HEAVY WATER ORGANIC COOLED REACTOR

PRELIMINARY ANNULAR UC FUEL CASTING DEVELOPMENT

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By

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ABSTRACT

An exploratory casting program was conducted to determine the feasibility of casting hyperstoichiometric uranium carbide in the shape of rings, as fuel for application in advanced Heavy Water Organic Cooled Reactor (HWOCR) annular element designs. Unique mold gating systems were developed for both single- and multiple-cavity molds. This resulted in the successful arc casting of uranium carbide fuel rings and hollow cylinders of various outside diameters, ranging from 3/4 to 3.5 in., all having a 1/4-in. wall thickness, and lengths up to 6 in.

The major problem areas pertinent to the development of a reliable multiple-cavity skull casting process for annular uranium carbide fuel have been isolated and analyzed. However, additional work is required to resolve existing problem areas and to develop advanced technology for a large-scale, economical, multiple-concentric-ring casting process for the advanced HWOCR concepts.

I. INTRODUCTION

An exploratory casting program was initiated to determine the feasibility of and problem areas associated with the development of a process for fabricating ring-shaped hyperstoichiometric UC fuel for application in advanced Heavy Water Organic Cooled Reactor (HWOCR) annular element design concepts.

From the standpoint of reactor design, the annular concept offers a number of advantages over the rod-cluster element, chief among them being design flexibility and more cross-sectional fuel area per element.⁽¹⁾ With regard to flexibility, each fuel ring and coolant channel may be varied in thickness, and the number of fuel rings may be varied over a wide range. This is not feasible for the rod-cluster element, where the use of more than two or three kinds of rods is impractical, and the number of rods per element is limited to bundles which fit symmetrically into a round process tube (e.g., 7, 19, 37, and 61 rods). The design flexibility of the annular element may be used to advantage to obtain a "balanced" design — one in which the coolant velocity in each coolant annulus in the element is the same, and in which the maximum cladding temperature on both sides of each fuel ring is the same. This approach can eliminate excess coolant, and should result in improved neutron economy.

In addition, the annular element may be designed with more cross-sectional fuel area per element than a rod-cluster element. In the rod-cluster element, as the fuel area is increased, the maximum cladding temperature of the central rods decreases. As the fuel area of the annular element is increased, the coolant area in the center of the element may be decreased, maintaining the limiting surface temperature on each fuel ring. Thus, the advantage of the annular element over the rod-cluster element increases with fuel area. Increased fuel area results in a reactor capital cost savings, by reducing the number of pressure tubes required in the core.

From the standpoint of fabrication, the state of the art regarding casting of annular UC fuel is virtually nonexistent. Several preliminary, unpublished, small-scale experiments, conducted at Atomics International in previous years, indicated that UC rings, particularly large diameter rings, were difficult to fabricate, due primarily to the high coefficient of thermal expansion and the inherent brittleness of UC.

The primary intent of the work described in this report was to initiate development of techniques for the casting of annular UC fuel of sound structure and with controlled dimensional variations. This report presents the status of the initial phase of the development of annular UC fuel for use in concentric fuel elements.

II. EXPERIMENTAL

A. MOLD GATING DESIGN

The reference procedure at AI for arc casting UC fuel in the form of solid rods consists basically of tilt pouring molten UC into multi-cavity graphite (ATJ grade) molds. The molten UC is allowed to solidify without restraint, usually resulting in uncracked rods. The casting of UC into an annular shaped fuel is considerably more complicated, because it requires the use of a mold core. The simplest approach (i.e., for metal fuel) is usually to use a solid core. However, earlier (unpublished) experimental efforts at AI had indicated that the use of solid graphite cores always produced catastrophic cracking of UC upon solidification, due to the large differential expansion between UC and graphite. Thus, solid-core casting was not pursued, and all efforts were initially directed toward designing a single-casting mold gating system which would give uncracked rings.

The use of a thin-wall graphite core was selected as a first approach, on the theory that the core should be strong enough to restrain the molten UC during solidification; but its strength should be sufficiently low that it would crush with contraction of the UC during cooling, and would not impose hoop stresses on the ring that would be large enough to fracture the casting in tension.

Several thin-wall cores, having a 0.010-in. wall thickness and a 1/4 in. OD, were fabricated from ATJ grade graphite, and were designed for casting UC tubes, 3/4 in. OD (1/4 in. wall) by 3 in. long. The cores (one is shown in Figure 1a) were fabricated from solid graphite blocks by first machining an oversized OD, boring the ID to exact dimensions, followed by a finished-dimension cut on the OD. This technique was used throughout the program, and was the only method available without resorting to development of special tooling and fabrication methods.

B. CASTING EXPERIMENTS - SINGLE-CAVITY MOLDS

1. 3/4 in. OD (1/4 in. wall) by 3 in. Long

The first series of arc casting experiments used a single-cavity graphite mold shown in Figure 1a and the thin-wall core (0.010 in. thick) described

UNC

7680-51154

a. Components

b. Assembled

Figure 1. Graphite Mold Used for Single-Cavity
Casting of 3/4-in. OD Annular
UC Fuel (~1/4 in. wall)

UNC 7680-51155

previously, assembled as shown in Figure 1b. The first single-cavity experiment (SC-1) consisted of melting a charge of 1.5 kg of hyperstoichiometric UC (~4.9 wt % C) in an atmosphere of purified argon at 23 in. Hg, and pouring at 2500°C (via the mold distributor) into the mold cavity between the OD of the hollow core and the ID of the mold. Instead of a hollow cylinder, a solid slug was formed, which was attributed to partial dissolution of the 0.010-in. thick core wall by the molten UC before solidification was complete. A duplicate experiment (SC-2) produced identical results. It was concluded that the heat transferred to the thin-wall core was not being dissipated rapidly enough to prevent dissolution of the core. The next experiment (SC-3) was similar to the previous two, with the exception that a solid graphite rod (Figure 1a) was added to the mold (inside the thin-wall core), loosely contacting the core wall along its entire length. The casting produced with this mold was a hollow cylinder, 3/4 in. OD (~1/4 in. wall) by 3 in. long, which had severely cracked throughout during cooling. The inability of the UC to crush the thin-wall core was a direct result of having insufficient clearance between the graphite rod and the core; in effect, this produced a solid graphite core which could not be crushed. However, the thin-wall core did not dissolve.

The mold was modified again, to overcome this solid-core effect; the radial clearance between thin-wall core ID and the graphite rod (heat sink) was increased from virtually zero to ~0.004 in. The melting and casting of UC was carried out (Heat SC-4), using the same parameters as in previous heats. This unique approach produced a hollow, uncracked annular casting, 3 in. long by 0.710 in. OD by 0.244 in. ID (shown in Figure 2a). Examination of the casting-mold assembly, after removal from the furnace, confirmed the theory that the UC would crush the thin graphite shell during cooling, and not build up sufficient hoop stress to crack the casting. The casting was easily removed from the mold, leaving all components of the mold intact (with the exception of the thin-wall core, parts of which adhered to the ID of the casting). The as-cast surface finish of the cylinder was comparable to that obtained for cast UC rods. Two additional heats (SC-5 and -6) were made, and produced duplicate results. The castings from these three experiments are shown in Figure 2b. A radiographic examination of the hollow cylinders revealed only slight porosity adjacent to the top of the casting, much less than that normally encountered in a solid slug.

a. Casting From Heat SC-4

UNC

7660-5119

UNC

b. Castings From Heats SC-4, -5, and -6

7660-5111

Figure 2. As-Cast Hollow UC Cylinders, Nominal $\frac{3}{4}$ in. OD
($\frac{1}{4}$ in. wall) by 3 in. Long

An important consideration (realized early in this program) is that, with the present mold design, the mold cavity may be completely filled; but it must be prevented from being overfilled and forming a header, which is the usual procedure in casting rods. With this design, the formation of a header would be followed by the molten UC solidifying and contracting around the solid graphite distributor plate [which also serves as a centering support for the thin-walled core and solid rod (heat sink)], resulting in severely cracked castings.

2. Scaleup to Larger Diameters

The development effort in casting annular UC fuel was continued, with emphasis on expanding the process to cast considerably larger diameters than 0.750 in., specifically 2.000 and 3.500 in. OD with a 1/4-in. wall thickness.

New mold designs were prepared, using the design for the 3/4-in. OD cylinder as a basis, and taking into consideration the total inside diametral contraction expected for 2.000- and 3.500-in. OD cylinders of UC (from liquid at 2500°C to ambient temperature), which were calculated to be ~0.042 and ~0.080 in. respectively. Adding clearance for the hollow core wall thickness, a mold for casting a 2.000-in. OD cylinder was designed with a 0.065 in. clearance, and a mold for the 3.500-in. OD cylinder was designed with a 0.115 in. clearance.

a. Casting Nominal 2.000-in. OD Hollow Cylinders

In actual fabrication of the 2.000-in. diameter mold, a machining error resulted in only a 0.015 in. clearance. One heat (SC-7) was made, using this mold. The resulting UC cylinder was 3 in. long and had two wide cracks, diametrically opposed, extending the length of the cylinder. Subsequent molds were fabricated with the required 0.042-in. clearance between the diameter of the solid graphite insert (heat sink) and the ID of the hollow core, or a total of 0.065 in. between the OD of the hollow core and the diameter of the solid graphite insert. The mold components for the 2.000-in. diameter mold assembly are shown in Figure 3a. Partial and complete assemblies of the components are shown in Figures 3b and 3c respectively. The next four heats (SC-8 to -11) produced three sound, crack-free cylinders having a mean OD = 1.936 in. and ID = 1.492 in., by 3 in. long. The three cylinders are shown in Figure 4. The fourth cylinder was found to have developed a crack which extended partially along the length. This occurred as a result of an overfill of UC around the graphite distribution plate;

a. Components

UNC

7680-51156

b. Partially Assembled (Both cores positioned within base plate)

UNC

7680-51157

c. Assembled

UNC

7680-51153

Figure 3. Graphite Mold Used for Single-Cavity Casting of 2.000-in. OD Annular UC Fuel (~1/4 in. wall)

UNC

Figure 4. Crack-Free, As-Cast, Hollow Cylinders of Nominal 2.000 in. OD and 1/4-in. Wall Thickness

7660-5115

UNC 7660-5121
a. From Heat SC-12, Showing
Diametrically Opposed Cracks

UNC 7660-5125
b. Crack-Free Cylinder, 1-1/2 in.
Long, Typical of Heats SC-13 to -17

Figure 5. As-Cast, Hollow Cylinders of Nominal 3.500 in. OD
and 1/4-in. Wall Thickness

UNC 7660-5123
Figure 6. As-Cast, Hollow Cylinders, 3/4 to 3.500 in. OD
and 1/4 in. Wall (Note excellent surface finish on ID of
2.000 and 3.500 in. OD cylinders)

upon solidification, the overfill cracked and propagated into the cylinder. This further emphasized the need to avoid pouring a header or riser above the cylinders. The surface finish of the cylinders was representative of that usually encountered in casting UC slugs. A radiographic analysis was made to determine the extent of primary pipe formation and other internal casting defects within the cylinder wall. Only one cylinder exhibited a small primary pipe formation which extended 1/4 in. down from the top of the cylinder. The other cylinders did not exhibit any defects.

b. Casting Nominal 3.500-in. OD Hollow Cylinders

The apparent success in casting the 2.000-in. OD cylinder led to the fabrication of a graphite mold and gating system for casting the 3.500 in. OD cylinder, based upon the design used for the 2.000 in. cylinder. The fabricated molds were similar to the components and assembly shown in Figure 3. Molds were fabricated with a total clearance of 0.080 in. between the diameter of the solid graphite insert (heat sink) and the ID of the hollow core, or a total of 0.115 in. between the OD of the hollow core and the diameter of the solid graphite insert. The length of the mold cavity was limited to 1-3/4 in. by the small UC melt capacity of the furnace and the relatively large diameter of the cylinder.

The first attempt (SC-12) at casting a 3.500-in. OD cylinder of hyperstoichiometric UC resulted in an overfill of molten material around the distribution plate. Subsequent shrinkage generated cracks, diametrically opposed, which propagated into the cylinder (Figure 5a). The next five heats (SC-13 to -17) produced one additional cracked cylinder, due to overfill, and four sound, crack-free cylinders with an average OD = 3.391 in., an ID = 2.936 in., and a length which ranged between 1-1/2 and 1-3/4 in. A typical as-cast cylinder is shown in Figure 5b. The outside surface condition of this cylinder was representative of that found for as-cast UC slugs. However, the inside surface, after removal of the hollow core insert, generally exhibited considerably less roughness and fewer surface defects. A good view of the inside surface of the nominal 3.500-in. OD cylinder is shown in Figure 6, which displays castings of different diameters.

One problem encountered after removal of the UC cylinder from the mold was delayed cracking, which occurred several hours later, but prior to removal

TABLE 1
DIMENSIONS OF SINGLE-CAVITY GRAPHITE MOLDS
AND AS-CAST CYLINDERS

Mold Dimensions (in.)		Casting Dimensions (in.)		Shrinkage (ΔD) (in.)	
Nominal 3/4 in. OD by 1/4 in. ID by 3 in. Long UC Casting					
Outer mold tube		OD		OD	
OD	1.000	Top	0.724	Top	-0.026
ID	0.750	Bottom	0.720	Bottom	-0.030
Inner shell core OD	0.270	ID		ID	
Solid core insert OD	0.240	Top	0.267	Top	-0.003
		Bottom	0.266	Bottom	-0.004
Nominal 2.000 in. OD by 1.5 in. ID by 3 in. Long UC Casting					
Outer mold tube		OD		OD	
OD	2.375	Top	1.937	Top	-0.063
ID	2.000	Bottom	1.935	Bottom	-0.065
Inner shell core		ID		ID	
OD	1.520	Top	1.490	Top	-0.030
ID	1.500	Bottom	1.488	Bottom	-0.032
Solid core insert OD	1.430				
Nominal 3.500 in. OD by 3 in. ID by 1-1/2 in. Long UC Casting					
Outer mold tube		OD		OD	
OD	4.000	Top	3.395	Top	-0.105
ID	3.500	Bottom	3.390	Bottom	-0.110
Inner shell core		ID		ID	
OD	3.000	Top	2.930	Top	-0.070
ID	2.970	Bottom	2.930	Bottom	-0.070
Solid core insert OD	2.855				

TABLE 2
DIAMETRICAL SHRINKAGE OF CAST
ANNULAR UC FUEL
(Measured vs Calculated)

Nominal As-Cast Cylinder OD (in.)	Diametrical Shrinkage (in.)			
	Measured (Avg)		Calculated	
	OD	ID	OD	ID
3/4	0.028	0.004	0.022	0.007
2.000	0.064	0.031	0.060	0.045
3.500	0.107	0.070	0.104	0.089

of the hollow core insert. This was attributed to a combination of factors, including residual hoop stresses and further contraction of the casting around the graphite. Maintaining a compressive stress on the cylinder circumference until the graphite insert could be removed by machining appeared to be the immediate solution to this problem. Stress relieving at elevated temperatures has been considered as an alternate solution for future investigation.

3. Analysis of Hollow UC Cylinders Cast in Single-Cavity Molds

a. Composition

Both carbon and oxygen analyses were made on each cylinder. The carbon contents, which were made to vary for the purpose of achieving either stoichiometric or hyperstoichiometric UC, were in the range of 4.72 to 5.02 wt % C. The oxygen content, obtained by vacuum fusion, ranged from 50 to 310 ppm, with the average being 138 ppm. The variation in carbon content did not appear to affect the quality of the castings produced, in terms of defects or cracks.

b. Internal Defects

A radiographic analysis was made to determine the extent of primary pipe formation and other internal casting defects within the cylinder wall. The analysis revealed a slight amount of porosity in one 3/4-in. OD cylinder, and a thin primary pipe in one 2-in. OD casting, extending 3/16 in. down from the top. All other cylinders examined were free of internal pipe formation. The number of defects found were only a small fraction of the total usually encountered in UC slugs.

c. Dimensions

A dimensional analysis was made on all as-cast cylinders, to determine the degree of shrinkage as a function of the nominal casting OD. Major emphasis was placed upon determining the total diametrical change of the cylinders, with the dimensions of the respective graphite molds in which they were cast serving as reference. The dimensions of the single-cavity graphite mold components, and the castings produced from them, are given in Table 1. The mean diametrical shrinkage (ΔD) was measured, and is given in Table 2, where it is compared to calculated shrinkage based upon the following assumptions:

10-21-66 UNC

7680-51238

Figure 7. Comparison of Measured and Calculated Diametrical Shrinkage of As-Cast Annular UC Fuel, as a Function of Diameter (Values taken from Table 2)

1) Mean coefficient of thermal expansion (α_1) for UC $\cong$ 16.0 in./in.-°C $\times 10^{-6}$ between 2550°C (estimated superheat temperature) and 2450°C (estimated solidification temperature for UC_{1+x}). This value was obtained by extrapolating thermal expansion data for hyperstoichiometric UC given in NAA-SR-8538.⁽²⁾

2) Mean coefficient of thermal expansion (α_2) for UC_{1+x}, from 2450 to 20°C, $\cong$ 12.3 in./in.-°C $\times 10^{-6}$.⁽²⁾

3) Molten UC contracts uniformly in all directions.

A further comparison of measured and calculated diametrical shrinkage is shown in Figure 7. It must be noted that the calculated ΔD includes only solid-state contraction, and is expected to differ from the measured ΔD by an amount which would include the contraction from:

- 1) Liquid at superheated condition to liquid at melting point of UC
- 2) Liquid-to-solid phase change
- 3) Errors in measurement of cylinder diameters.

d. Metallography

A metallographic analysis was performed on the nominal 2.000 and 3.500 in. OD cylinders, to ascertain microstructural characteristics and homogeneity. The results indicate a uniform microstructure transversely across the wall thickness, as shown in Figure 8 for stoichiometric UC and in Figure 9 for hyperstoichiometric UC. The analyses were limited to the 2.000 and 3.500 in. OD cylinders; since they represented the most difficult diameters to cast, and on the contention that, if nonuniform properties were present, they would most likely show up in the larger diameter castings.

C. CASTING EXPERIMENTS — MULTIPLE-CAVITY MOLDS

The initial development work described in Section B was carried out using single-cavity graphite molds, with casting performed in an experimental size (~3000 amp) arc-melting furnace capable of pouring a maximum of 1.2 kg of molten UC.

a. Adjacent to ID

UNC

6237-23-2

b. Center

UNC

6237-23-4

c. Adjacent to OD

UNC

6237-23-6

Figure 8. Typical Transverse Microstructure of As-Cast, Hollow, Stoichiometric UC Cylinder of Nominal 2.000 in. OD and 1/4-in. Wall Thickness

UNC

6237-36-2

a. Adjacent to ID

UNC

6237-35-4

b. Center

UNC

6237-36-6

c. Adjacent to OD

Figure 9. Typical Transverse Microstructure of As-Cast, Hollow, Hyperstoichiometric (~4.92 to 5.02 wt % C) UC Cylinder of Nominal 3.500 in. OD and 1/4-in. Wall Thickness

UNC

7660-4003

Figure 10. Multiple-Cavity Graphite Mold, Assembled for
Use in Skull-Cast Tilt-Pour Furnace (Note conical
graphite distributor and flat distributor
plate later added to top of mold)

The next phase of the annular fuel casting program was directed toward scaleup of both the length of the 3-1/2-in. OD cylinder (from 1-1/2 to ~6.00 in.) and the quantity of cylinders cast per heat. This entailed designing a completely new mold gating system, for use in conjunction with a large (10,000 amp) skull-cast tilt-pour furnace. A multiple-cavity mold, for casting five cylinders per heat, was designed and fabricated. The initial design for each individual mold cavity was similar to the design for the single-cavity mold used in casting the nominal 3-1/2-in. OD rings. An assembled multiple-cavity mold is shown in Figure 10.

The first attempt at casting five cylinders simultaneously was Heat MC-1, which consisted of skull melting a total charge of ~4 kg of hyperstoichiometric UC (~5.0 wt % C) and pouring at an estimated temperature of 2650°C. (The skull-casting furnace is estimated to produce molten UC, superheated to at least 100°C higher than the small arc-melting furnaces used in the single-cylinder casting experiments.) An analysis of the results of this heat indicated that the hollow core inserts had burned through, resulting in the formation of short thick-walled cylinders which cracked severely upon cooling. A second heat, MC-2, produced almost identical results, with the exception that one 1-1/2-in. long by 3-1/2-in. OD cylinder was found to be crack free.

Prior to making any additional heats, the design of the multiple-cavity mold was modified. A large, conical graphite distributor (shown in Figure 10) was added to the mold, to provide a more laminar flow and to direct the flow of UC into the cavities. A second modification was a flat distributor plate (shown in Figure 10), added to the mold to chill the molten UC before it entered the cavities. The next three heats (MC-3, -4, and -5) resulted in a total of three partially filled mold cavities; the remainder were unfilled, due to excessive chilling and premature solidification of the molten UC. As the distributor plate appeared to provide too much chilling and restriction to the flow of UC, it was removed for the next heat (MC-7), and only the conical distributor was left in the mold. The results were similar to the initial heats (i.e., hollow-core burn through, producing thick-walled cylinders which cracked severely upon solidification and cooling to ambient temperatures). The major problem was the development of a method for achieving the correct amount of heat dissipation. The mold design, in which the solid core (heat sink) was separated from the hollow core, had been

UNC

7660-4002

a. Components

UNC

7660-4001

b. Assembled

Figure 11. Graphite Mold for Multiple-Cavity Casting of
3-1/2 in. OD Annular UC Fuel Cylinders

UNC

7660-51137

Figure 12. Crack-Free Hollow UC Cylinder,
3-1/2 in. OD (1/4 in. wall) by 6 in. Long,
Cast in Multiple-Cavity Mold (Note
smooth, defect-free ID surface,
as compared to porosity
of OD surface)

successful for small-scale experiments using single-cavity molds. In this application, the pour temperature was appreciably lower than in the multiple-casting process; and the heat dissipation was better, since there was more mold mass per casting. However, the design had to be modified for multiple casting, to provide rapid dissipation of heat from the hollow core and prevent burn through. The design was changed to bring the solid insert (heat sink) in direct contact with the hollow core. The insert was fabricated in four sections, and two graphite spacer springs (at top and bottom of the mold) kept these sections apart and in contact with the core. The springs allowed the sections to contract during solidification and cooling of the UC cylinders without generating sufficient hoop stress to crack the cylinders. The mold components and the assembled individual mold are shown in Figure 11. Five of these individual molds were assembled in a mold housing, as shown in Figure 10, for multiple casting.

The new mold design was evaluated in Heat MC-8, which was similar in most respects to the previous multiple-casting heats (MC-1 to -7). The heat resulted in two complete crack-free cylinders, having a nominal 3-1/2 in. OD (1/4 in. wall thickness) and 6 in. length, as shown in Figure 12. The remaining three cavities produced incomplete or cracked cylinders, primarily due to overfill or leakage around the center plug. The two crack-free cylinders produced were similar in grain structure to the cylinders produced in the earlier single-cavity casting experiments. The inside surfaces of the cylinders were very smooth, and comparable to the inside surfaces present on the 3-1/2-in. OD single-cavity cylinders. On the other hand, the outside surfaces exhibited more porosity than had been encountered previously. This was attributed to incomplete outgassing of the heavy-wall graphite mold, against which the OD of the cylinder was formed, as compared to more complete outgassing of the thin-wall hollow core which was used to form the inside surface.

Further experimental work in the development of economic processes for the casting of annular UC fuel cylinders should include additional studies of mold gating and distribution systems.

III. DISCUSSION OF RESULTS

A. FEASIBILITY DEMONSTRATION

The initial objective of the first phase in the development of a process for casting annular UC fuel (specifically, feasibility demonstration) has been achieved. The series of single-cavity experiments has shown that UC rings, or hollow cylinders of various diameters, can be cast without cracks and with as-cast surfaces comparable to those obtained on reference process UC slugs. Problem areas which require further investigation are outlined in the following section.

B. MAJOR PROBLEM AREAS

The mold gating system design, which is the major variable in the process (as regards its capability of producing minimum-defect, crack-free cylinders), was found to be less complex for the single-cavity mold design than for the multiple-cavity mold. The need for adequate heat dissipation became more critical with the higher pouring temperature of molten UC and the decrease in mold volume per casting which were experienced in multiple-cavity casting. The graphite spring spacer design used for multiple-cavity skull casting appears to provide the rapid dissipation of heat required; however, considerably more experimental data is needed to establish the level of reliability of this design. The mold-gating system for multiple casting of concentric cylinders is expected to be even more complex, but is also expected to substantially increase process efficiency.

The following problem areas in casting and mold-gating design, which are basically inseparable, attributed to the failure to form and/or maintain complete, crack-free cylinders:

- 1) Hollow core burn through
- 2) Uncontrolled cylinder contraction during solidification
- 3) Overfill formation of header (riser)
- 4) Residual hoop stresses.

Burn through, as indicated earlier in the report, occurred at the levels of superheat experienced in both the small-scale single-cavity arc casting and in the multiple-cavity skull casting experiments. The solution to this problem was either to decrease the superheat or to provide better heat dissipation from the hollow core. Decreasing the superheat was impractical, as this would invariably result in incomplete mold fill and severe cold shuts. Thus, it was necessary to modify the mold design to improve the heat dissipation from the hollow core. The graphite spring spacer design appears to have solved this problem for multiple-cavity casting, by transferring heat from the UC to the quartered heat sink inside the hollow core. Since acceptable 3-1/2-in. OD (1/4 in. wall) cylinders were cast by this technique, it is now considered feasible to cast any hollow cylinder up to 3-1/2 in. OD (and, projecting beyond this, to at least 4-1/2 in. OD) with the same (~1/4 in.) wall thickness. Additional experimental work is required to determine whether the technique is suitable for casting cylinders with a wall thickness appreciably greater or less than the 1/4 in. used in Phase I development.

Most of the cylinder cracking was caused by inadequate clearance allowance for total cylinder shrinkage (liquid to solid state + thermal contraction) around both the hollow core and the heat sink. For the single-cavity design, this problem was solved by providing mold component clearances which matched the total actual shrinkage experienced with a given cylinder diameter. The same approach was attempted for multiple-cavity casting, but was unsuccessful, because skull casting produced higher UC superheat which caused burn through of the thin-wall hollow core mold component. The spring-spacer design produced crack-free cylinders; but reliability has not been established, due to insufficient experimental data. However, the spring-spacer design technique will be the reference process for casting annular UC fuel, unless it is proved to be inadequate or unreliable.

Another major problem area which has not been completely resolved is mold overfill, which occurs when either the amount of molten UC poured exceeds the volume of the cavities or the correct mass of UC is unevenly distributed to the cavities. A conical graphite distributor, centrally located, was used to reduce turbulence and equalize distribution. This approach would work if the stream of molten UC could be directed and maintained immediately above the distributor.

However, the present pouring technique was established for skull casting slugs with a header (riser), and it would have to be modified. In future development, considerable effort will be needed, to determine an optimum gating system.

Contrary to the usual practice of casting UC slugs with a riser, annular UC shapes may not require a riser to the same extent, if at all. This was indicated by radiographic analyses, which revealed very thin primary pipe adjacent to the top of the casting. The large center mass, usually present in slugs, is eliminated in annular fuel castings, thereby eliminating the region where severe shrinkage and pipe formation often occur. An added advantage of casting without a riser is that considerably less charge material is required per heat, or using the same quantity of UC can produce more castings. This is expected to increase the casting efficiency and reduce operating and product costs; because, in the reference slug casting process, 30 to 50% of the total weight of UC poured is header (riser), and the balance is in the form of slugs.

Another possible cause of cylinder cracking is the residual hoop stresses within the cylinder, formed by nonuniform solidification and contraction during cooling from the liquid state to ambient temperatures. This cooling is controlled by the rate of heat dissipation from the OD and ID of the casting, which is a function of the mold design. The problem has not been resolved, in terms of finding the optimum mold design; however, a proposed solution is to maintain the cylinder in compression, diametrically, until a stress-relieving treatment can be applied.

The economic feasibility of production casting annular UC fuel has not been the subject of this report, and cannot be adequately assessed until additional development is performed in the following areas:

- 1) Continued multiple-cavity casting development, until a reliable process is established
- 2) Scaleup of the multiple-cavity casting process, and modification of existing mold designs to include concentric cylinder casting. A program would be required to determine the feasibility of concentric cylinder casting and its eventual scaleup.
- 3) Development of a suitable, economical process for surface finishing annular fuel to meet HWO CR design requirements. The large surface area

to mass ratio requires an economical machining process, and also a good as-cast surface finish which will minimize total stock removal. This problem area would be greatly minimized in a fuel element design which used a liquid metal bond between fuel and cladding.

IV. CONCLUSIONS

The feasibility of casting UC into ring-shaped fuel, for use in advanced annular element designs, has been demonstrated. The casting process developed incorporates a unique mold gating system, used in conjunction with conventional melting parameters established for preparing molten UC for casting UC slugs.

The maximum OD of 3-1/2 in., wall thickness of 1/4 in., and length of 6 in. attained during this initial phase of development were by design, and are not considered to be limiting dimensions.

While bench-scale arc-casting and production-oriented skull-casting furnaces have been used successfully to cast annular fuel in single-cavity and multiple-cavity molds, respectively, a considerably greater development effort will be needed to establish a high reliability level for the latter.

The major causes of cylinder cracking have been isolated and analyzed. It is believed that they can be resolved, for multiple-cylinder (and probably multiple-concentric-cylinder) casting, through the development of adequate mold gating systems.

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