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DESIGN OF A REMOTE SYSTEM FOR FABRICATION
OF (Th-²³³U)O₂ METAL-CLAD FUEL ELEMENTS*†

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ABSTRACT

ILLEGIBLE

A major portion of the design of a remote fabrication system for fabricating metal-clad oxide-containing fuel elements by the bulk oxide, vibratory compaction, mechanical assembly route has been completed at ORNL. The process equipment was designed to operate on a pilot-plant scale of 40 rods per 8-hr shift in the heavily shielded Thorium-Uranium Recycle Facility. The major objective was to establish economics and unit processing times that would be amenable to a full-scale production plant. The design approach, the equipment layout in the cell, and a description of each piece of process equipment are given.

INTRODUCTION

One of the principal problems in nuclear technology yet to be solved is that of demonstrating technically feasible and economical refabrication processes for fuel elements containing bred fuel from converter and breeder reactors. The primary problem is that such fuels require that the operators be protected from penetrating radiation during the refabrication process.¹

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This fact alone introduces major questions concerning accurate prediction of economics and technical feasibility. Obviously we must at least have experience in such operations on a suitable pilot scale.

In our Thorium Utilization Program at ORNL, we are developing methods by which we can define economical refabrication procedures. The initial task assignment was to demonstrate the feasibility of remotely fabricating metal-clad (Th-²³³U)O₂ fuel elements, primarily for water-cooled reactors. During the development of the equipment design for this task, a comprehensive study² of advanced converters conducted at ORNL indicated that such reactors were not the most attractive type for utilizing thorium in an advanced converter program. Accordingly the direction of our development has changed. However, at that point we had completed a major portion of the design of a remote fabrication system for the metal-clad fuel elements. Even though this particular system will not be constructed immediately, we believe that the concepts and ideas can be applied to similar fuels, from other fuel cycles and reactor types, or to similar remote processing problems. Accordingly, we shall discuss the criteria, design, and development of the process and equipment for remote refabrication of metal-clad oxide-bearing fuel elements.

Many of these design principles are currently being used in the development of our equipment design for fabricating fueled-graphite fuel elements for an HTGR.³

THORIUM-URANIUM RECYCLE FACILITY

The process and equipment design criteria were affected by the features of the Thorium-Uranium Recycle Facility (TURF), in which the demonstration

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was to occur. Briefly, this is a pilot-scale development laboratory, now being completed and having heavily shielded cells for carrying out all phases of a fuel cycle. The facility can accommodate integrated recycle processes with equipment scaled down from production-plant sizes to provide realistic and reliable basis for technical and economical analysis.

The facility, which is an irregularly shaped three-story building approximately 162 ft long $\times$ 124 ft wide, contains five shielded cells and associated gloved maintenance room and air lock. A pictorial cutaway of the cell bank is shown in Fig. 1. The four operating cells (mechanical processing, chemical processing, contaminated fabrication, and clean fabrication) are shielded by an equivalent of 5 1/2 ft of normal concrete up to the electromechanical manipulator bridge level and 4 1/2 ft of concrete above this level. The rod fabrication operations will be contained in approximately one-half of the contamination and clean fabrication cells. These cells have inside dimensions of 20 $\times$ 41 $\times$ 24 ft and 16 $\times$ 20 $\times$ 30 ft, respectively. A more detailed description of the facility was presented at last year's conference.⁴

THE PROCESS

The process selected for making the rod-type fuel elements was based on our Kilorod experience.⁵ The steps are (1) sizing of the sol-gel oxide,⁶ (2) vibratory compaction of fuel rods, (3) fuel-rod end-cap welding and inspection, (4) fuel rod decontamination, (5) assembly of fuel rods into fuel elements, and (6) final inspection. A detailed flow diagram is shown in Fig. 2.

In the process, bulk oxide produced by the sol-gel process in the adjacent cell first is sized and separated into size fractions by a system of crushing, grinding, and classification as required for vibratory packing. For equipment-design purposes, we assumed that a combination of three particle sizes of the bulk oxide would be vibratorily packed. Following comminution and classification, fuel for one fuel rod loading is dispensed into a blend-transfer device, which simultaneously blends and conveys the fuel to the vibratory-compaction apparatus, where it is packed into fuel tubes.

Following compaction, each fuel rod is weighed, and the axial density variation of the column of compacted fuel is measured with a gamma-ray-absorption scanner. Next, the fuel rod is capped, the cap is fusion welded to the fuel tube, and the fuel rod is moved to the decontamination apparatus. This apparatus also serves as a transfer device for moving the rod from the powder-preparation and rod-fabrication area (contaminated fabrication cell) to the inspection and fuel-element-assembly area (clean fabrication cell).

In the clean fabrication cell, the rods are checked immediately for contamination. Then the end-cap welds are inspected, and the rods are tested for dimensional conformity. The final steps are the mechanical assembly of the fuel rods into prepared assemblies and final fuel element inspection.

DESIGN APPROACH

The criteria for the equipment was that it be versatile, capable of accommodating fuel rods 2 to 10 ft long and 1/4 to 3/4 in. in diameter, and with a production capacity of 35 kg oxide per 8-hr shift. Adaptability to the wide dimensional variation of rods was to be achieved by minor adjustments of

components if the unit processing time was not sacrificed for versatility and the cost of construction was not appreciably increased. The design of equipment units with minimum cycle time for a process operation was the overriding consideration, as our major objective for the line was to establish a unit processing time that would be amenable to a full-scale production plant. As a basis for design, we selected a fuel rod that was 0.450 in. OD and 72 in. long assembled mechanically into a 5- x 5-rod array to form an element. Using these assumptions and the 35 kg/shift capacity, a production rate of 40 rods per 8-hr shift was established.

The layout of the fabrication equipment was divided into contaminated and clean zones according to the degree of contamination that is expected from the operations. Each item of equipment located in the contaminated fabrication cell was designed as a module capable of being remotely installed, maintained, and removed by the cell remote-handling system. In addition, each module was made up of subassemblies so that motors, switches, and complex mechanical components, which are susceptible to wear, damage, or failure would be replaceable with a minimum of effort and without removal of the entire module. Each subassembly was designed to be dismantled as easily as possible to further facilitate repair when the subassembly reaches the gloved maintenance area.

The capability of contact maintenance in the clean fabrication cell somewhat lessened the design problem for its process equipment. However, the general inaccessibility of the cell and the need to shield radiation sources during contact maintenance required equipment similar to the contaminated fabrication equipment to minimize maintenance time.

We used mild steel or aluminum extensively to minimize costs. Stainless steel was used only for parts in direct contact with the fuel or where corrosive liquids or atmospheres dictated its use. Elastomers and organic materials were used only where absolutely necessary and then with provisions for easy replacement.

One of the principal problems involved in remote fabrication is that of the transfer of materials between steps in the process. At the start we recognized that special handling systems would be required to precisely locate and quickly transfer the article being fabricated from one operation to the next. Our analysis showed that if the general manipulation provided in the cell complex were used for transfer, the degree of utilization of the process equipment would be extremely low; that is, the principal bottleneck in the process would be the general purpose manipulators. Therefore, the bulk solid material is transferred from one step to the next by gravity flow through pipes or by enclosed powder conveyors, and fuel rods or other large components are transferred between steps with special transfer machines.

The general control criterion for the oxide line was that all operations, as far as practicable, should be designed with closed-loop control circuits. This was stipulated so that we could be assured that any operation that was initiated actually occurred. The simplest type of closed-loop system is a motor circuit with a limit switch. Open-loop devices, such as stepping motor circuits or timed actuators, can cause an operation to occur out of sequence by erroneously indicating externally that an operation has occurred when, in fact, it has not. An integrated automatic sequence control of each process station, the transfer device, and central data collection was stipulated.

PROCESS EQUIPMENT

Plan and sectional views of the equipment for oxide fabrication are shown in Fig. 3. The equipment is laid out in modules so that each station is a separate unit completely independent of other items.

The contaminated fabrication cell contains 25 major equipment items for two principal types of operations: powder preparation and rod fabrication and inspection.

Powder-Preparation Equipment

In the powder-preparation equipment, bulk oxide is crushed and ground, classified, and dispensed in a form suitable for loading a fuel tube. Since the oxide is dry, a severe contamination problem is present. Therefore, the powder-preparation equipment was designed insofar as practicable to contain the dust. However, absolute dust containment, as experience has shown in the Kilorod Program,⁵ is extremely difficult. A detailed layout of the powder-preparation equipment is shown in Fig. 4. The bulk oxide is crushed and ground by two disk pulverizers. These pulverizers use two opposing disks - one stationary and the other rotating at approximately 1700 rpm. The amount of particle reduction is a function of the separation of the disks. The disk pulverizers were selected because the amount of comminution can be easily controlled remotely, the material holdup is minimal, and the "tramp" contamination from Al_2O_3 disks is less than from a comparable ball-milling operation. The disk crushers can process sol-gel $(Th,U)O_2$ shards at a rate of approximately 60 kg/hr at a coarse setting (approximately 0.100-in. disk separation) and 10 to 20 kg/hr at a fine setting (0.005-in. disk separation).

Two 18-in. vibratory-type classifiers are used. The powders in the process are conveyed by gravity, vibratory powder-elevation mechanisms, and vibratory trough feeders as appropriate. Vibratory feeders have also been used to eliminate sliding valves. Hoses made with polyurethane rubber and fitted with specially designed permanent magnet quick disconnects are used to transfer powder between units. The use of elastomer hoses to transfer powder is a departure from our general criteria; however, the large amount of movement associated with the operation of the vibratory classifiers and elevators and the difficulty of remotely connecting and disconnecting metal pipes justified the use of the hoses. In the maximum radiation environment of 10^4 r/hr anticipated in TURF, the hoses have a life expectancy of greater than 1 year based on the 10^8 r/hr integrated dose tolerance of polyurethane.

The process is controlled by weighed hoppers and flow-indicating devices used to monitor the powder flow at various places in the processes. The rate of material flow to the crushers and classifiers is controlled by monitoring the rate of weight loss from the feed hopper. The comminution and classifying equipment is operated on a batch basis.

The quantity of each size fraction required for one rod loading is dispensed by an automatic batch-weigher. This device employs a flexure-pivot spring-type balance with a differential-transformer remote readout and is capable of weighing out three increments of powder simultaneously. The quantity of each powder increment making up a rod batch loading can be varied remotely within wide limits. After the batch composition for one rod loading is obtained, the fuel is emptied into a blending container on the blend-transfer device, which simultaneously blends and transfers the powder to

the vibratory compactor. The unique design principles of this unit are discussed in another paper at this conference.⁷

Fabrication and Inspection

Following powder preparation, the other equipment items in the contaminated fabrication cell consist of a series of processing stations with a common transfer device used to convey the rods between the stations. All of the processing stations have an integral means of interchanging a rod with the transfer device. The vibratory compactor and the gamma-scanning stations must be capable of processing two rods simultaneously to meet the production requirement of 40 rods per 8-hr shift.

The controls for the fabrication and inspection equipment consist of individual station controls that automatically sequence the equipment by solid-state logic circuitry and a master controller that initiates the operation of individual stations, controls the operation of transfer devices, and serves as the central data collector.

The tube-transfer machine, which operates on a track running the length of the cell, shuttles rods between the processing stations. The functional part of the device consists of two arms, which operate alternately in interchanging rods at each processing station, and is mounted on a carriage that travels the length of the cell. The operation of the tube-transfer machine is illustrated in Fig. 5, which shows the operating times of processing stations superimposed in the path of the transfer machine in the contaminated fabrication cell. The dotted lines indicate alternate paths of the transfer device if a rod is rejected during processing. The transfer device,

which is controlled on a demand basis by solid-state logic circuitry, is positioned at each station by a closed-loop servomechanism.

Fuel is introduced into the fuel tube and compacted on the vibratory compactor with a bottom-actuated pneumatic-vibrator system. The compactor⁸ consists of two single-rod compaction units mounted on a common frame. Each single-unit compactor has three principal components: (1) the rod receiver, which accepts a rod from the tube-transfer machine; (2) the filling mechanism, which obtains fuel from the fuel-transfer device and then feeds the fuel into the fuel tube; and (3) the chuck, which grasps the fuel rod and transmits the compaction force to the fuel rod.

The check weigher serves as a final check on the operation of the batch-weighing machine and is used in computing the material balance for the process. The check weigher has a weighing head, a tube receiver, and a supporting framework. The weighing head is a commercial flexure pivot scale with a differential transformer for remote readout. The rod is weighed suspended vertically.

After compaction and check weighing, the loaded fuel rod is moved to a gamma-absorption scanning device,⁹ where the axial density variation of the filled rod is determined. The gamma scanner is capable of detecting a 2% density variation over a 3/8-in. interval of rod length. The gamma scanner is designed to independently receive and scan two fuel rods in a vertical attitude. Each side of the scanner has a collimated gamma beam, a NaI detection crystal, and a means of moving the rod through the gamma beam. Present data indicate that the gamma source should be ⁶⁰Co for scanning 1/2- to 3/4-in.-diam fuel rods and ¹³⁷Cs for scanning 1/4- to 1/2-in.-diam fuel rods.

The capping machine consists of a wire brushing device for cleaning the weld area, another device for inserting the end caps and accessories into the fuel tube, and a vacuum chamber for evacuating and backfilling the tube with helium. The vacuum chamber also contains a press mechanism for seating the end cap in the fuel tube after backfilling it. The equipment at this station has a minimum cycle time on the order of 5 min.

After the end cap is inserted, the rod is moved to the welding station, where the end caps are fusion welded by the tungsten inert-gas process. The welding device consists primarily of a "chill block" rotating mechanism, a torch-positioning mechanism, and an integral means of receiving a rod from the tube-transfer device and inserting the rod in the rotating mechanism. The welding electrode is positioned with a commercially available automatic welding head. Welding electrodes are changed by means of a quick-change welding torch. The welding unit is capable of speeds up to 20 in./min and has a cycle time on the order of 30 sec.

The closure welds are checked for leak-tightness by a mass-spectrometer leak detector. This system includes a vacuum chamber, in which the end of the fuel rod is inserted, and a conventional helium-leak-detector system. The design sensitivity of this system is 1×10^{-10} std cm³/sec.

New fuel tubes are introduced in fabrication lines in the fuel tube magazine. This magazine, which is loaded with empty tubes in the gloved maintenance area, holds 40 tubes. The device consists of the magazine, an indexing unit, and a support stand.

Completed acceptable fuel rods are collected at the end of the contaminated fabrication process in a magazine that later serves as a cleaning basket in the cleaner-transfer device. This station consists of a magazine, which holds 10 fuel rods, and an indexer for positioning the basket to receive rods from the tube-transfer device. Mechanically the reject-rod magazine is identical and is used to store rods rejected in the process.

The cleaner-transfer unit, which is located in the wall between the contaminated and clean fabrication cells, cleans particulate matter from the external surfaces of the fuel rods and serves as an air lock between the two cells. The device incorporates an ultrasonic cleaning bath and a mechanism for transferring the cleaned rods into the clean fabrication cell. Cell cranes are used to transfer rod magazines into and out of this unit.

Clean Fabrication Equipment

The equipment in the clean fabrication cell also consists of a series of individual process stations with a common transfer device. The transfer device is identical to the one located in the contaminated fabrication cell.

There are four major process stations in the clean fabrication cell:

- (1) alpha monitor, (2) weld radiograph, (3) dimensional inspection, and
- (4) fuel element assembly and inspection.

The fuel rods, immediately upon entry to the clean fabrication cell, are tested for surface contamination by means of an alpha monitor. The monitor consists of a series of ZnS phosphor probes with appropriate readout instruments and a means of positioning and rotating a fuel rod in front of the probes.

The alpha monitor can measure a contamination level of 400 dis/min per foot of rod, and a 5-min scan is required to obtain a confidence level of 95%. Preliminary tests and calculation on the ZnS probes indicate that 73% of the alpha activity present can be discriminated in the presence of a 24 r/hr ^{60}Co gamma source, and the presence of a neutron intensity of 3×10^3 neutrons/sec over the detector area will produce an error of no more than 10%.

The quality of the end-cap weld is evaluated by radiographic inspection; an x-ray source coupled with an x-ray-sensitive television camera is used. A fuel tube in correct position is rotated 360° while being scanned. The unit, which can detect defects as small as 0.002 in., inspects for weld porosity, voids, and inclusions.

In the dimensional inspection station, the fuel-rod bow, diameter, and length are measured. The measuring device consists of a tube receiver, which accepts the fuel rod, and a series of linear differential transformer probes mounted on a carriage.

A single device is used for fuel element assembly and inspection. This unit provides jigs for the assembly of a complete fuel element and also is equipped to carry out dimensional inspection of the finished element. Fuel rods are inserted into a preassembled lattice by the electromechanical manipulator. When the bundle has received its full complement of fuel rods, the top end fitting is positioned by the electromechanical manipulator and mechanically attached to the bundle. The rod-to-rod spacing is measured with eddy-current probes.¹⁰

The assembled fuel element will then be withdrawn from the clean fabrication cell through the port into a shielded shipping cask.

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FIGURES

Fig. 1 (ORNL-DWG 64-5605R) Cell Bank in TURF.

Fig. 2 (ORNL-DWG 65-9952) Flowsheet for Fabrication of Metal-Clad Oxide Fuel Bundles in TURF.

Fig. 3 (ORNL-DWG 66-4216 R1) Plan and Sectional Views of Oxide-Fabrication Equipment Designed for Operation in the TURF.

Fig. 4 (ORNL-DWG 66-6759) Detailed Layout of Powder-Preparation Equipment in Line for Fabrication of Metal-Clad Oxide.

Fig. 5 (ORNL-DWG 66-4215 R1) Operating Times of Processing Stations Superimposed on the Path of the Tube-Transfer Machine in a Portion of the Oxide-Fabrication Line.

Fig. 1 (ORNL-DWG 64-5605 R) Cell Bank in TURF - J. D. Sease, Design of Remote System ...

Fig. 2 (ORNL-DWG 65-9952) Flowsheet for Fabrication of Metal-Clad Oxide

Fuel Bundles in TURF - J. D. Sease, Design of Remote System ...

1 POWDER PREPARATION EQUIP.	10. REJECT RACK
2 FUEL TRANSFER MACHINE	11 CLEANING AND TRANSFER BASKET
3 VIBRATORY COMPACTOR	12 FUEL ROD TRANSFER MACHINE
4 TUBE MAGAZINE	13. CLEANER TRANSFER MACHINE
5 CHECK WEIGHER	14. FUEL ROD BASKET
6. GAMMA SCANNER	15. CONTAMINATION MONITOR
7. CAPPING MACHINE	16. WELD RADIOGRAPHY MACHINE
8 WELDING MACHINE	17 FUEL ROD DIMENSIONAL CHECK
9 LEAK CHECK MACHINE	18 FUEL ELEMENT ASSEMBLY AND INSPECTION MACHINE

Fig. 3 (ORNL-DWG 66-4216 R1) Plan and Sectional Views of Oxide-Fabrication

Equipment Designed for Operation in the TURF - J. D. Sease, Design of Remote System ..

Fig. 4 (ORNL-DWG 66-6759) Detailed Layout of Powder-Preparation Equipment
in Line for Fabrication of Metal-Clad Oxide - J. D. Sease, Design of Remote System

Fig. 5 (ORNL-DWG 66-4215 R1) Operating Times of Processing Stations Superimposed on the Path of the Tube-Transfer Machine in a Portion of the Oxide-Fabrication Line - J. D. Sease, Design of Remote System ...