500	0.004
8	5.3	6	0.496 - 0.501	0.499 - 0.502	0.012

*TIR: Total (dial) indicator reading, determined as the difference between the highest and lowest point along the length of a slug rotated between two V-blocks.

smallest diameter ranged from 0.5130 to 0.5169 in., while the largest diameter varied from 0.5133 to 0.5178 in., with ovalities ($\text{diameter}_{\text{max}} - \text{diameter}_{\text{min}}$) ranging from 0.0001 to 0.0014 in. at each interval. The largest ID's and ovalities were located near the center of the mold length.

When the study of machine finishing of cast slugs was started, it became evident that slug bow (nonstraightness) seriously restricted the centerless grinding operation. This technique is normally used for the removal of only minor amounts of material; the as-cast slugs were requiring more massive stock removals (0.020 to 0.030 in., diametrically). To prevent excessive slug breakage, it was necessary to make several "skinning cut" passes (removing 0.001 to 0.002 in.), to approach near-straightness, before heavier cuts could be made. This procedure was expensive, in that it was very time consuming. Consequently, an effort was made to reduce the bow in the as-cast slugs.

It was felt that shrinkage stresses, imposed on the casting by the header, could be one cause of the large TIR readings. This situation probably was exaggerated in the small furnace; in this furnace, the slug is cast and cooled at an angle, which can permit the unsupported casting to sag in the middle producing a bowed slug. Several castings (6 in. long, 1/2 in. diameter, ~4.9 wt % C) were made without a header, so that the cooled slugs (after shrinkage) would

be fully supported by the mold; these slugs were compared with slugs cast with a header (Table 3).

TABLE 3
EFFECT OF HEADER ON STRAIGHTNESS OF UC SLUGS

Casting Method	Nonstraightness TIR (in.)	
	Individual Slugs	Average
With Header	0.016, 0.010, 0.007, 0.016	0.012
Without Header	0.006, 0.003, 0.006, 0.007, 0.007, 0.004, 0.003	0.005

Based on these promising results, several casting heats were made in a large, tilt-pour production furnace, in an attempt to confirm these findings. A total of 37 UC slugs (9.5 in. long, 0.600 in. diameter, ~5.1 wt % C) were cast in each heat, using a single, multicavity graphite mold, outgassed at 2300°C. To cast these slugs without a header, the power input was adjusted to a level which would produce a molten UC volume slightly less than that required to fill the mold cavities. These preliminary tests produced a header of ~1/8 in., considerably thinner than the ordinary header of ~1 in. Table 4 presents the bow measurements of slugs from the first two heats, with the data grouped according to position in the mold.

An average TIR of 0.016 in. or less for these slugs was a significant improvement over the 0.025 to 0.030 in. TIR typical of slugs cast previously in the large furnaces. The improved straightness of slugs cast closer to the middle of the mold reflects the reduced header stresses arising during melt cooling. The relatively high TIR values of the castings from the large furnace, as compared to those of castings from the small furnace, are partly due to the longer casting lengths, and may also be due to the somewhat higher melt pouring temperatures. The castings made with reduced header thickness exhibited slightly greater "piping" problems and/or some incomplete cavity filling. However, these undesirable effects were offset by the benefits realized in facilitating the centerless grinding operation and in reducing total material waste. This technique has since been adopted as a standard casting procedure for HWO CR fuel requirements.

TABLE 4
BOW MEASUREMENTS OF SLUGS CAST WITH REDUCED HEADER

	TIR (in.)							
	Heat I				Heat II			
	Outer* Ring	First Inner Ring	Second Inner Ring	Center Slug	Outer* Ring	First Inner Ring	Second Inner Ring	Center Slug
	0.011	0.007	0.010	0.012	0.013	0.007	0.012	†
	0.014	0.004	0.012		0.007	0.004	0.004	
	0.015	0.015	0.008		0.010	0.010	0.004	
	0.022	0.008	0.013		0.007	0.008	0.009	
	0.030	0.017	0.011		0.006	0.007	0.011	
	0.020	0.021	0.015		0.008	0.007	0.005	
	0.015	0.009			0.018	0.009		
	0.028	0.018			0.011	0.008		
	0.020	0.008			0.005	0.012		
	0.018	0.016			0.016	0.012		
	0.010	0.025			0.014	0.007		
	0.014	0.007			0.013	0.013		
	0.022				0.005			
	0.011				0.019			
	0.010				0.018			
	0.012				0.015			
	0.007				†			
	0.014				†			
Average	0.016 ±0.006§	0.013 ±0.007	0.012 ±0.003	0.012	0.012 ±0.005	0.009 ±0.003	0.008 ±0.004	-

*The graphite mold accommodated 36 cavities, arranged in a pattern of concentric hexagonals, plus a 37th cavity in the center. The first hexagonal (outer ring) consisted of 18 cavities, the second (first inner ring) of 12, and the third (second inner ring) of 6.

†Incomplete fill; no measurements made.

§Variability, expressed as one standard deviation.

C. SURFACE FINISHING OF CAST UC BY MACHINING

As discussed previously, centerless grinding was the only machining method considered feasible for meeting the economic goals on HWO CR fuel. Cursory feasibility tests were performed on the small centerless grinding attachment and the Royal Master machine. The more extensive grinding studies and proof tests were conducted with the Cincinnati grinding unit.

1. Preliminary Data From Centerless Grinding Attachment

The initial tests (6-in. long slugs, 1/2 in. in diameter) indicated that the support and drive wheels were too narrow, causing the slugs to tilt. When shorter slugs (3 in. long) were used, the grinding action was satisfactory; grinding was performed on a 10-in. diameter by 1/2-in. wide 60-grit diamond wheel, which incorporated either a metal or a vitrified bond. The results of these tests are listed in Table 5.

TABLE 5
INITIAL GRINDING TESTS ON CAST UC, USING A
CENTERLESS GRINDING ATTACHMENT

Slug No.	Carbon (wt %)	Length (in.)	Bottom OD (in.)	Top OD (in.)	TIR (in.)	Stock Removal Required for Cleanup (in.)	Grinding Method
11-A	4.9	3-1/3	0.497 - 0.499	0.493 - 0.496	0.003	0.032	Wet grind, with metal-bonded wheel
11-B	4.9	3-1/3	0.499 - 0.501	0.497 - 0.502	0.006	0.037	
12-B	4.8	3-1/3	0.501 - 0.502	0.495 - 0.498	0.005	0.028	
13	4.8	3-1/3	0.497 - 0.499	0.494 - 0.498	0.007	0.029	
14	4.9	3-1/3	0.500 -	0.491 - 0.500	0.007	0.034	
15	4.9	3-1/8	0.497 - 0.499	0.491 - 0.498	0.004	0.032	
16	4.9	3-1/3	0.498 -	0.493 - 0.497	0.003	0.023	Dry grind, with metal-bonded wheel
17	4.9	3-3/8	0.499 -	0.496 - 0.498	0.004	0.024	
19	4.9	3	0.496 - 0.498	0.491 - 0.498	0.004	0.031	
20	4.9	3-3/8	0.497 - 0.499	0.492 - 0.498	0.005	0.029	
21	4.9	3-3/8	0.497 - 0.501	0.493 - 0.497	0.006	0.038	
25	5.3	3-3/8	0.500 - 0.501	0.493 - 0.500	0.006	0.035	Dry grind, with vitrified bond
26-A	5.2	2-1/2	0.497 - 0.501	0.480 - 0.500	0.012	0.041	
26-B	5.2	3-1/4	0.491 - 0.498	0.480 - 0.498	0.016	0.038	
27-A	5.2	3	0.500 - 0.504	0.500 - 0.504	0.010	0.038	
2-A*	4.9	3	0.497 - 0.500	0.492 - 0.498	0.007	0.017	Wet grind, with metal-bonded wheel
2-B*	4.9	3	0.500 - 0.504	0.495 - 0.501	0.004	0.027	
3-A*	4.9	3	0.494 - 0.497	0.496 - 0.498	0.004	0.015	
3-B*	4.9	3	0.501 -	0.499 - 0.503	0.005	0.020	

*These slugs were cast into preheated, outgassed molds; slugs in other three grinding groups were cast into preheated or ambient molds which had not been outgassed.

These tests confirmed the feasibility of the operation. Although machining parameters were not optimized during this familiarization period for the operator, the data did suggest that slugs with initial straightness equivalent to ~ 0.010 in. TIR on a 6-in. length could be:

- 1) "Cleaned up" with < 0.030 -in. diametric removal
- 2) Ground with diametric stock removals of 0.003 to 0.004 in. per pass, after some "skinning" cuts were made for moderate "true ups"
- 3) Controlled to ± 0.0008 in. on OD roundness.

The last group of slugs in Table 5 show the improvement in surface quality of castings made into outgassed molds; while TIR values were similar in each case, ~ 0.031 in. of stock was removed from the diameters of slugs cast into molds that were not outgassed (first three groups in Table 5), as compared to ~ 0.020 in. for slugs cast into outgassed molds.

From these tests, it was found that ~ 18 sec were required for a 0.003-in. stock removal per pass on a 3-in. long slug, and that surface finishes of 120 to $180 \mu\text{in.}$ were readily attained. There appeared to be no difference in the rate of stock removal, or time per pass, between wet and dry grinding techniques. While dry grinding created a dust problem, it was felt that this problem could be overcome easily with normal ventilation-controlled enclosures, as used in cutoff operations.

In later tests, stock removals of at least 0.004 to 0.005 in. per pass were possible, which suggested greater operator familiarity and/or more effective alignment of the machine. Cleanup was accomplished with 0.025 to 0.030 in. diametric stock removal, and overall out-of-roundness of the finished slugs was reduced to less than ± 0.0004 in. These data were encouraging to production personnel who had anticipated diametric stock removals of 0.050 to 0.080 in. for production planning procedures.

After only these superficial studies, this unit was used successfully in a small production effort (U-305 Experiment) which involved grinding ~ 300 ft of $1/2$ -in. diameter slugs containing 4.82 to 5.4 wt % carbon. Initially, the slugs were finished to 0.500 ± 0.0005 in., from a 0.550-in. cast diameter, with very little difficulty. As a result, the diameters of the as-cast slugs were reduced to 0.530 in., which agreed with the previous experimental "cleanup" data

requirements. Production rates were reported as ~ 1 ft/hr on average slug lengths of only 1 to 2 in. (slug lengths limited, due to cracks, breakage, etc.) However, this speed was not representative of the centerless grinding operation, since it included:

- 1) Cutoff operations
- 2) An "Elox" operation, to form a dish-shaped end
- 3) An elaborate procedure to maintain a continual record of slug orientation.

It was reported that material in the 5.2 wt % C range was the most difficult to grind due to a preponderance of crack and slug breakage. However, it was also reported that slugs such as these, which would have been unsuitable for grinding by the previous OD technique, could be handled in the centerless grinding unit.

2. Grinding Tests With Royal Master Unit

Preliminary grinding tests, performed on the Royal Master unit with the 12-in. diameter by 3-in. wide vitreous SiC wheel which was supplied with the unit, were most encouraging. This 5-hp unit was able to handle 6 in. lengths readily, and this length could be ground (0.003 to 0.004 in. diametrical stock removal) in only 12 sec at approximately half the rated speed of the machine. Diametrical tolerances (roundness) were controlled to 0.0002 to 0.0003 in., and surface finishes of $\sim 75 \mu\text{in.}$ were attained. This vitreous wheel was used until a 10-in. diameter by 1-in. wide, 60 grit, metal-bonded diamond wheel became available.

While grinding could be accomplished with the SiC wheel, it was unsuitable for the long-range goal of dry grinding, to eliminate subsequent slug cleaning (i.e., degreasing, retorting, etc.) In dry-grinding tests, the vitreous wheel "filled up" too fast, necessitating frequent cleanup and "dressing" operations. Superior slug finishes could be obtained from the SiC wheel ($\sim 75 \mu\text{in.}$, compared to $\sim 160 \mu\text{in.}$ from the diamond wheel), but the higher wheel maintenance on the vitreous wheel precluded its use for production considerations. This factor was even more important than the shorter life of the SiC wheel, which cannot compete economically with the diamond wheel even though the latter costs as much as 30 times the price of the vitreous wheel. Thus, these studies

TABLE 6
SERIES I* CENTERLESS GRINDING DATA FROM ROYAL MASTER UNIT

Slug No.	Carbon (wt %)	Diameter† (in.)		TIR (in.)	Cleanup Diameter (in.)	Number of Grinding Passes	Slug Breakage (Pass)	Total Stock Removal§ (in.)	Finished TIR (in.)
		0°	90°						
1	4.95	0.492	0.496	0.008	0.473	2	2	-	-
2	4.90	0.494	0.497	0.011	0.475	6		0.022	0.002
3	4.98	0.490	0.497	0.018	0.470	10		0.027	0.004
4	4.95	0.493	0.499	0.030	0.455	11		0.044	0.005
5	4.90	0.493	0.499	0.014	0.475	7	4	0.024	0.004
6	4.95	0.495	0.499	0.025	-	7	7	-	-
7	4.98	0.493	0.498	0.030	0.466	12		0.032	0.008
8	4.95	0.493	0.499	0.011	0.470	9		0.029	0.004
9	5.20	0.493	0.499	0.029	0.469	9		0.030	0.006
10	5.00	0.494	0.499	0.012	0.470	8		0.029	0.003
11	5.10	0.491	0.498	0.030	0.450	17		0.048	0.003
12	5.02	0.478	0.500	0.030	0.470	11		0.030	0.008
13	5.25	0.492	0.499	0.025	0.469	10		0.030	0.006
14	5.60	0.491	0.499	0.020	0.469	9		0.030	0.007
15	5.11	0.492	0.498	0.025	-	1	1	-	-
16	5.20	0.495	0.499	0.015	0.470	11		0.029	0.006
17	5.20	0.495	0.499	0.007	0.470	8		0.029	0.002
18	5.40	0.484	0.496	0.030	0.470	13		0.026	0.004
19	5.25	0.487	0.498	0.021	0.470	10		0.028	0.007
20	-	0.481	0.499	0.021	-	-	7	-	-

*These slugs, cast into molds that had not been outgassed, were the same series discussed previously and shown in Figure 13b.

†The difference in diameters, measured 90° apart, is equivalent to the ovality of the slug.

§Diametric removal for nominal slug cleanup, as arbitrarily determined by the operator from visual quality of the machined slug.

brought about the adoption of the metal-bonded diamond wheel as the standard cutting tool for carbide fuels at AI. While the vitreous wheel has been rejected for dry grinding, it would probably be suitable for wet-grinding techniques used elsewhere.

During this testing period, it was also determined that overheating during dry grinding was not excessive, and that an air environment in a customary plastic box enclosure with normal ventilation-control practices was suitable.

Tables 6 and 7 list the results of wet grinding tests made on 7-in. long slugs with the Royal Master unit, using the 1-in. wide, metal-bonded diamond wheel. The ground slugs from these tests are shown in Figure 20. The slugs are arranged, from left to right, in the order in which they were both cast and ground. The average surface finish for each series of ground slugs (determined from ~5 slugs) was ~150 μ in.; overall out-of-roundness (ovality) of the finished slugs was within ± 0.0003 in. Though the surface quality of the as-cast slugs in Series II (from outgassed molds) was superior to that of the slugs in Series I (from molds that were not outgassed), both groups required approximately the same stock removal (0.031 to 0.032 in. on the diameter). This was apparently due to similarities in bow and cold-shut severity. The data show that the required number of passes per slug through the grinder was a function of the bow; a slug with a TIR of 0.030 in. usually required as many as seven passes, at 0.002 in. diametric removal per pass, before a maximum removal rate of 0.004 in. per pass could be made. If larger stock removals were attempted initially, excess slug breakage occurred. It appears as though the grinding parameters and slug breakage are not related to carbon composition. In Series II, the slug breakage was only about a third of that in Series I, primarily due to increased experience in the grinding operation.

Large TIR values in the as-ground slugs are not typical of efficient, centerless grinding operations. Investigation revealed that this was the result of improper support of the slug during grinding, caused by:

- 1) Inadequate length of the feeder rest guide
- 2) Inadequate length of the work blade which supports the slug during grinding and after it leaves the grinding wheel
- 3) The narrow widths of the cutting and backup wheels.

TABLE 7
SERIES II* CENTERLESS GRINDING DATA FROM ROYAL MASTER UNIT

Slug No.	Carbon (wt %)	Diameter† (in.)		TIR (in.)	Cleanup Diameter (in.)	Number of Grinding Passes	Slug Breakage (Pass)	Total Stock Removal§ (in.)	Finished TIR (in.)
		0°	90°						
21	4.8	0.493	0.498	0.018	0.464	9		0.034	0.007
22	5.0	0.493	0.497	0.026	0.465	10		0.032	0.009
23	5.0	0.491	0.498	0.011	0.466	9		0.033	0.005
24	5.2	0.493	0.498	0.030	0.466	10		0.032	0.009
25	5.1	0.491	0.498	0.028	0.466	10		0.032	0.010
26	5.2	0.489	0.498	0.022	0.467	10		0.031	0.012
27	5.0	0.490	0.498	0.030	0.465	11		0.033	0.014
28	5.1	0.492	0.499	0.024	-	-	1	-	-
29	5.0	0.495	0.497	0.030	-	-	1	-	-
30	5.3	0.492	0.498	0.023	0.467	9		0.031	0.006
31	5.3	0.494	0.498	0.030	0.467	10		0.031	0.011
32	5.2	0.492	0.498	0.026	0.467	10		0.031	0.006
33	5.3	0.494	0.498	0.025	0.467	9		0.031	0.009
34	5.3	0.493	0.499	0.016	0.467	10		0.031	0.004
35	5.3	0.490	0.498	0.026	0.467	10		0.031	0.009
36	5.1	0.491	0.498	0.019	0.467	10		0.032	0.006
37	5.3	0.493	0.498	0.021	0.467	10		0.031	0.009
38	5.0	0.489	0.498	0.022	0.467	10		0.031	0.009
39	4.9	0.490	0.498	0.025	0.467	11		0.031	0.009
40	5.1	0.494	0.497	0.012	0.466	5		0.031	0.004

*These slugs, cast into outgassed molds, were the same series discussed previously and are shown in Figure 13a.

†The difference in diameters, measured 90° apart, is equivalent to the ovality of the slug.

§Diametric removal for nominal slug cleanup, as arbitrarily determined by the operator from visual quality of the machined slug.

a. Series I

Figure 20.. Slugs After Centerless Grinding on Royal Master Unit
(Sheet 1 of 2)

3-6-67 UNC

7660-51145A

b. Series II

Figure 20. Slugs After Centerless Grinding on Royal Master Unit
(Sheet 2 of 2)

The inadequate lengths of the rest guide and the work blade were causing slug "cocking," at both the lead and tail ends of the casting, resulting in a taper at the ends of the ground slug. The short rest guide (just a few inches long, on the feed side) which was standard design for the Royal Master unit is shown in Figure 21a. This was extended to a total of ~ 2 ft (Figure 21b), to facilitate continuous slug feeding. Similarly, the work blade length was increased to a total of ~ 8 in., to fully support the length of the slug as it left the grinding machine. In addition to these modifications, a 3-in. wide diamond wheel (10 in. diameter, 60 grit, 100 concentration, metal bonded) was installed on the Royal Master unit; these changes essentially solved the problem of large TIR values in the as-ground slugs.

This unit was used for several small production jobs, including the finishing of enriched fuel slugs for the Piqua Core II Prototype and the HWO CR WR1 Experiments;⁽⁵⁾ in the latter case, over 200 ft of fuel were required for two specific designs (WR1-953 and WR1-954). While high-quality surface finishes were not required for these designs, dimensional and OD (ovality) tolerances of ± 0.0005 in. and TIR tolerances of 0.001 in. were specified and were easily maintained during production.

3. Grinding Tests With Cincinnati Unit

This machine is a heavier unit than the Royal Master, has higher precision (better bearings, etc.), and has more convenient controls and adjustments. Figure 22 shows slugs that were finished on this unit.

The condition of the as-cast slugs made it impossible to obtain the maximum stock removal on the first two passes. With the work blade (Figure 2) set at the normal position for conventional grinding, a crushing action was observed, and excessive slug breakage was experienced; with the blade set much higher than normal, excessive chatter and breakage were experienced. The height of the work blade was adjusted with the use of flat shims, and its closeness to the grinding wheel was adjusted by the size adjustment setting on the unit. Test runs (Table 8) determined that the best operating procedure was to set the blade $\sim 1/32$ in. away from the grinding wheel on the first two passes to prevent crushing; on subsequent passes, this distance was reduced to $\sim 1/64$ in. This distance was contingent on the straightness of the slug; but, for dry grinding, it had to

3-6-67 UNC

00-18486A

a. Original Equipment

Figure 21. Royal Master Unit Rest Guide
(Sheet 1 of 2)

3 6-67 UNC

7680-1818A

b. As Modified

Figure 21. Royal Master Unit Rest Guide
(Sheet 2 of 2)

Figure 22. Slugs Finished on Cincinnati Centerless Grinder

TABLE 8
POSITIONING OF WORK BLADE ON CINCINNATI UNIT

Diameter (in.)		Shims Required Under Blade (in.)	Distance From Grinding Wheel (in.)
Rough	0.493	0 - 1/32	1/32
Finished	0.475		1/64
Rough	0.473	1/32	1/32
Finished	0.462		1/64
Rough	0.363	1/32 - 1/16	1/32
Finished	0.354		1/64
Rough	0.285	3/32 - 1/8	1/32
Finished	0.271		1/64

be sufficient to allow the sludge to flow through. The work blade was raised (1/32 to 1/8 in.) above its normal position, in proportion to the slug diameter. The higher above center that the work was placed, the quicker the rounding action. However, a limit was reached at which the work started jumping away from the work blade.

From tests made on the Queen City Disc Grinder, it was proved that abrasive belts will cut UC. In order to speed up the first two passes of the slug finishing operation, some preliminary investigations were made using a centerless belt grinder. It might be feasible to use a dual head centerless belt grinder to remove high spots on the periphery of a slug or bow in a slug, thereby approaching a more cylindrical shape. However, belt grinders will not normally hold close diametric tolerances; therefore, the conventional centerless grinder is recommended for the final passes.

Tests (Table 9) were run to determine the optimum speed on the regulating wheel for the various passes through the grinding unit.

TABLE 9
STOCK REMOVAL vs REGULATING WHEEL SPEEDS

Pass	Stock Removal (in.)	Wheel Speed (rpm)
1	0.002	40 - 50
2	0.002 - 0.003	50
3	0.004 - 0.005	50
4	0.004 - 0.005	50 - 60
or Final	0.002 - 0.003	50 - 60

If more than 0.003 in. of stock was removed in one pass, difficulty was experienced in maintaining the 0.0005-in./OD tolerance, especially when "cleanup" on the slug surface was poor or incomplete; if less than 0.003 in. was removed, this tolerance could be maintained. As less stock was removed, the rpm of the wheel could be increased slightly, but this procedure is not recommended for rough slugs. Once the surface was ground, a maximum stock removal of 0.005 in.

did not have any effect on slug breakage; however, it did affect the accuracy of the finished slug. This is the reason for recommending that a maximum of only 0.003 in. be removed for the final pass.

Tests were also run to determine the relationship between the diameter of the slug and the stock removal that could be made per grinding pass. Table 10 shows the results of these tests.

TABLE 10
MAXIMUM DIAMETRIC STOCK REMOVAL PER
GRINDING PASS vs SLUG DIAMETER

Test Run	Slug Batch Size (kg)	Average Slug Diameter (in.)		Total Number of Passes	Maximum Diametral Stock Removal Per Pass (in.)				
		Before Grinding	After Grinding		Pass Number				
					1	2	3	4	5
1	20	0.493	0.475	5	0.002	0.003	0.005	0.005	0.002
2	11	0.493	0.475	5	0.002	0.003	0.007*	0.005	0.002
3	8	0.473	0.461	4	0.002	0.003	0.005	0.002	-
4	12	0.473	0.462	4	0.002	0.003	0.004	0.002	-
5	3.5	0.364	0.354	4	0.002	0.003	0.003	0.002	-
6	8	0.364	0.354	4	0.002	0.003	0.004	0.001	-
7	4	0.281	0.272	4	0.002	0.002	0.003	0.002	-

*0.007 in. removal per pass was eventually reduced to 0.005 in. to minimize slug breakage.

In order to realize the maximum output of the centerless grinder, the quantity of processed slugs should be as much as Criticality Control determines can be safely handled in one operation. Once this limit is established, it would be preferable to set up one machine to handle the first two rough passes and a second machine to handle the third and final passes. Also, the schedule should be set up to handle one size as long as possible, to eliminate numerous "setup" changes. With the feeds and speeds more or less fixed on the machine, the only other major factor to achieve maximum production would be the input capacity through the wheel. This rate would be controlled largely by the operator. Certain modifications (e.g., making the process a sitdown operation, providing

proper feed trays, and modifying the glove box enclosure) could reduce the fatigue factor for the operator, and thereby increase his productivity rate. An input trough was developed, but there was insufficient time to install it on the grinder during this study; by developing this tooling, it is anticipated that it may be possible to increase production by 10 to 20%.

On the basis of the limited data available from the test runs completed, a preliminary centerless grinding production throughput rate for UC slugs, correlated to slug diameter, is given in Table 11.

TABLE 11
MASS RATE OF FINISH GRINDING AS A FUNCTION
OF SLUG DIAMETER

Slug Diameter (in.)	Mass Rate of Slugs Processed (kg/hr)	Total Length of Slugs Processed (in./hr)
0.475	9	240
0.462	8	240
0.354	6	240
0.272	4	240

These data are based upon a measured average capacity of 240 in./hr for all slug diameters tested.

Slug length also has an effect on the overall efficiency of the centerless grinding process. Table 12 shows this effect, where efficiency is measured by production rate of finished slugs.

As mentioned previously, the output conveyor belt can handle any quantity of slugs that might be processed; it also increases the efficiency of the grinding process and decreases slug breakage.

Tests showed that the Queen City Disc Grinder could handle the end trimming operation, processing UC slugs at the rate of 3/min, or 630 slugs per machine shift (7 hr). Being a dual disc grinder, the one machine could be set up for two operators, if required, or one operator could change over without any maintenance delay. Assuming an output of 600 slugs per day (allowing for possible breakage), this machine could supply sufficient slugs to fully utilize the centerless grinder.

TABLE 12
EFFECT OF SLUG LENGTH ON PRODUCTION RATE

Slug Length (in.)	Production Rate of Finished Fuel Slugs (in./hr)
1	208
2	211
3	225
4	238
5	242
6	245
7	242
8	241

This study shows that use of the Cincinnati unit (equipped with output conveyor) and the Queen City unit can process UC slugs more satisfactorily than previous methods tested. In conjunction with improvements made in slug finishes through modification of the casting process, the HWO CR tolerance requirements can be met and production economies can be effected.

V. SUMMARY

Extensive melting and casting tests were performed on 1/2-in. diameter, hyperstoichiometric UC slugs, in an effort to improve the surface quality and straightness of the castings. Results indicated that the surface quality of cast slugs was not affected by:

- 1) Carbon content of the UC
- 2) Length of the casting
- 3) Wall thickness or finish of the mold
- 4) Cooling time of the cast slug
- 5) Use of alternate mold materials (vitreous carbon, pyrolitic graphite, or TS-360 Grade graphite).

However, significant improvements in surface quality were achieved by:

- 1) Outgassing the molds (vacuum heating at 2300°C for 1 hr)
- 2) Preheating the molds to 900 to 1000°C before pouring
- 3) Heating the melt to slightly greater superheat.

Marked improvements in slug straightness were made by casting slugs without headers or with a reduced header thickness.

Data from this study suggested that surface defects are strongly affected by gas evolution arising directly from the mold or from reaction products formed on the interior of the mold (i.e., an initial carbide layer which subsequently forms an oxide that is chemically reduced by molten UC to form CO and/or CO₂). Based on these findings, further investigation to decrease surface defects should include study of: alternate, more corrosion-resistant mold materials, process techniques for reconditioning used molds, or bottom-pouring methods which might facilitate the escape of evolved gases. Slug straightness might be improved by casting shorter lengths; the casting economies effected in producing longer slugs could be offset by lower finishing costs (faster grinding speeds, less end finishing, and less breakage) for the shorter slugs.

Centerless grinding has proved feasible and economical for surface finishing UC slugs. Approximately 0.030 in. diametric stock removal is required for moderate "clean-up" from a 1/2-in. diameter casting (~11%). Dimensions and

OD roundness can be controlled to better than ± 0.0005 in., TIR straightness can be maintained to within 0.001 in., and surface finishes better than 200 μ in. can be attained readily. A 3-in. wide, metal bonded, 60-grit diamond wheel has proved more satisfactory than the vitreous (SiC) wheels that were evaluated. In moderate production efforts completed recently at AI, in which full cleanup and high surface finishes were not required, only 4 to 5 grinding passes (0.014-in. diametric stock removal) were necessary to achieve dimensional and TIR tolerances of ± 0.0005 and 0.001 in., respectively.

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