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EXPERIENCE IN THE FABRICATION OF URANIUM-233
BEARING ThO₂-UO₂ RODS IN A LIGHTLY
SHIELDED FACILITY AT ORNL*

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INTRODUCTION

The potential of the thorium fuel cycle for achieving low nuclear fuel costs is complicated by the presence of ^{232}U associated with ^{233}U formed in the reactor. The decay of the ^{232}U daughters produces penetrating radiation making the consideration of shielding and fast processing times mandatory. The construction and operation of a lightly shielded, semiremote facility, known as the Kilorod Facility, in which fuel rods containing $(\text{Th}-3 \text{ wt } \% ^{233}\text{U})\text{O}_2$ are fabricated, is the first step in determining the technical feasibility and economy of the thorium fuel cycle. This facility, which is presently operating at the Oak Ridge National Laboratory, was designed to fabricate fuel rods that will be used in zero-power, criticality experiments at the Brookhaven National Laboratory. The fuel rods are produced by vibratory compaction of sol-gel produced oxide in Zircaloy-2 tubes to near 90% of the theoretical density of the powder. The facility was designed to produce 10 rods/day; however, the attainment of this production rate was secondary to the collection of engineering data on the process itself.

The processing of the fuel may be divided into two distinct phases: (1) preparation of the bulk oxide by the sol-gel process and (2) rod fabrication. This paper is concerned with the operating experience of the rod fabrication portion of the facility. The sol-gel process is presented in another paper;¹ the engineering and development of the rod fabrication process and equipment is available elsewhere.²

FUEL ROD DESIGN

The configuration of the reference fuel rod to be fabricated in the facility for the BNL critical experiments is shown in Fig. 1. The BNL

experiments require 900 of these rods and 200 rods identical in design except that they are 18 in. in length instead of 46 1/16 in.

The nominal compaction density was not specified by BNL but will be determined from the average density of the fuel rods fabricated. It was specified that the rods will have a fuel density of $\pm 2\%$ of this determined average density and the density within a fuel rod will be $\pm 2\%$ of the average for that fuel rod. Based on experience with depleted (U,Th)O₂ in the "cold" operation of the facility, an average density of 90% of theoretical is expected.

The cone-shaped Zircaloy-2 bottom fitting, which will be used to direct the rod in the critical lattice at BNL, is welded onto the tube in a gas tungsten-arc welding operation, which is done outside the facility. The annular groove in the bottom plug is used as a handling aid during fabrication. In the facility, the top plug, ceramic spacer, and spring are inserted into the fuel tube after compaction as a unit. The ceramic spacer and spring are used in the void area at the top of the fuel rod to prevent redistribution of the fuel during handling. The Zircaloy-2 top end plug, joined onto the fuel tube by a fusion edge weld in the facility, is threaded to accommodate the stainless steel hanger fixture. This hanger fitting will be used to facilitate handling of the fuel rod in the critical lattice.

PROCESS

The rod fabrication process (Fig. 2) starts with the delivery of the bulk sol-gel oxide to the powder preparation equipment. The material is first crushed in a jaw crusher and separated by a continuous screen classifier into three size fractions: +6, -6+16, and -16. Through

recycling of the +6 fraction and judicious charging of the ball mill with the -6+16 and -16, sufficient amounts of coarse and fine powders consisting of 55% -6+16 and 45% unclassified fines are produced. The development of the process to produce the fine fraction will be considered in the "cold" operation section. The two fractions are then separately weighed out on an automatic batch weigher, blended in a "V" blender, and, using a vibrating feeder, fed into the rods. The powder is densified using an air driven vibratory compactor during feeding followed by additional densification with a weighted rider rod resting on top of the fuel column. The end cap, spacer, and spring are then placed in the rod and the end-closure weld made. Next, the rod is ultrasonically cleaned and gamma scanned to determine the density fluctuations along the long axis. The welds are then helium leak checked and the rod smeared and cleaned until the smear count is < 2000 dis/min. Finally, the rod is loaded into the carrier for shipment.

FACILITY AND EQUIPMENT

The rod fabrication facility occupies the lower two levels of a three-level facility shown in Fig. 3. The third level houses the sol-gel process. The facility was constructed in an unused chemical-processing cell to take advantage of the air-handling equipment and to use the existing cell walls for secondary containment. Located in one corner of the first level and extending to the top of the second level is the 4-X 7-ft powder preparation shaft. Adjacent to this shaft, on the first level, are the three fabrication cubicles. The first cubicle contains the vibratory compaction apparatus and the automatic welder, the second the ultrasonic cleaner, and the third the gamma-ray densitometer and helium leak detector vacuum chamber.

Directly over the first two cubicles on the second level is the glove maintenance area. Access into the powder preparation shaft is through a shielding door in the side of the shaft opening into the maintenance area. Access to the fabrication cubicles is through roof hatches opening into the same area.

The operation of the fabrication equipment is performed either by castle joint manipulators or gloved hands. The powder preparation equipment is operated by flexible shafts extending through seals at the shielding wall. The facility is gamma shielded by 4 1/4-in. armor plate and alpha sealed with an inner liner of 11-gage mild steel. Three bag-out ports are provided for the entry of small support equipment and removal of debris and samples.

The powder preparation equipment (Fig. 4), which is located in the powder preparation shaft, utilizes gravity to transport the fuel through pipes from one equipment unit to the next. All of the equipment in the powder preparation shaft is remotely controlled either electrically or by flexible shafts. Minor repairs are made in-place through glove-access ports. To facilitate major repair, the equipment is mounted on movable racks in the front half of the shaft. The defective piece of equipment can be removed by pushing the equipment rack to the rear and lifting the piece to the repair area with a hoist.

The vibratory compaction apparatus is shown in Fig. 5. An air driven impact hammer is used as the compaction device.

The functions of the end-cap welding machine (Fig. 6) include evacuation of the rod, backfilling with helium, seating the end plug, and making the fusion end-closure weld.

The ultrasonic cleaning device with its attendant power supply is shown in Fig. 7. This unit fills with water, ultrasonically cleans the

rod, drains, sprays the rod with fresh water, and dries the rod in a blast of warm air. These operations are controlled from a console in the operating area.

The gamma-ray densitometer is shown in Fig. 8. The variation in compacted fuel density is measured by the attenuation of the radiation from a ^{60}Co source as it passes through the fuel bed. The beam is collimated by a $1/8 \times 3/8$ -in. slot between the source and fuel rod.

OPERATING EXPERIENCE WITH STAND-IN OXIDE

During the initial operation of the fabrication equipment with stand-in oxide [depleted $(\text{U,Th})\text{O}_2$], it soon became evident that the powder-conditioning equipment was the area of major concern. Despite efforts to contain dust within the system, an unexpectedly large quantity of oxide dust accumulated on the exterior of the equipment. Obviously, this very abrasive dust can cause excessive wear of bearing and bearing surfaces. The abrasive nature of the powder caused extensive trouble with the ball mill (Fig. 9). The requirements of the mill to be rotated about three axes simultaneously necessitated the use of several types of bearings. Extensive modifications were essential to obtain a suitable working situation. Even after apparently solving the bearing problem, other modifications were necessary because of the wearing of bearing surfaces causing extraneous material to be introduced into the fuel. Before operation, there was concern that the classifier screens might blind during operation; however, during the cold runs there was no evidence of screen blinding. The remainder of the powder-conditioning equipment has performed satisfactorily. In the complete system, a material holdup of approximately 2 kg was observed during the cold runs.

During the operation of the vibrator system, several modifications were necessary. The need to observe the feeding of the fuel into the

rod required the elimination of the dust boot over the end of the feeder trough. Although the elimination of the boot increased the dusting, it was felt that adequate feeder control could not be obtained without observing the feeding. The chuck for holding the rod was designed to utilize a slightly modified Swagelok tube coupling. This coupling uses a standard 1/2-in. pipe to 1/2-in. tube male connector with specially machined split ferrule. During the "cold" operations, failure of the Swagelok chuck was usually observed after 10 to 12 rods; therefore, it is planned to change the Swagelok tube coupling after the compaction of six rods. Also, a number of failures in the other components of the vibrator-chuck assembly are anticipated because of the extremely high levels of acceleration associated with the Branford* vibrator (reportedly as high as 20,000 to 100,000 times the acceleration due to gravity). Along with daily maintenance checks on all fasteners on the unit, spare components to the entire vibratory compaction assembly are considered absolutely essential.

In operating the vibrator, it was found that the freedom of the anvil, to which the rod to be filled is attached and upon which the pneumatic hammer impinges, is a very important factor. The anvil must be allowed to move a finite distance (in the order of 1/16 in.) to obtain the desired compaction. If the anvil is not allowed to reciprocate, a reduction in compacted density of from 8 to 10% is observed. Some difficulties were experienced with the Branford vibrator due to component failures within the vibrator unit.

*Manufactured by the Branford Co., New Britain, Connecticut.

After demonstrating the ability of the powder-preparation equipment to produce powders of three size fractions for loading into the fuel tubes, it was decided to modify the system to produce powders of a binary-size distribution. The decision to operate the system with two size fractions was based on two factors: (1) the binary system is equal to the ternary in compaction density that is attainable and (2) the binary is much easier to operate, especially with a remote system. During the cold runs, the binary-size distribution was optimized and now consists of a charge of 55% of a classified -6+16 mesh fraction and 45% of an unclassified ball mill fraction. The ball mill fraction is controlled by the weight of charge and the time spent in milling. A set of conditions was determined which would result in the most practical use of the distribution produced by the jaw crusher and which would compact to acceptable densities. The ball mill fraction has the following approximate composition:

-16+50	20%
-50+140	30%
-140+200	20%
-200+325	25%
-325	5%

With this distribution, 20 cold samples were compacted that had an average bulk density of 90% of theoretical with a deviation from rod to rod of < 1%. The density profile measured with the gamma scanner within these rods was well within the specified $\pm 2\%$ with the majority showing a deviation of < 1 1/2%. The results were most gratifying as results of this nature had not been predicted from laboratory experience. Apparently, a wider distribution range of powders can be utilized with the bottom-actuated pneumatic device used in the facility than can be used with an electromechanical

device similarly or on a beam system. The greater breakup of powder during compaction with the pneumatic device can account for this observation.

HOT OPERATION

After developing the process and equipment to the point that a sustained period of acceptable rod production with the stand-in oxide was obtained, the entire system was dismantled, cleaned, and reassembled before the introduction of the ^{233}U -bearing fuel. The initial operation with the ^{233}U fuel was not smooth as numerous difficulties again appeared. The remotely operated ball mill continued to give trouble and was replaced with one operated with gloved hands. After these initial problems were solved, the equipment performed with minimum difficulties.

The reject-rod rate during the production of the first 100 rods was 25%; this was attributed to lack of experience in the operation and process. After this initial operation, the rejection rate was greatly reduced and is presently at the tolerable figure of 3% of the production. The rejection rate is more accurately described as a reprocessing rate as neither the hardware nor the fuel is lost. When a rod is rejected, the fuel is simply emptied from the rod and the tube reloaded.

In rod production, the most difficult specification to maintain has been the $\pm 2\%$ on the density profile. The bulk density and fuel bed height specification have not accounted for a single reject. The rejects on density profile have been traced to either poor preparation of the fine fraction or failure of some component of the vibrator system. Typical traces produced by the densitometer of an acceptable and rejected rod are shown in Fig. 10. The decision to accept or reject a rod is made by comparing the extremes of the scan with the separation produced by a set of

standards which are scanned with each rod. In Fig. 10, the trace of the standards is shown to the right of the two rod traces.

Rod production has been divided into campaigns for fuel accountability and criticality considerations. At the end of each campaign, a material balance is made, the operation reviewed, and equipment alteration made, if necessary. To date, 416 acceptable fuel rods containing over 390 kg of fuel have been produced in four campaigns. A sustained production rate of 10 rods/day has been achieved over the last 100 rods with a maximum production rate of 19 rods/day being accomplished on several occasions.

SUMMARY AND CONCLUSION

Through the design, construction, and operation of the Kilorod Facility and its fabrication equipment, the practicability and economics of refabrication of $(^{233}\text{U}, \text{Th})\text{O}_2$ -bearing fuel rods are being assessed. Although a complete assessment of the facility cannot be made at this time because production is still in progress, the operation of the facility has proven the feasibility of a bulk oxide vibratory compaction method of fuel element fabrication. Using a binary powder-preparation system developed in the facility in conjunction with a pneumatic-type vibrator, it has been shown that 100% of the fuel produced can be utilized in the fabrication of acceptable fuel rods.

The following conclusions have been made based on the operating experience gained at approximately the half-way point in the project:

1. The engineering feasibility of the vibratory compaction method for producing oxide-filled rods has been proven.
2. Rods of $(90 \pm 2)\%$ of theoretical density, of $\pm 2\%$ or less variation

along the long axis, and of 42 ft $\pm$ 1 in. fuel bed height have been routinely produced.

3. A method of producing a fine fraction by control of operating parameters has been devised and proven.

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2. J. D. Sease, A. L. Lotts, and F. C. Davis, Thorium- ^{233}U Oxide (Kilorod) Facility — Rod Fabrication Process and Equipment, ORNL-3539 (April 1964).

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WELDING CHAMBER

TORCH

END PLUG PRESS

ELEVATOR