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THE REMOTE REFABRICATION OF REACTOR FUELS^(a)

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SUMMARY

Interest in reactor fuel cycles has been stimulated by the realization that the fertile isotopes U^{238} and Th^{232} must ultimately be the main source of nuclear power. These isotopes can be used by converting them to Pu^{239} and U^{233} in nuclear reactors and recycling the products into the power reactor system.

Recycle of fuel creates new problems for fabricators. Highly irradiated or multiply recirculated plutonium contains large percentages of Pu^{240} , Pu^{241} and Pu^{242} . The uranium produced in the $Th-U^{233}$ cycle contains small quantities of U^{232} while the thorium constituent builds in Th^{228} and Th^{234} . The decay chains of these parasitically produced isotopes result in surface dose rates of radiation that preclude extensive glovebox or contact operations, and such fuels must be fabricated by remote or semiremote methods.

There are three fuel cycles under extensive development in the U.S.A.: (1) plutonium recycle in thermal converter reactors, (2) the thorium- U^{233} cycle for both thermal converter and breeder reactors, and (3) plutonium recycle in fast breeder reactors. Work on the thermal

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converter fuel cycle is actively being carried on by Hanford Laboratories using $\text{UO}_2\text{-PuO}_2$ fuels from the Plutonium Recycle Test Reactor (PRTR). Oak Ridge National Laboratory is demonstrating the technical feasibility of processing and fabricating $\text{U}^{233}\text{O}_2\text{-ThO}_2$ and $\text{U}^{233}\text{C}_2\text{-ThC}_2$ fuels. Argonne National Laboratory has developed processes and facilities for fast reactor fuel cycling and is presently demonstrating the recycle of metallic fuel from the Experimental Breeder Reactor II (EBR-II). Fast reactors are little affected by relatively large concentrations of fission products, and the EBR-II work features a simple pyrometallurgical process that eliminates only part of the fission products.

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These three cycles typify remote refabrication of fuels at three different levels of radioactivity; (1) relatively low radiation level fabrication of solvent-extracted plutonium from thermal reactor recycle, (2) intermediate radiation level and remote refabrication in the case of the U^{233} thorium fuels, but semiremote maintenance of equipment and facilities, and (3) very high radiation levels in the case of EBR-II^{ies} fuel with ^{and partially decontaminated} PRTR completely remote operation, maintenance and replacement of equipment.

The first section of this chapter outlines the purposes, problems and principals of remote fabrication. Section two covers the semiremote and remote fabrication and remote inspection, rejuvenation and repair of PRTR fuels at Hanford. The third section describes the processing and fabrication of intermediate radiation level thorium- U^{233} fuel. The pyrometallurgical processing and refabrication of EBR-II fuel are described in section four. The final section covers plans for the fabrication of target elements for High Flux Isotope Reactor (HFIR).

SECTION I

PURPOSES, PROBLEMS AND PRINCIPALS OF REMOTE FABRICATION

A society ultimately dependent upon nuclear power should achieve the efficient use of its total nuclear energy reserves. Single-pass fueling of reactors consumes only part of the fissile content of the fuel and is inefficient. Recovery and refabrication of the fissile elements from the fuel is required even by short-term economics. In order to use nuclear resources efficiently, the abundant fertile isotopes U^{238} and Th^{232} should be utilized in addition to the less abundant U^{235} ; this can be done in nuclear reactors. Both the fertile and fissile materials can be reclaimed from the irradiated fuels. Recognition of these facts has stimulated interest in fuel cycle systems that reprocess irradiated fuels, recover the fertile and fissile materials and refabricate them into fuel elements for return to the reactors.

The naturally occurring fissile isotope, U^{235} , accounts for only a small part of our potential nuclear reserve. The naturally occurring isotopes, U^{238} and Th^{232} , can be converted into the fissile isotopes, Pu^{239} and U^{233} , in converter and breeder reactors. Theoretically, fast breeder reactors can produce as much as 1.9 times as much plutonium as they burn⁽¹⁾. Breeding rates of 1.4 to 1.6 appear to be more immediately practical. The conversion rates of thermal reactors fueled with uranium or plutonium are limited to 0.4 to 0.6 of the fuel burned⁽²⁾. It seems likely that the capital cost of the breeder reactor per megawatt of

power will remain considerably greater than that of the thermal reactor. Furthermore, justification for high-conversion-rate breeders depends upon the continuing market for plutonium. It, therefore, is logical to predict an economy in which the excess plutonium produced in fast breeder reactors makes up the deficiency in conversion from thermal reactors.

The second system of interest is the $\text{Th}^{232}\text{-U}^{233}$ system. The high η^* value of U^{233} in the thermal and epithermal regions is the principal advantage of the $\text{Th}^{232}\text{-U}^{233}$ cycle. Kasten⁽³⁾ has observed that U^{233} permits a higher conversion ratio than either U^{235} or Pu^{239} for a fuel of given enrichment. If structural materials of low neutron cross section are used and the fission product accumulation is limited, the $\text{Th}^{232}\text{-U}^{233}$ cycle shows promise of breeding in thermal reactors as well as in fast reactors.

The real potential of the power reactor fuel cycles depends upon the development of economic methods for recovering and refabricating the irradiated fuel. In both fuel cycles an equilibrium will be established between the newly generated fissile isotope and highly irradiated thorium or uranium-plutonium alloys. In the $\text{U}^{238}\text{-Pu}^{239}$ fuel cycle, the composition can vary from nearly pure Pu^{239} to plutonium containing 40 percent or more of Pu^{240} , Pu^{241} and Pu^{242} at irradiation levels of approximately 50,000 megawatt days per ton⁽⁴⁾.

Aqueous decontamination processes are used in most of the fuel recycle schemes employed today. These reduce radioactivity from the

* η - neutrons emitted per neutron absorbed

fission products to very low levels. Glovebox refabrication of the decontaminated plutonium fuel is practical with low and moderately irradiated fuels. The multiple recycle of the fuel will increase the concentration of higher isotopes of plutonium and uranium. This in turn effects sharply increased levels of radiation in the decontaminated fuel. Remote refabrication will ^{may} ~~probably~~ be necessary for such fuels even though the fission products are completely eliminated. ~~This is a factor which makes~~
~~In this case, it appears likely that~~ lower-cost nonaqueous fuel processing will ^{more} ~~become~~ attractive. These processes do not remove all of the fission products and the fuel will consequently have much higher gamma radiation intensities than the completely decontaminated fuel.

Radiological Hazards

The methods by which power reactor fuels can be refabricated depend upon the intensities of alpha, beta, X-ray, gamma and neutron radiation associated with the fuel. Handling limitations are imposed in each case. If alpha contamination alone occurs, protection must be provided to personnel against air contamination and direct contact. This is usually accomplished by tight glovebox systems with ventilation control. Exposure to hands may be too great for glovebox operation due to high surface-dose rates from beta particles, soft X rays and gamma rays, or neutrons. Local shielding and semiremote or mechanical handling within gloveboxes can, in some instances, reduce contact exposure to permissible limits. At still higher intensities of X rays and gamma rays and neutrons, thick shielding and remote handling techniques must be employed.

There are three sources of penetrating radiation associated with highly irradiated plutonium. Neutrons are generated by the spontaneous fission of Pu^{238} , Pu^{240} and Pu^{242} and from the (α, n) reaction with light elements. X rays and low-energy gamma rays are emitted from U^{237} and from Am^{241} , which build into the fuel from the decay of Pu^{241} . Hard gamma rays from residual fission products may also present a significant hazard even in chemically decontaminated fuels.

The half-life of Pu^{241} is 13 years. A small percentage transforms to U^{237} by alpha decay. A second source of U^{237} in irradiated fuels is $(n, 2n)$ reaction with U^{238} . The U^{237} has a half life of 6.7 days and reaches equilibrium in the plutonium in about 20 days. It beta decays to Np^{237} yielding a gamma-ray plus X-ray spectrum ranging from 33 Kev to 371 Kev. Over 99 percent of the Pu^{241} decay events produce Am^{241} . The half-life of Am^{241} is 460 years and it continues to build into fuel containing Pu^{241} . The gamma radiation from this source exceeds that of the U^{237} in about 120 days. Am^{241} decays to Np^{237} producing a broad spectrum of gamma and X rays ranging from 99.0 Kev to 17.7 Kev. The build up of hard radiation in highly exposed plutonium fuel is an incentive to fabricate as soon after processing as possible.

A similar situation exists with the Th^{233} fuel. Unshielded gloveboxes can be employed in the fabrication of U^{233} only if the concentration of U^{232} is very low. In practical recycle fuels containing U^{232} , local shielding and semiremote fabrication is possible only if

complete fabrication can be accomplished in about two weeks after chemical purification. If the U^{233} contains more than 200 ppm U^{232} or residual fission products, remote refabrication in a shielded facility is necessary.

The chief source of radioactivity from U^{233} after Thorex processing of thorium-uranium fuels is the decayed products of U^{232} . The decay chain produces both energetic gamma rays and neutrons from the (α, n) reaction with light elements. The main production of U^{232} is initiated by the $(n, 2n)$ reaction with Th^{232} . This reaction is as follows:

Arnold has noted that both the amount and the ratio of U^{232} to U^{233} increase with the increasing neutron flux and irradiation time⁽⁵⁾. The ratio of U^{232} is also highly dependent upon the neutron energy distribution in the reactor, since only neutrons with energies above 6.37 Mev produce the $(n, 2n)$ reaction. The U^{232} has the following decay chain:

Neutron Emission

Neutron emission from recycled reactor fuels is derived from two sources: (1) the (α, n) reaction with light elements and from (2) spontaneous fission. Energetic alpha particles from all uranium and plutonium isotopes and from Am^{241} and Np^{237} react with light elements, which may be present as alloys, chemical compounds or impurities. These reactions may yield neutron fluxes of sufficient intensities to require radiological protection. Plutonium isotopes in the even mass number also yield neutrons by spontaneous fission. The neutron yields from fission and from the (α, n) reaction in fluorides and oxides are shown in Table I from data compiled by Steindler⁽⁶⁾.

In many operations the concentration of Pu^{238} is normally so low that it can be neglected; but the (α, n) neutron flux has forced the mechanization and semiremote operation of large-scale plutonium-fluoride operations, even with quickly generated materials. Less specific data are available on the (α, n) flux from aged fuels containing relatively

TABLE I

Neutron Emission/Gram of U or Pu per Second

Isotope	Fission	Compound	
		-O ₂	-F ₄
U ²³²	---	1.86×10^4	1.86×10^6
U ²³³	---	5.9	4.2×10^2
U ²³⁵	---	1.04×10^{-3}	3.8×10^{-2}
U ²³⁸	---	1.48×10^{-4}	5.9×10^{-3}
Pu ²³⁸	3.4×10^3	1.4×10^4	2.1×10^6
Pu ²³⁹	0.02	45	4.3×10^3
Pu ²⁴⁰	1.0×10^3	170	1.6×10^4
Pu ²⁴²	1.7×10^3	2.7	1.7×10^2

large amounts of Am^{241} and Np^{239} . The very high specific alpha activity of these elements would lead to the conclusion that they would produce very high (α, n) neutron dose rates.

Americium, curium and the transamericium elements are presently of interest as radioactive heat and neutron sources. Several isotopes of curium, berkelium and californium have very short spontaneous fission half lives. They emit large quantities of neutrons, which add to the problems of processing the transplutonium target material.

Nichols⁽⁷⁾ and his coworkers have calculated the expected neutron activation of concrete walls, windows, manipulators and process equipment inside the cells of the Transuranium Processing Facility at the Oak Ridge National Laboratory. The probable source was of the order of 3×10^{12} neutrons/sec. These calculations predicted that the surface gamma dose rate on the various items will be less than 1 rem/hr after decay of ten days. They conclude that these levels of activation are tolerable since they do not prohibit removal of decontaminated process equipment from the cells or limited access of personnel to decontaminated cells.

Radiation Protection

Essentially all the fission products, americium, curium and U^{237} , are removed from weapons-grade plutonium by the solvent-extraction process. The product, which contains more than 90 percent Pu^{239} , is normally fabricated in gloveboxes by contact methods. Shielding is usually applied locally to those gloveboxes where radiological monitoring indicates that the radiation levels approach permissible limits. Similar techniques have been applied to limit exposure in laboratory or pilot operations on plutonium containing up to 25 percent $Pu^{240} + Pu^{241}$. The increased radiation and neutron dose rates require close surveillance and rotation of personnel as required to limit personnel exposure.

Much higher dose rates result for large-scale fabrication of solvent-extracted recycle plutonium, which will contain in excess of 40 percent Pu^{240} , Pu^{241} and Pu^{242} . Local shielding and leaded gloves do not offer sufficient protection from high-energy gamma and neutron radiation associated with recycle fuels. Although complete fission-product separation is achieved, semiremote or remote fabrication of these fuels appears to be necessary, *desirable in some cases.*

A similar situation exists in the thorium- U^{233} fuel cycle. Glovebox fabrication is practical only if the concentration of U^{232} in the U^{233} is very low. In recycle fuels containing U^{232} , local shielding and semiremote fabrication is permissible only if the operations can be completed within two weeks of chemical purification.

If the U^{233} contains more than 200 ppm of U^{232} or residual fission products, remote refabrication in shielded process cells becomes necessary. In the thorium- U^{233} cycle, the increase in radiation from recycled thorium is due to the increase in Th^{228} and Th^{234} . Arnold⁽⁵⁾ has given data indicating that such reprocessed thorium will require fabrication in shielded cells.

It becomes apparent that for each practical power-reactor fuel—plutonium, U^{233} and the fertile thorium—^{a degree of} remote fabrication will be necessary where fuels are subject to high burnup or multiple recycle. This will be true even for fuels from which fission products have been completely separated.

What will be the penalty, then, for using a less expensive process that removes only part of the fission product? The principal disadvantage appears to be the transition from comparatively low-level radiation-shielded operation to high-gamma-level operations. This increases the problems of radiation protection and process manipulation and introduces the factors of radiation heating and radiation damage to equipment.

From the reactor physics standpoint, the fission products are parasitic neutron absorbers. In fast reactors the parasitic effect may be relatively small and require only a small increase in the fuel enrichment. In thermal reactors the fission product accumulation must be held to rather low levels.

Fission Product Radioactivity

The difficulties and cost of complete decontamination of reactor fuels increases with the concentration of radioactive fission products. The radioactivity of discharged reactor fuels is usually reduced by allowing time for the short-lived fission products to decay. For short-cycle power-reactor fuels, this practice results in excessive inventory charges for the nonproductive fuel. Aqueous decontamination of enriched fast reactor fuels becomes particularly costly when small-batch or safe-geometry limitations are imposed by nuclear-criticality control. Recognition of these facts, and a growing awareness that recycle fuels may require remote fabrication, has prompted an interest in nonaqueous fuel processing.

Burris and Dillon⁽⁸⁾ have estimated the fission-product spectra from fast reactor fuels irradiated with one Mev neutrons for periods varying from ten days to 1000 days and cooled from zero days to ten years. A fuel discharged at two percent burnup during 135 days of irradiation and cooled for 15 days is estimated to have a (gamma + beta) radioactivity of about 45 curies per gram. Approximately two-thirds of the radioactivity comes from gammas of over 0.75 Mev energy. The nonaqueous processing of this fuel reduces the radioactivity of the fuel to approximately 15 curies per gram. The radioactivity of this fuel may increase somewhat as the fuel is recycled due to the build up of long-lived fission products. This will be discussed in greater detail under the EBR-II fuel cycle.

An analysis was made to predict levels of gamma radiation during reprocessing and refabrication of 10 Kg batches of the above fuel⁽⁹⁾. Radiation levels were calculated for a number of fuel configurations and process conditions. A plot was made on the floor plan of the EBR-II Fuel Cycle Facility showing radiation levels vs. distance from the multiple sources. This plot, shown in Figure 1, indicates radiation levels from less than 10^4 R/hr some distance from the process material, to over 5×10^6 R/hr at approximately one foot from the melt refining crucible. At these levels of radiation the 3:1 decontamination factor makes little difference in required shielding. Shielding requirements depend in part on isotopic content, degree of decontamination and cooling time.

Variations in shielding requirements for irradiated PRTR fuel are shown in Tables II and III. A PRTR 19-rod cluster containing approximately 110 pounds of $1w/o\text{-PuO}_2\text{-UO}_2$ irradiated to 10,000 Mwd/ton is used as a model. The criteria for shielding assumes that, under normal operating conditions, the maximum dose rate at any routinely occupied location normally should not exceed 0.2 mrem/hr.

The shielding calculations for the model fuel element assume that this element is placed two feet from the cell wall and that the operator routinely stands one foot from the cell wall.

With respect to isotopic content, the gamma and X-ray exposure rate from 5 Kg of plutonium of the following composition will

TABLE IIVariation in Shielding Requirements with Cooling TimeModel PRTR Fuel Element

<u>Cooling Time (Days)</u>	<u>Shielding Requirement 18.5 te/m³ (235 lbs/cu ft) Concrete Thickness</u>	
	<u>cm</u>	<u>Inches</u>
0	132	52
15	130	51
30	124	49
365	86	34

TABLE IIIVariation in Shielding Requirementswith Decontamination FactorModel PRTR Fuel ElementCooled 30 Days

<u>Decontamination Factor</u>	<u>Shielding Requirement 18.5 te/m³ (235 lbs/cu ft) Concrete Thickness</u>	
	<u>cm</u>	<u>Inches</u>
3	114	45
10	104	41
30	97	38
100	86	34

be approximately 4 rad/hr. at the surface: Pu^{239} - 55.5%, Pu^{240} - 25.1%, Pu^{241} - 12.1%, and Pu^{242} - 7.3%. The amount of lead required to reduce 4 rad/hr to 0.2 mrad/hr is 3/8 of an inch. However, the neutron exposure rate from 5 Kg of the same material shielded by 3/8 inch of lead is approximately 10 mrem/hr. To reduce the neutron exposure rate to 0.2 mrem/hr would require approximately 18 inches of lead. A better neutron absorber should therefore be considered in such circumstances.

Additional factors of radiological protection in high-level process cells include possible window damage, fire hazards and effects of dispersed process dusts. Where windows are exposed to gamma dose rates in excess of 10^4 R/hr, darkening takes place in cerium stabilized glasses at predictable rates. Recently the problem of internal electrical discharge in windows has been analyzed⁽¹⁰⁾. In both cases damage occurs within the first few inches of thickness in which radiation is absorbed. If the exposed slab is made replaceable, the damaged windows can be repaired and returned to service.

Fire is a significant hazard in processing and fabricating highly radioactive fuels. Flammable organic solvents, reagents and ion exchange resins are used in fission product separation. Metallic and carbide fuels are combustible, and the hazard is increased by radiation heating and activation. Because a large-scale fire involving radioactive materials is extremely serious, fire-prevention and containment measures must be considered in the design of the

facility. A complete inert-atmosphere system may be required for handling metallic or carbide fuels.

Quantities of smoke-like dust are generated in nonaqueous processing, casting, grinding, screening and fabrication operations. If these dusts are exposed to the cell atmosphere, they soon contaminate all exposed surfaces within the process cell. Unless the cell can be completely decontaminated, human access for maintenance, repair or replacement of process equipment becomes impossible. Provision must therefore be made to keep the equipment in operation and to replace it when necessary without human entry into the process cell. Retention of radioactive dusts and inert atmospheres requires very tight process cell construction or secondary containment. Glove-box-like structures have been used for local containment of dusts within shielded cells. Welded metal cell liners have been used to obtain a high degree of tightness for inert atmospheres.

Process Engineering Considerations

The following factors influence the choice of process and design of remote fabricating equipment:

1. The materials and design of the fuel elements to be fabricated.
2. The degree and kind of radioactivity of the fuel.
3. Radioactive heating effects.

4. Nuclear criticality control measures.
5. Inert atmosphere requirements.
6. Expected life of the process or equipment.
7. Size of shielded space.
8. Availability and the limitations of manipulators, cranes, viewing and remote repair facilities.
9. Economic factors.

A fuel element to be fabricated remotely should be designed specifically for remote fabrication. Liquid or gas bonding (for fuel-to-jacket heat conduction) allows the fuel to be separated cleanly from the jacket. Fuel-element components should be fastened together mechanically where possible rather than metallurgically to facilitate disassembly. Large clearances should be provided for remote assembly with mechanical tightening devices where required.

Remote fabrication is a strong incentive to simplify processing. The number of fabrication steps to produce fuel in the desired shape must be minimized. Vibratory compaction of powders into jackets and the precision casting of metals are single-step fabricating processes that have been successfully employed in fuel-element fabrication.

The process equipment must be as simple and rugged as it can be made. It is necessary to weigh the speed and operating convenience

of automatic machining against the difficulties of remote maintenance and adjustment. Where equipment must be worked upon by manipulators and viewed from shielding windows, the accessibility of parts requiring adjustment will strongly influence the design. Where complex operations are required, it is useful to design simple component assemblies as plug-in units. These subassemblies can be demounted and moved to a window and manipulator station for adjustment or repair.

Radiation Damage to Equipment

Radiation dose rates and radiation damage to machinery are important considerations in the design of equipment for fabricating highly radioactive fuels. Where fission products have been eliminated from plutonium fuel by solvent extraction or aqueous processing, radiation-resistant machine components are not required. Commercially available machine elements can usually be adapted to semi-remote, mechanical operation. Considerable modification is usually required for gloved access when equipment is installed in shielded gloveboxes. Shielding may be incorporated in the process equipment itself, to reduce the amount of glovebox shielding required. Unshielded gloveboxes for fabricating low-radiation materials have been operated from remote control rooms. In this case, distance is substituted for shielding. Self heating presents only a minor problem in the fabrication of decontaminated fuels.

Processes that remove only part of the fission products result

in materials with much higher radiation. Where radiation levels are above 10^5 R/hr, consideration must be given to the radiation effects on the function of equipment. Electrical leakages increase and solid-state devices⁽¹¹⁾ change their characteristics under high radiation. Cumulative radiation damage to materials also presents a problem. Common organic paints, insulators and lubricants are damaged rapidly and if long life is required, radiation-resistant varieties must be substituted. Halogen-containing plastics tend to form corrosive decomposition products. Glasses darken and many ceramics change in either optical or electrical properties.

Dry inert atmospheres, required for fabricating metal and carbide fuels, present additional problems to those contributed by high-radiation levels. Where the moisture must be kept at very low levels, graphite becomes nonlubricating⁽¹²⁾. Graphite seals and motor brushes wear rapidly under these conditions. Soap base greases, that depend upon a small quantity of water in their composition, deteriorate rapidly. Many other natural and synthetic materials cannot withstand complete drying. The effects of low-moisture content of the atmosphere has caused failure of manipulator motors and of atmosphere-processing equipment exterior to the shielded cells.

Special radiation-resistant components are costly. Often a lower overall cost can be achieved by using easily replaced conventional machine components and accepting the short life. In this case the cost of process delay and remote replacement of the component must be taken into consideration as well as the low first costs.

Where radiation-sensitive components must be used, local shielding may sometimes be employed to reduce the gamma dose rates to values that allow the equipment to function with reasonable life expectancy. Similarly, radiation-sensitive auxiliaries, such as vacuum pumps and direct-connected controls, may be isolated in semi-remote equipment rooms. Such equipment can then be serviced by personnel entering for limited periods of time.

Radioactive Heating

The absorption^P of alpha, beta and gamma radiation results in the heating of fuels as they come from the reactor. There is only a small reduction in such heating after partial fission-product separation. The calculated radioactivity and heat energy released for the 135-day irradiated, two-percent burnup fuel is shown in Table IV.

Pyrometallurgical processing reduces the newly formed fission products by about two-thirds. But since the residual fission elements build up to an equilibrium concentration of five to seven percent, the reduction of radioactivity and heat release is less than two-thirds. Experimental studies by Scheiblehut⁽¹³⁾ showed that the center rod of a 15-day cooled, two-percent burnup, EBR-II element would reach 530°C with unrestricted natural air convection. With convective ports blocked to simulate cooling failure, the center fuel pin reached the melting temperature (1200°C) in about 16 minutes.

Lazar, et al⁽¹⁴⁾ studied self-heating of reprocessed fuel in

TABLE IV

Total Fission Product Activity and Activity

(from ANL-6605)

Days Cooled	Curies		Energy (watts)					
			Beta		Gamma		Total	
	6070 g	10,000 g	6070g	10 kg	6070g	10 kg	6070g	10 kg
15	2.7×10^5	4.5×10^5	490	800	730	1200	1220	2000
30	2.0×10^5	3.3×10^5	335	550	470	775	805	1325
60	1.3×10^5	2.2×10^5	210	340	290	480	500	820
120	0.7×10^5	1.2×10^5	135	220	145	240	280	460
240	0.3×10^5	0.5×10^5	75	125	50	80	125	205

various configurations and for air cooling, argon cooling and radiation in a vacuum. The calculated results are summarized in Table V⁽⁹⁾.

Economic Factors

The method used for fabricating any fuel element requires a thorough economic evaluation. In the thorium-U²³³ cycle, it is necessary to consider the radioactivity of Th²²⁸ in both the recycle fraction and the thorium fraction. This in turn varies with the degree of separation and the times since chemical separation of the U²³³ from the fuel. In the U²³⁸-Pu²³⁹ cycle, it will be necessary to consider the radioactivity of each isotope at recycle equilibrium, the length of time after processing and the completeness of decontamination.

Systems providing only partial removal of the fission products can be simpler than solvent extraction. The disadvantages of these simple systems are (1) that the fuel must be remotely refabricated and jacketed and (2) the fission products that remain provide some poison. In thermal reactors, this poisoning must be overcome by the use of additional plutonium or other enrichment. The costs should be compared on the basis of the complete fuel cycle. The economic evaluation should be made of the cost of complete decontamination and semiremote refabrication versus partial fission product removal and remote refabrication. If chemical decontamination required delayed reprocessing for fission product decay, the inventory costs must be weighed in the evaluation. If partial fission product removal is practiced, the cost of added fissile material to overcome the parasitic effects of the fission products should be considered.

TABLE VTemperature and Cooling Requirements - VariousArrays of EBR-II Fuel

<u>Fuel Array</u>	<u>Temperature (°C)</u>	<u>Cooling Method and Flow Rate</u>
15 day cooled fuel element	120	760 cm/sec (25 ft/sec) Air
30 pin tray-unreprocessed fuel rods	150	Free Convection Air
30 pin tray-unreprocessed fuel rods	270 - 340	Radiation in Vacuo
30 pin tray-unreprocessed fuel rods	170	Free Convection Argon
10 kg reprocessed billet	540	Radiation and Free Convection Argon
160 close-packed gravid molds	390	Free Convection Argon
160 close-packed gravid molds	110	3040 cm/sec (100 ft/sec) Argon
65 fuel pins in single layer	180	Free Convection Argon
Single fuel rod	270	Radiation in Vacuo
Single fuel rod in bonding magazine	210	Free Convection Air
Single fuel rod in bonding magazine	60	300 cm/sec (10 ft/sec) Air
Reprocessed fuel element	100	300 cm/sec (10 ft/sec) Air

The magnitude of the process often determines whether the process will be economical. Most conventional fabrication processes, (extrusion, rolling, drawing, etc.) must be tonnage operations to achieve maximum economy. They become uneconomical and wasteful of materials when applied to small batches. Highly enriched fast-reactor fuels are particularly penalized when per kilogram costs are compared with thermal-reactor fuels fabricated on a tonnage basis.

SECTION II
REMOTE FABRICATION OF
PLUTONIUM RECYCLE FUELS

Plutonium utilization research and development work at Hanford involves both "clean" solvent extraction processed plutonium and partially decontaminated plutonium compounds. Plutonium processed by solvent extraction processes is processed into fuel elements for the Plutonium Recycle Test Reactor. It is also processed for other reactors and for a wide variety of physics test purposes. Up to 1000 pounds per month of mixed $\text{PuO}_2\text{-UO}_2$ is processed into PRTR fuel elements in configurations including 19-rod clusters, nested tubes and internally cooled "inverted clusters". As much as 1000 pounds of mixed oxide per month has been processed into special purpose fuel elements for other reactors and physics test elements.

Metallic plutonium is processed in alloy form for fuel elements and for physics test elements. Plutonium aluminum alloys have been processed at a rate up to 500 pounds per month. Special handling requirements for compounds bearing plutonium processed by solvent extraction vary with the isotopic content. As mentioned previously, penetrating radiation intensity increases with increasing Pu^{240} content.

Plutonium with a Pu^{240} content as high as 25 percent has been processed into fuel elements in the form of 2v/o- PuO_2 - UO_2 mixed oxide and 20w/oPu-Al metal⁽¹⁵⁾ with only glovebox-type shielding.

^{4P} Partially decontaminated plutonium-bearing compounds generally have a high level of penetrating radiation and require handling by completely remote techniques. Plutonium is used in many forms. Work at Hanford includes the investigation and utilization of various ceramic forms of plutonium, of ceramic mixtures containing a plutonium ceramic, of plutonium-bearing cermet, of plutonium alloys and of pure metallic plutonium.

Hanford Integrated Plutonium Recycle Facilities

Complete facilities for the development of technology for the use of plutonium as a power-reactor fuel are in use or under construction at Hanford. Most of these facilities are geographically located within a radius of less than one-fourth mile. Facilities for the development of plutonium recycle methods include the Fuels Recycle Pilot Plant, 325 Building laboratory facilities, and Plutonium Recycle Test Reactor, and the Plutonium Fabrication Pilot Plant.

The Fuels Recycle Pilot Plant (Figure 2), currently under

construction and scheduled for completion in mid 1965, contains several heavily shielded cells for the development of separations and cladding processes.

The 325 Building, approximately fifty yards from the Plutonium Fabrication Pilot Plant, contains laboratory facilities for chemical development work on plutonium and plutonium-bearing compounds, and fuel development facilities for the development of improved configurations and processes for fuel cladding. One of the facilities in the 325 Building is a lightly shielded cell for the development of remote fabrication equipment and techniques and the cladding of partially decontaminated fuel materials (Figure 3).

The Plutonium Recycle Test Reactor is a 70 megawatt (thermal) heavy water cooled and moderated zirconium pressure tube reactor. Fuel channels consist of 85 Zircaloy tubes, 3-1/2" O.D. by 3-1/4" I.D. by 17'5" long, arranged in 8-inch equilateral triangular spacing. The effective core diameter is six feet six inches. Core compositions include 1.8w/o Pu in Al, natural UO_2 , and 0.48w/o and 1.0w/o PuO_2 -natural UO_2 mixed oxides. Fuel configurations include 19-rod clusters, nested tubes and inverted clusters (Figure 4). Facilities for remote examination and repair of irradiated fuel elements are included in the PRTR complex.

The Plutonium Fabrication Pilot Plant is a ~~versatile~~-pilot scale laboratory with approximately 40,000⁽¹⁶⁾ square feet of floor space (Figure 5). The building contains many types of glovebox-enclosed fabrication equipment for plutonium work, and facilities for research work

on plutonium and plutonium-bearing compounds. This facility is mentioned here because it is an integral part of the Plutonium Recycle Program. Operations are primarily glovebox operations and are not considered to be remote operations.

These four buildings provide complete facilities for the development of plutonium recycling methods. Also readily available for the development of plutonium processes are the complete separations and development facilities currently utilized primarily for the production of plutonium and for research and development work in connection with the weapons program.

Fuels Recycle Pilot Plant (Under Construction, to be completed early in 1965)

The Fuels Recycle Pilot Plant was designed to permit studies of promising concepts including chemical and pyrochemical separations of irradiated experimental fuel assemblies, and the remote fabrication and inspection of irradiated fuels⁽¹⁷⁾. The building is divided into four primary functional areas: (1) Hot Pilot Cells, (2) Hot Metallurgical Cells, (3) Low Level Canyon, and (4) Cold Canyon (Figure 2). The primary work areas are planned for versatility and future expansion. Supporting facilities include a cask handling area with truck lock, wet storage basin and decontamination chamber, regulated shop, service and sample galleries, operating galleries, chemical makeup rooms, laboratories, cold shop, change rooms, lunchrooms, offices, basements, filter rooms, high level liquid storage tanks, and ventilation exhaust stacks.

General Description

The facility provides for⁽¹⁷⁾: (1) pilot mechanical and metallurgical processes on an engineering scale involving plutonium and large quantities of fission products, (2) demonstration of new methods for processing fully irradiated fuels for the recovery of fissile and by-product materials and removal of poisons therefrom and subsequent treatment of high-level radioactive wastes, (3) fabrication of fuel assemblies containing highly radioactive fissile material, (4) testing and inspection of irradiated fuels both nondestructively and destructively, (5) cold chemical and process-equipment engineering development work, and (6) engineering development of chemical processes in which tracer amounts of fission products are used. The building includes the basic facilities and equipment to receive, handle and dispense radioactive and nonradioactive materials to fabricate, modify, operate and evaluate experimental equipment, and to contain, stabilize and ship radioactive wastes.

The shielding for each hot cell is based on the maximum activity associated with a 15-day cooled, 19-rod fuel element that has been irradiated in the Plutonium Recycle Test Reactor to 10,000 Mwd/ton U.⁽¹⁷⁾ Dose rates have been established at 0.2 mrem/hr, maximum for routinely occupied areas, and 2.5 mrem/hr for nonroutinely occupied areas⁽¹⁸⁾.

Hot Pilot Cells

Access to the four Hot Pilot Cells is through a shielded air lock

that provides positive shielding and ventilation control during cell transfer operations. The air lock also serves as a sampling handling area, "hot" shop, primary decontamination station, and radioactive loading and unloading area.

A pair of mechanical manipulators will be installed above each viewing window. In addition to mechanical manipulators, boom manipulators, post manipulators and mobile manipulators will be used in the cell complex.

Each shielding door is remotely controlled and provides the same shielding as the wall. Each door contains an inflatable seal for ventilation control.

Three remote cranes serve the cell complex.⁽¹⁹⁾ A 5-ton crane serves the Hi Bay Cell, air lock and the Mechanical Cell. A 2-ton crane is installed in the Pyrochemical Cell, and a 6-ton crane serves the Low Bay Cell. The 5-ton and 6-ton cranes provide complete remote handling of equipment into or out of the cells. Remote transfers into the Pyrochemical Cell will be accomplished by the use of remotely controlled dollies. Crane service to each air lock will be provided by a 30-ton crane located in the cask handling area.

The internal dimensions of each cell, thickness of shielding and type of viewing are shown in Table VI.

Hot Metallurgical Cells

The Hot Metallurgical Cells are designed for alpha, beta and gamma containment. Access is through the shielded air lock, which provides

TABLE VI

Hot Pilot Cell Description

Fuels Recycle Pilot Plant

<u>Hot Pilot Cells</u>	<u>Internal Dimensions</u>			<u>Shielding</u>	<u>Viewing</u>
	<u>length</u>	<u>width</u>	<u>height</u>		
Air Lock	22'	x 21.5'	x 34'	4.5' normal concrete ⁽²⁾	Window ⁽⁴⁾ , TV ⁽⁵⁾
Hi Bay Cell	9.25'	x 21'	x 34'	4.5' normal concrete	TV
Low Bay Cell	22'	x 25'	x 30.5'	4' dense concrete ⁽³⁾	Windows, TV, Periscope ⁽⁶⁾
Pyro. Cell	12'	x 19.3'	x 17'	4' dense concrete	Windows, TV, Periscope
Mech. Cell ⁽¹⁾	13'	x 21'	x 15'	4' dense concrete	Windows, TV, Periscope

(1) Located over Pyrochemical Cell in Figure 2.

(2) Normal concrete approximately 150 pounds/ft³.

(3) Dense concrete approximately 235 pounds/ft³.

(4) Lead glass, oil-filled windows, free view area, 18" x 30".

(5) Closed circuit television.

(6) Kollmorgan wall periscope with camera adaptor.

positive ventilation control during cell transfer operations. The air lock is also used for equipment decontamination and irradiated fuel assembly inspection.

The Preparation Cell is for the preparation of fuel feed material. It is designed to be equipped with an inert-atmosphere recirculation system for the processing of pyrophoric materials such as plutonium carbides.

The Fabrication Cell will contain equipment for complete remote fuel fabrication. Both ceramic and metallic fuels up to 12 feet in length can be processed. The cells are constructed of normal and high-density concrete, and all viewing is through lead-glass oil-filled windows, with provisions for periscope and TV viewing. The cell descriptions are summarized in Table VII.

Manipulation will be by master-slave manipulators located at each viewing window. Material handling will be accomplished by remotely controlled overhead bridge cranes located in each cell. Each shielding door is remotely controlled and provides the same shielding as the wall. Doors are sealed air-tight by the use of inflatable neoprene rubber seals.

Cask Handling Area

The Cask Handling Area serves the regulated shop and the air lock of each cell complex and contains the wet storage basin, truck locks, decontamination stall, liquid-waste storage tank vaults and liquid-waste transfer station. A shielded conveyor connects each air lock with the wet storage basin.

TABLE VII
Hot Metallurgical Cells

	<u>Internal Dimensions</u>			<u>Shielding</u>	<u>Viewing</u>
	<u>length</u>	<u>width</u>	<u>height</u>		
Air Lock	20'	16'	18'	4' dense concrete	Windows
Preparation Cell	23'	16'	18'	4' dense concrete	Windows
Fabrication Cell	50'	16'	18'	4' dense concrete	Windows

- (1) Provisions are installed for periscope and TV viewing.
- (2) Dense concrete approximately 235 lbs/ft³.
- (3) Lead glass, oil-filled windows, free view area, 18" x 30".

If less than six 19-rod fuel elements are stored in the wet basin with a lattice spacing of at least 8 inches, it will be critically safe even if the basin is inadvertently drained. The facility is planned to handle, store and process materials having the following dimensions and weights:

Fuel element, 12" diameter x 10' long, weighing 300 pounds;

Cask, (fuel element), 4' diameter x 13' long, weighing 30 tons;

Cask, (liquid), 6' diameter x 7' high, weighing 30 tons.

Remote Fabrication Facility - 325 Building

The purpose of this facility is to provide for the remote fabrication, refurbishing, inspection and testing of fuel elements or assemblies and the development of equipment and process^{es} for the same purposes (Figure 3).

The facility is located in the basement of the 325 Building, approximately 25 feet from the truck entrance. The cell is 12-feet long, 9-feet wide, 16-feet-6-inches high. Shielding at present is only the 1/4-inch steel shell. The frame is constructed so additional shielding can be added, either temporarily or permanently.

Two boom-crane mounted manipulators provide complete cell coverage. Each manipulator has a 90-pound capacity, when fully extended, and a 200-pound capacity in straight lift. Each manipulator has eight degrees of mechanical freedom with shoulder rotation in addition to the normal operations of shoulder, elbow, wrist, wrist rotate, hand open and close,

and arm extend. Each manipulator unit contains a 500-pound, remotely controlled hoist located on the horizontal boom beneath the manipulator.

A vibration exciter and associated control system (mounted outside the cell with extensions into the cell) provides variable programing of vibrational frequencies from 5 to 3000 cps. The force output which is 5000-pounds, is capable of providing 100 gravities acceleration throughout most of the range. Independent control of displacement and vibration permits wide control for use in powder compaction, vibration and fatigue testing of nonirradiated, irradiated or radioactive units or assemblies.

A smaller 750-pound force output vibrator is also available for use with this facility.

The welding power supply is capable of either consumable or non-consumable inert-gas metal-arc welding and may be programed for complete weld sequencing of welding variables.

A 1000-pound capacity servo-speed controlled turntable for accurate rotational control of weld-positioned pieces and inert-gas welding chambers is installed in the cell. All equipment is "remotized" for complete remote-control operation.

In-cell viewing is entirely by closed-circuit TV with complete remote controls, zoom camera lens and camera-locating facilities.

Refurbishing Tank

A part of the remote-fabrication facility in the 325 Building is

a 4' x 4' x 10' tank located in a pit with the bottom of the tank approximately eight feet below floor level. This tank is used for the development of equipment for repairing fuel elements in the reactor basin. Several tools have been developed here. A collection of tools and their use is shown in Figure 6. This tank is set up in such a way that tools can be developed here on "cold" fuel elements and then can be taken directly to the reactor basin and used to repair fuel elements under approximately eight feet of water.

Plutonium Recycle Test Reactor

Two facilities are available to examine irradiated fuel elements at the PRTR. The first of these is a specially designed facility for fuel-element handling and viewing with the fuel element in air (Figure 7). The fuel element is lowered into a chamber below the reactor hall floor, using the reactor fueling vehicle. In the chamber it can be viewed optically at up to 5X magnification. When in the chamber, a mechanism is used to rotate, raise or lower the element. Air is forced over the element to cool it while in the viewing chamber.

The other method of fuel element viewing involves using a small, high-quality reflecting-type telescope mounted over the reactor fuel storage basin. The fuel-element handling tray in the basin can be used to rotate, raise or lower the fuel element with the fuel resting in a horizontal position. The telescope magnifies from 40X to 160X through changeable eyepieces. With clear basin water this system is relatively inexpensive and works very well. The fuel-element handling equipment in the basin is used in refurbishing, as well as in examination.

PLUTONIUM FABRICATION PROCESSES

General

Remote fabrication work in connection with the Plutonium Recycle Program at Hanford includes the remote canning of recycle material, the rejuvenation of irradiated fuel elements by means of plutonium enrichment without decladding, and the repair or refurbishing of fuel elements that have suffered some damage during reactor operation, but still have a significant amount of reactivity left in them. Work directed towards the exchange of fuel elements between fast and thermal reactors is also in progress. Refurbishing techniques are largely applicable to the interreactor modification required for an exchange element.

The recycle program includes dissolution of the fuel, separation of plutonium and fission products and recanning of the plutonium, possibly with other materials, by remote means.

Rejuvenation consists of adding fissile material to an irradiated fuel element to compensate for fissile material burned and to overcome the reactivity loss from fission-product buildup. This may be done by opening an irradiated fuel element, adding fissile material and reclosing the fuel element. Another technique under consideration in this category is the replacement of rods in the coolant channels of an "inverted cluster" fuel element (Figure 8).

Fabrication in gloveboxes in the Plutonium Fabrication Pilot Plant involves conventional ceramic-fuel fabrication methods. The

principal process currently used includes the pneumatic impaction of mixed plutonium and uranium oxides, crushing and sizing of the impacted product, and vibratory compaction of the sized ceramic into the cladding.

Recycle

The flowsheet for a typical process for use in the Fuels Recycle Pilot Plant is shown in Figure 9.

An irradiated fuel element from the PRTR is opened mechanically and the ceramic core removed. The $\text{PuO}_2\text{-UO}_2$ core material is oxidized, the UO_2 being converted to U_3O_8 . The oxide mixture is dissolved in potassium or chloride salt, then, under an oxidizing atmosphere, electrolytically reduced to $\text{UO}_2\text{-PuO}_2$.

The electrode deposit is subsequently removed mechanically. The mixed-oxide deposit, which is normally near theoretical density, is crushed and sized with conventional powder preparation equipment. In the meantime, the components have been preassembled and cleaned to the maximum possible extent. The components are set up in a glovebox and the sized powders are then brought to the cell. The powder is vibrationally compacted into the fuel element and the end closure is made. Currently, the end closure is examined only visually. However, it is possible to develop nondestructive tests if this should prove desirable. Hanger attachments are then fastened to the fuel element. The new fuel element is placed in the cask and transferred back to the reactor basin.

A more detailed discussion of the fabrication part of this process follows:

Particle Preparation

The preparation of particles from ceramic material of high density is a fairly standard process. A typical mixture of particle sizes for vibrational compaction into a half-inch diameter tube is -6+10 mesh, 60 percent; -65+100 mesh, 20 percent, and -225 mesh, 20 percent. Many variations of this size might be used for slightly differing geometries, differing vibrational conditions or varying particle size availability in initial mixes. A mix such as this, assuming the particles are 99 percent of the theoretical density or better, can be vibrationally compacted to approximately 87 percent of the theoretical density, with virtually no special considerations. With minor development work, 89 percent of the theoretical density can be achieved in a fuel rod (of 1/2-inch diameter or more) on a routine production basis. With a considerable amount of development work and very special handling, a density of 92 to 93 percent may be achieved. Densities in the 87 to 90 percent range are satisfactory for most types of fuel elements.

Equipment used for crushing is fairly standard equipment, and the cost generally is low enough so that for pilot quantities of material, only rudimentary repairs would be attempted. If any significant amount of maintenance was required, the equipment would be buried and replaced with new equipment.

Powder preparation equipment includes jaw crushers, disc pulverizers and ball mills, and screening equipment. A typical powder preparation setup is shown in Figure 10.

Filling

Fuel rods or tubes for filling are clamped to a vibration source. The clamp should be quite rigid and should be designed to minimize stress concentration areas on the material being vibrated. The powder mix is placed in a hopper and slowly poured into the tube during vibration. During final stages of vibration, a follow rod is used to prevent the material from vibrating back up into a loosely packed condition.

Closure

After filling of the tube, the area to be welded has to be decontaminated in order to prevent mixing of core material with the weld metal and subsequent release of radioactivity into the reactor environment or corrosion of the metal. Decontamination is generally accomplished by swabbing with alcohol until no contamination can be detected on the swabs. The closure is then made by inserting the closure cap and welding it into place. This equipment includes a turntable, which is placed in the cell, and an inert-gas box with guide rollers and torch. The controls for both the welding turntable and the welder, and the welder power supply, are all outside of the remote fabrication cell.

Assembly

Assembly of components is accomplished primarily with manipulators. Components are generally designed for this type of assembly and in such a

way that a minimum of assembly operations is required. An inverted cluster configuration, which requires only one closure after filling, is shown in Figure 4.

Inspection

Inspection after assembly is primarily a visual inspection by means of direct viewing through windows, television cameras and microscopes. Because of the extremely high irradiation associated with partially decontaminated recycle material, many of the conventional techniques, such as autoradiography, radiography and ultrasonic tests, are not used. However, closure technology is generally such that extremely reliable closures can be produced with this type of inspection. Preinspection of components and of prefabricated components is, of course, done to the maximum practical extent. This preinspection will include ultrasonic inspection of tubing and radiography, and possibly ultrasonic inspection of welds.

Fuel Design

As mentioned above, fuels are designed for a minimum of remote fabrication steps, even though remote fabrication steps can in many cases be carried out almost as simply as contact (glovebox) fabrication steps. The nested tube and inverted cluster configurations shown in Figure 4 are steps toward simplified configurations.

Rejuvenation

Rejuvenation is one of several concepts to overcome the burnup of fissile material and buildup of poisons in a reactor core without reprocessing of the core material.

These concepts include spiking, burnable poisons and Phoenix fuels. Spiking refers to the utilization of fuel elements with relatively high fissile content used to boost the average reactivity of a reactor core. Burnable poisons, used in some fuel elements to repress initial activity and minimize control requirements, are materials such as samarium, which have a very high neutron-capture cross section, but are converted to low cross-section materials during irradiation. Phoenix fuels are fuels that employ a balance of fissile and fertile isotopes. The fertile isotopes are converted to fissile isotopes at about the same rate that the fissile isotopes are burned. This can result in a stable reactivity over a long period of time.

Rejuvenation refers to the addition of fissile material to an irradiated fuel element. Rejuvenation methods under investigation include the addition of fissile material to the core of an irradiated fuel element and the replacement or addition of extra-fissile components in an irradiated fuel element.

Initial Void

Under the proper irradiation conditions, a void will exist in the

center of a ceramic core fuel element.

Figure 11 shows a rejuvenation type fuel element after initial irradiation. This particular fuel element was built to test a rejuvenation concept with a simulated second cycle. This work is currently in the early experimental stage. Feasibility has been demonstrated and economic incentive evaluated. Practicality of various methods has not yet been established. In the figure, the external fuel core material is depleted UO_2 . The next area in is zirconia. The next area inward is enriched UO_2 . The enriched UO_2 was packed solidly into the zirconia tube. After a single cycle of irradiation in the MTR at approximately 200,000 $\text{Btu}/(\text{hr})(\text{ft}^2)$, to an exposure of 500 Mwd/ton , the element was removed from the MTR and sectioned. Subsequent irradiation of similar rods is shown in Figure 12. As may readily be seen in Figure 12, the enriched UO_2 relocated from the center of the fuel element towards the outside and left a central void. This is a fundamental feature that may make rejuvenation practical in full-size fuel elements.

Post-Irradiation Void

The number of cycles through which a fuel element can be rejuvenated and still retain a central void is a function of many factors. These include starting void conditions, the degree of enrichment in rejuvenation material, operating temperature of the fuel element, and fuel element size.

It has been estimated that only about 150 grams of plutonium is necessary to rejuvenate a full-size 19-rod cluster PRTR fuel element

weighing approximately 110 pounds to provide an additional 5000 Mwd/ton of reactivity. This very small amount of material is indicative of the fact that only a very small void is required to provide for complete rejuvenation.

In the second cycle of an original rejuvenation fuel element, it was found that a 1/8-inch hole existed throughout almost the entire length of the 12-inch fuel rod. If this hole were reduced by 20 percent for subsequent rejuvenations, it would still be possible to utilize the central voids for several cycles.

Filling

Several concepts are being evaluated for the filling of rejuvenation fuel elements. These include packing with powder by simply pouring the powder in, packing by means of vibrational compaction, and the utilization of wire enrichment.

Wire enrichment is simply the insertion of a plutonium-zirconium alloy wire into the void. Fuels so rejuvenated have been irradiated. The added plutonium provides the needed additional reactivity without unfavorable reactions with the UO_2 or with the cladding material.

Closure

Equipment for closure of a typical rejuvenation fuel element is shown in Figure 13. With the equipment shown, the dimensional settings

are made prior to placing the equipment in the cell. Each fuel element must be measured and the equipment set manually by contact means between each welding operation. If rejuvenation should prove feasible as a production process, it would be desirable to establish means of presetting the equipment to individual fuel elements without removal from the cell.

Inspection

As with recycle closures, inspection of the closure on the rejuvenation type fuel elements is primarily by visual means.

Fuel Design

While very little is necessary in the way of special design considerations to utilize the rejuvenation concept, it is quite possible that special considerations will provide vastly improved potential for the process. The value of plutonium could be such that a fuel element could be made with a main core body of depleted UO_2 and an initial central core of PuO_2 . This could utilize stockpiles of depleted uranium. The PuO_2 would relocate to leave a central void.

Another concept potentially useful would be to fabricate a fuel element with UO_2 with a central void, and to enrich after the fabrication is completed by either inserting a plutonium-zirconium alloy wire into the center, or pouring PuO_2 into the center. This would simplify the problems of fabricating fuel elements with the toxic plutonium, since all steps except the final enrichment step could be carried out with this relatively non-toxic UO_2 .

The possibilities presented by the proven migration of enrichment material from the center of the fuel element towards the outer circumference are unlimited.

Designs such as the inverted cluster, Figure 8, will permit the rejuvenation of any element by the addition of clad components without opening the irradiated fuel element. Work of this type can be done in the reactor basin with tools of the type used for refurbishing.

Refurbishing

Examination

Examination facilities for fuel-element refurbishing are described above. With these facilities, it is possible to establish such things as the depth of a defect in a fuel element surface, the condition of hangers, and the overall condition of the fuel element.

Repair

A typical repair consists of the splicing of a broken wire wrap with a 19-rod cluster. Seven of the outer eleven rods have wire wraps to provide adequate spacing between rods. It is possible to repair any or all of these by the use of the underwater operations shown in Figure 11. One development is a wire-wrap splice consisting of a small block with two slightly oversized holes built in. This is used on either end of a broken wire wrap, the wires being inserted by means of a special tool. This block is crimped onto each wire with a crimping tool. One end of the wire is attached to the web of an end fixture. This requires drilling

SOCKET WRENCH

CRIMPING TOOL

WIRE SPLICE HOLE FINDER

DRILL

REFURBISHING TOOLS

PRTR FUEL ELEMENT EXAMINATION FACILITY

a hole and inserting a bolt and threading a nut onto the bolt, all under eight feet or so of water. The refurbishing tools are shown in Figure 6.

One of the more difficult jobs is the replacement of a defective rod. Because most of the 19-rod cluster fuel elements were designed to be assembled completely all at the same time, a special fuel rod was designed for use as a replacement rod. This rod utilizes end caps with female threads so the rod can be inserted into the existing structure and bolted in place without movement of the end fixtures.

Tooling of this type for relatively primitive underwater work has progressed to the point that a defective fuel element can be completely disassembled and the good parts utilized to create a new fuel element.

SECTION III

PROGRAMS FOR REMOTE FABRICATION OF Th-U²³³ FUELS

The development of techniques for remote processing and refabrication of fuels containing thorium and U²³³ is an important step toward fulfilling the economic potential of the Th-U²³³ fuel cycle system. The demonstration of technical feasibility and the establishment of economics for both reprocessing and refabrication are unquestionably essential for accurate determinations of the worth of the thorium fuel cycle to nuclear power systems. The technical feasibility of reprocessing has been demonstrated and the economics of processing is reasonably well established. Very little work has been done in the area of refabrication technology; and, accordingly, little is known about refabrication technology and its economics. A number of programs are being conducted to develop economical processes and systems for remote fabrication of Th-U²³³ bearing fuels, and in all of these programs fuels containing U²³³O₂-ThO₂ or U²³³C₂-ThC₂ are of immediate interest because of possible near-future applications in reactors, such as the Spectral Shift Control Reactor (SSCR) and the High-Temperature Gas-Cooled Reactor (HTGCR) in which, respectively, these fuels would be utilized.

Semiremote Fabrication of Fuel Elements Bearing (Th-U²³³)O₂

For metal-clad oxide fuels, the most promising of the various possible processing schemes appears to be the Thorex-solvent extraction process followed by the sol-gel particle preparation and fuel-element fabrication by vibratory compaction of the sol-gel oxide particles into

fuel tubes. This approach represents a significant simplification of existing processes and, thus, is particularly attractive for fuels requiring semiremote or remote handling.

Thoria-Uranium²³³ Fuel Rods at ORNL

Development of the processing procedure based on Thorex sol-gel preparation and vibratory compaction for fabrication has reached the pilot-plant scale at ORNL, where a facility in which these processes are used is in operation. The facility, known as the Kilorod Facility⁽²⁰⁾⁽²¹⁾, has produced approximately 900 rods of the design shown in Figure 15. The rods are to be used in zero-power criticality experiments at BNL. Although the facility and its equipment were specifically designed for making these fuel rods at a production rate of 15 rods per day, other fabrication tasks not accommodated by the BNL fuel-rod equipment can be accomplished by substituting process equipment in the facility.

The processing of fuel in the Kilorod Facility encompasses two distinct phases: bulk-oxide preparation by the sol-gel process and rod fabrication. The sol-gel process is shown in Figure 16. In the process, oxide that is readily dispersible to stable sol particles of about 70 Å in diameter is prepared outside the Kilorod Facility by means of a rotary steam denitrator. In making the sol, following volume and concentration measurement, uranyl nitrate solution is transferred to a criticality safe slab tank blender. While the solution is being recirculated and heated to 80°C, preweighed thoria powder is flushed with the correct

amount of water through a funnel into the uranyl nitrate solution, adjusted to a NO_3^-/Th mole ratio of 0.077, then mixed and digested for about one hour to ensure its dispersion to a stable uranium-thorium oxide sol. After dispersion, the sol is pumped to the tray drier where a constant-level overflow in the center of each of the trays distributes five kg of oxide as sol to each tray. The batches of sol are then dried with sufficient preheated air to maintain a drying temperature of 80°C . The drying is complete in about 24 hours for a 10-kg batch of gel, which breaks away from the walls and sides of the trays and forms fragments from one cm in size down to approximately $150\ \mu$. After drying, the gel is placed into crucibles for calcination. The temperature is increased from 200 to 500°C at the relatively slow rate of 100°C/hr , to eliminate nitrogen, CO_2 and H_2O without shattering the gel, and then at 300°C/hr to 1150°C , at which temperature it is calcined in air for one hour to densify the gel. The air is then swept from the furnace with argon, and the calcination is continued for four hours in noncombustible 4% H_2 -Ar to reduce higher uranium oxides to UO_2 . The calcined gel is then cooled to 200°C under argon and removed from the furnace. After further cooling to room temperature, the material is discharged to a 1.3-cm (1/2-inch) screen to the rod fabrication system.

The procedures employed in the rod fabrication part of the facility are shown diagrammatically in Figure 17. The particle-size distribution required to achieve maximum density by vibratory compaction consists of a mixture of either two or three fractions. For design purposes, the reference size distribution consisted of a mixture of three size-fractions

produced by a system of crushing, classification and ball milling. After comminution and classification of the bulk fuel into the two or three working fractions, quantities of each fraction needed for one fuel rod loading are apportioned and blended together.

In the vibratory-compaction operation, the blended fuel is loaded into a fuel tube that has one end plug welded in place and the fuel is vibrated to the specified density. This loaded fuel tube is transferred to a welding fixture where the final end-closure weld is made and visually inspected.

At this juncture the loaded and sealed fuel rod is decontaminated by ultrasonic cleaning in water and smeared to check for surface contamination. The integrity of the end closure weld is evaluated by helium leak checking and the density of the fuel is determined by attenuation measurement with a gamma source and a scanning device. A hanger fitting is attached and, finally, the fuel rod is loaded into a shipping cask.

Design of the Facility and Equipment

The sol-gel and rod-fabrication process equipment is located within a 20 x 19 x 27-ft. high chemical processing cell (Figure 18), which provides secondary containment of airborne contamination in the event of an accident. There are three operating levels provided with enclosures of either 4.5-inch armor plate or 8-inch barytes concrete for gamma-ray shielding and an all-welded steel liner, for primary alpha-particle containment, that completely surrounds and seals all operation space. Areas outside the shielding are personnel-access areas from which operations can be conducted semiremotely or remotely.

Operation of the third-level cubicle (the sol-gel process) is conducted by gloved access or by remote solution transfer. The rod fabrication operations in the cubicles on the first and second levels are accomplished by castle manipulators or by gloved access.

Located on one corner of the first level and extending to the top of the second level is the 4 x 7-ft. powder-conditioning shaft. Directly adjacent to this shaft on the first level are three fabrication cubicles that extend along two walls. The first of these cubicles is used for vibratory compaction and welding, the second for decontamination, and the third for inspection. A gloved repair box is located on the second level adjacent to the powder-preparation shaft and directly above the cubicles housing the vibratory compaction, welding and decontamination equipment. The box is equipped with a large bag-out port and a monorail crane that runs the length of the glovebox and is used to lift and convey equipment. Access to the powder-preparation shaft is through a door in the side of the shaft, while access to the fabrication cubicles is through ports in the floor of the box.

The fabrication cubicles have 20 windows; 31 ports are provided to allow outfitting with either gloves or manipulator tongs and allow interchange of gloves and tongs without loss of containment. The rod fabrication process is operated with nine manipulators and two glove ports. The remaining 20 glove ports are used for maintenance.

Standard commercially available units were used as process equipment wherever practicable; however, the majority of the equipment was

specifically designed for the process. Where commercial units were used, it was usually necessary to do extensive modification before the units could be incorporated into the process scheme. As would be expected from experimental equipment of this nature, a large number of flaws were present in the as-designed stage. In order to evaluate this equipment, it was necessary to test each piece of equipment under simulated conditions before installing it in the facility. After the installation of the equipment in the facility, the process line was again thoroughly evaluated with stand-in oxide before the U^{233} -bearing fuel was introduced.

Reconstitution Equipment

For the sol-gel process, the major items of equipment are the blend tank, the uranyl nitrate measuring tank, the tray drier, the dry-gel transfer system and the calciner. A cursory description follows.

Blend Tank - The blend tank is of slab-type construction, 3/4-inch thick x 40-inch wide at the top with a "V" bottom, and has a capacity of 31 liters. A centrifugal pump produces a mixing action in the tank by recirculating solution from the bottom of the tank to a side inlet.

Uranyl Nitrate Measuring Tank - The measuring tank is a constant diameter 2-inch glass pipe approximately five feet long.

Tray Drier - The tray drier has eight shallow trays installed inside a box through which warm air is passed slowly. Exit air is drawn through a cooler where it is dehumidified and this is discharged into the plant off-gas system.

Dry-Gel Transfer System - A lift table and a tray dumper constitute the dry-gel transfer system. The lift table is essentially an elevator, the position of which can be varied to match the elevation of any drier tray as well as the opening on the side of the tray dumper. The tray dumper consists of (1) a device to receive, hold and invert one tray at a time, (2) a housing to prevent spread of dust, and (3) a funnel-like chamber to direct the contents into a calcining crucible.

Calciner - The calciner is a modification of a commercial metal resistor muffle furnace. The modifications provide for water jacketing to prevent excessive heating of the cubicle, intermittent air cooling to provide a faster cooling cycle, and a modified door suited to operations under the conditions imposed.

Refabrication Equipment

Equipment for powder preparation, vibratory compaction, welding, decontamination and inspection is used for the fabrication operations.

Powder-Preparation Equipment

One of the unique features of the facility is the powder-preparation equipment. It was designed to afford maximum dust confinement and to transport the fuel by gravity through pipes between equipment units. All the equipment in the powder-preparation shaft is remotely controlled either electrically or by flexible shafts.

The jaw crusher and ball mill are located on the top rack of the shaft. A valve directly above the jaw crusher controls the rate of feed. The classifier, located directly below the jaw crusher and ball mill, continuously classifies the feed material into dispensing hoppers. The rate of feed to the classifier is controlled either by the feeder valve controlling the feed to the jaw crusher or by a feeder valve controlling the feed rate from the ball mill. Six transparent-glass storage hoppers (three for the working fractions and three for the recycle fractions) are located around the base of the classifier. The three recycle hoppers are connected directly to a recycle manifold. The recycle manifold empties into a recycle hopper that conveys material to the jaw crusher or the ball mill for recycling.

Directly below the classifier is a remote weigher by means of which exact quantities of each of the working fractions are obtained. As each fraction is weighed, it is dumped down from the weigher directly into the blender. The blender is a V-type, modified to facilitate loading and discharging.

Vibratory-Compaction Equipment

The vibratory-compaction equipment consists of two principal components, the tube-filling assembly and the chuck assembly. The tube-filling assembly, which is located in the powder-preparation shaft at the upper right corner of the vibratory-compaction and welding cubicle, is separated from that cubicle by a nylon iris valve. The fuel tube is inserted through the iris into the filler mechanism.

The tube-filling assembly consists essentially of a receiving hopper for blended fuel and a vibratory feeder that enables close control of the fuel feeding. Also included in this assembly are a funnel for directing the fuel into the tube without spreading dust and a mechanism for applying a static load to the fuel column during vibration.

The vibrator-chuck assembly consists of an anvil, to which the chuck is attached and through which the vibrational energy is transmitted, and a pneumatic vibrator. The chuck and anvil are placed inside the cubicle. For convenient servicing, the vibrator is located outside the cubicle and is sealed from the cubicle by a neoprene diaphragm.

End-Cap Welding Machine

The end-cap welding machine was specifically designed to weld the top end plug onto the fuel rod by a fusion lip weld. The unit is also equipped with a press for seating the top end plug on the fuel rod immediately after the rod has been evacuated and backfilled with helium. The welding machine is comprised of two main components -- the rod elevator and the welding chamber.

The rod elevator employs a synchronous-drive motor and a lead screw for inserting the fuel rod into the welding chamber. The elevator also actuates a vacuum seal around the fuel rod as it is seated in the welding chamber.

The tungsten-arc torch and the end-plug press are located in the welding chamber. The press uses a lead screw and a synchronous motor drive arrangement for inserting the end plugs. The torch is positioned by two high-ratio, lead screw motor arrangements. During welding, the rod is rotated by a constant-speed motor.

Decontamination Equipment

A 1-kw ultrasonic cleaner is used to decontaminate the completed fuel rods one at a time. The cleaner is equipped with a cover in which is housed a mechanism for holding and rotating the rods during cleaning. The cleaning cycle, which is manually controlled, consists of filling, cleaning, emptying, spray-rinsing and drying.

Helium Leak Detection System

The welded and decontaminated rod is checked for leaktightness with a mass-spectrometer helium leak detector. The system includes a chamber in which the fuel rod is placed, a standard leak, the leak detector, and a roughing vacuum pump station. Particulate filters are used to isolate the vacuum chamber for the rod from the pumping and detection station.

Density Scanner

The density of each rod is determined by means of a gamma-attenuation scanning device. The scanner consists of a 1-curie Co^{60} source, collimated through a $1/8 \times 3/8$ -inch longitudinal slot, and a detecting crystal with its associated power supply, amplifier, and

recorder. A trolley is provided to drive the fuel rod through the collimated beam at a constant rate.

Shipping Cask

The shipping cask of 120-rod capacity is loaded in the horizontal position in the facility and then discharged vertically at its destination. For loading, the cask is held on a dolly in the horizontal position and secured to the cubicle door with turnbuckles. A lattice structure provided in the cask to position the rods is partially inserted into the loading cubicles to facilitate loading by tongs. After loading, the lattice is retracted into the cask, the top secured, and the cask removed with an overhead crane.

Operating Procedure

The facility is operated on campaigns of 120 fuel rods. At the end of each campaign, a balance of material is made and the campaign is assessed. Detailed preventive maintenance is accomplished, repairs are made, and the facility is prepared for the next campaign.

In the direct operations, four operators and one operating supervisor are employed. Maintenance is accomplished either through glove manipulator ports, by repairing equipment that has been removed to the gloved repair area, or by persons who use air suits to enter the cubicles.

Operating Experience

The Kilorod Facility, which has been in operation with U²³³ since

mid-1963, has produced 900 fuel rods meeting specifications. On the first pilot runs, considerable difficulty was experienced in getting consistent results in the process and with equipment failures. However, after producing about 100 fuel rods, the operation became more routine and is now performing at the design capacity. In conclusion, the engineering feasibility of the system has been demonstrated, and sustained production at the design rate has been attained.

Thorium-Uranium²³³ Oxide-Bearing Fuel Elements

The advantages of Th-U²³³ have led the Babcock and Wilcox Company to seriously consider the cycle for the Spectral Shift Control Reactor (SSCR). Their analysis of the fuel cycle in the SSCR showed that a very low fuel makeup is required when the bred U²³³ is recycled. One of the important conclusions of their analysis was that actual fuel cycle costs achieved will be strongly sensitive to the relative costs of fabricating recycled and natural fuel. Because of the uncertainty of the fabrication costs, they have constructed facilities and equipment for demonstration of refabrication on a pilot plant scale. Operations with natural fuel were just recently started, and expectations are that, in 1964, U²³³ operations will commence.

The designers⁽²²⁾ of the Babcock and Wilcox pilot line have observed that the buildup of gamma activity in U²³³ forces a choice of either conducting fabrication operations behind shielding or selecting a process of such simplicity that rapid, direct glovebox manipulators for most operations preclude the need for shielding. After exhaustive

studies of expected dose rates from highly irradiated U^{233} , the approach of unshielded gloveboxes for most operations was chosen. The fabrication method chosen was the simplest yet developed for high performance reactor fuels -- one incorporating the sol-gel method for preparation of thorium-urania, vibratory compaction of oxide into Zircaloy tubes, and mechanical assembly into fuel elements under water.

Design of the SSCR Fuel Element

The production of an SSCR fuel element is to be demonstrated in the Babcock and Wilcox pilot facility. The structural parts that make up the fuel-element assembly are preassembled to form a structure into which fuel rods can be inserted. The reference fuel element has 196 fuel rods, which have a diameter of 0.421 inch.

Radiation Hazards

Dose rates from gamma and neutron radiation at a distance of one foot from a single SSCR fuel rod, as reported by Schileo and Weissert⁽²²⁾, are presented in Figure 19. Decay-product-activity buildup was computed on the assumption that all daughter products were removed at zero time.

Refabrication Process

The complete recycle process is similar to that being used in the ORNL Kilorod Facility. Aqueous processing is used for recovery and purification of the U^{233} . The remainder of the operations includes those of oxide preparation, fuel-rod fabrication, and fuel-element assembly. Because of the similarity of the procedure to that of the Kilorod Facility,

further discussion of most of the process will be omitted. The assembly operation, however, is unique.

Because the assembly operation falls at the end of the process when gamma activity is highest and because a large quantity of fuel material is involved, the assembly of fuel elements cannot be accomplished in gloveboxes. However, the design of the SSCR fuel element allows the assembly operations to be performed under water.

After release from the glovebox line, the finished and inspected fuel rods are briefly stored in an underwater rack in an assembly canal. As soon as the number and types of rods for one fuel bundle are available, the assembly operations can start. The preassembled structure is then placed and held underwater by a specially designed machine that performs the operations of transferring and inserting the fuel rods from the rack into the fuel element structure.

After the final inspection to check that the specified tolerances are met, the completely finished fuel assemblies are stored underwater. Owing to the gamma activity buildup, the finished fuel bundles must always be shielded before their insertion and re-use in a reactor.

Fully Remote Fabrication of Fuel Elements Containing Uranium²³³ and Thorium

Thorium-Uranium²³³ Oxide-Bearing Fuel Elements in the PCUT Plant*

The Comitato Nazionale Per l'Energia Nucleare (CNEN) and the Allis-Chalmers Manufacturing Company have undertaken a joint program

* PROGETTO CICLO URANIO-THORIO (Pilot Thoria-Urania Reprocessing and Refabrication Plant)

to develop and demonstrate the thorium fuel cycle for central station power reactors⁽²³⁾. The principal undertakings in the program are the design, construction and operation of a pilot plant for reprocessing and fabricating reactor fuels containing thorium and uranium. The plant will extract usable fuel material from the spent fuel elements of a thorium-uranium reactor, reconstitute the extracted material in a suitable form, and assemble new fuel elements for use in the same reactor.

This project has been incorporated as a key effort in the Italian Atomic Energy Program; and the facility, which will initially process and refabricate Elk River Reactor (ERR) fuel elements, has been designed to permit future conversion to process thorium loadings of the Societa Eletttronucleare Nazionale (SENN) Reactor now under construction in Italy.

The designers of the plant concluded that remote handling is required in all the processing steps, not only because of the fission-product activity but because of the radioactivity associated with U^{232} and Th^{228} . Therefore, the refabrication system is completely remote in a "warm" cell, thus providing protection from alpha activity and shielding against gamma radiation. The advantages of remote fabrication over direct fabrication cited by F. Fumagalli⁽²⁴⁾ and his co-workers are as follows: (1) no need for quick fabrication; (2) no periodic decontamination problems for the fabrication equipment.

The plant was designed for a capacity of 15 kg of thorium-uranium oxide per day. The designers believe that minor additions to principally the dissolving and recycling areas will permit a processing rate of

30 kg/day, which is a capacity consistent with the fuel throughput of one of the Italian power reactors if it were converted to the thorium-uranium fuel cycle. When working ERR fuel, the plant factor will be about 50 percent.

Design of the Reference Fuel Element

The fuel assembly for which the plant is now designed is that of the Elk River Reactor. This assembly is 81-5/8 inches long, approximately 3-1/2 inches square, and weighs about 86 pounds. It consists of 25 stainless steel tubes filled with ceramic pellets of uranium oxide and thorium oxide, grid castings at each end to hold the tubes in a 5 x 5 array, top and bottom end fittings that support and position the assembly in the reactor core, and clamps to maintain the correct spacing between rods over the length of the assembly.

Fuel Reconstitution and Refabrication Flowsheet

The processing sequence in the plant consists of four major phases: disassembly, recovery of the fuel material, reconstitution of the recovered fuel material, and assembly of a new element. The reconstitution and refabrication steps are represented schematically in Figure 20.

The input to the reconstitution step is the product of aqueous processing, thorium-uranium nitrate. The aqueous product solution is concentrated and adjusted to ensure the proper thorium-to-uranium ratio.

Formic acid and urea are added to the adjusted solution; then the mixture is heated to 60°C and passed through a bed of alumina pellets containing 5w/oPt catalyst. This reduces the uranium valence state from +6 to +4 and permits precipitation of both uranium and thorium with oxalic acid. The resulting slurry of thorium and uranium oxalates is centrifuged to remove the supernatant liquid. The thorium-uranium oxalate solids are then passed through a calcining furnace where the volatile materials are driven off and uranium and thorium oxides are formed. These oxides of uranium and thorium are the end products of the fuel-recovery phase.

The dry mixed oxides of uranium and thorium are passed through a "Mikro-Pulvizer" to break up any aggregate bodies formed during the calcining step. The resulting oxide powders are blended with water, an organic binder, and an extrusion aid in a Muller-Mixer prior to loading the resulting "clay" into an extrusion press. There the blend is extruded in 91-cm lengths, air dried, and cut to pellet length. The "green" pellets are then sintered at temperatures up to 1700°C to produce pellets of the required high density.

The sintered pellets will be ground to the specified diameter using a centerless grinder. Pneumatic gauging attachments on the machine will permit continuous measurement of dimensions and continuous weighing of the finished pellets. Density values will be calculated with a computer from a continuous input of these measurements.

The finished pellets are loaded into new fuel tubes under a vacuum and the tubing is sealed by welding in a helium atmosphere. The completed fuel rods are heated in a vacuum chamber connected to a helium leak detector. The helium in the fuel rods ensures a positive test of the integrity of the rods. Bundles of 25 rods are assembled and fitted with spacer clamps after which the end pieces are pressed into position. Specially designed snap rings lock the rod bundles to the end pieces and obviate further remote welding which is complicated and difficult.

Design of the PCUT Plant and Equipment

The operations are carried out in two shielded cells (Figure 21) - a hot cell for operations with materials of high activity and a warm cell for operations involving lower levels of activity. The hot cell, which is an exclusion area, contains the high-activity-level chemical process equipment. A decontamination cell (12-1/2 x 14 x 17 feet high) is located at one end of the hot cell.

The ceiling of the decontamination cell has removable shielding plugs for handling material vertically in the cell and for removal and introduction of material and equipment from the service corridor on the first floor.

The warm cell is a shielded enclosure that permits remote handling of the low-activity chemical processing equipment and of the mechanical equipment necessary for fuel pellet production and fuel element assembly.

The warm cell is shown in the center of Figure 21; it is 13-feet wide, 56-feet long and 16-1/2-feet high. The warm cell is equipped with glass shielding windows, a pair of manipulators for each of nine windows, and a single manipulator for the tenth window. The equipment also includes an electromechanical arm and a 3-ton hoist, which are used primarily to assist in servicing the machines and transferring material.

In addition to openings in the cell wall required for manipulators and machinery operators, there are removable roof plugs opening to the service corridor to permit the passage of machinery and equipment, including the cell cranes. Clearance around the cell in the cell operating area is about 14 feet to allow for the removal of the manipulators.

A transfer lock near the east end of the warm cell is used to raise the refabricated fuel elements into the transfer flask in the corridor over the warm cell. Nonradioactive materials are also introduced into the cell through the transfer lock.

During construction and startup operations (that is, before active material is in the cell), personnel may enter and leave the cell through an opening in the east wall. Before hot operation begins, this opening will be semipermanently closed. Other openings in the warm cell include a small transfer drawer, with which small objects may be placed into or removed from the cell, and a number of wall plugs for instrumentation leads, utilities lines and mechanical linkages.

Equipment in the warm cell is fastened to base plates with locating pins and quick-disconnect clamps and is easily removable. When a piece of equipment must be repaired or replaced, the quick-disconnect clamps are removed with an impact wrench fastened to a cell crane and guided by manipulators. The item to be removed is first enclosed in a polyethylene bag to prevent contamination of the corridor, then lifted by the cell crane, and moved beneath one of the cell covers. The equipment is lifted out of the cell with the corridor crane and placed in the decontamination cell. In the decontamination cell, the polyethylene bag is removed and decontamination is begun with manipulators and external sprays. When the activity level of the equipment is acceptable for personnel entry, the equipment will be repaired or replaced and returned to service.

The support facilities are sufficient to make the PCUT plant a self-sufficient complex capable of performing all operations necessary to reprocess and refabricate fuel assemblies.

Current Status

The PCUT plant is now under construction.

Thorium-Uranium²³³ Fuel Elements in the Thorium-Uranium Fuel Cycle Development Facility (TUFCDf)

A versatile, integrated facility, the TUFCDf, for development of all phases of the thorium fuel cycle is being designed by ORNL⁽²⁵⁾. The objective of the TUFCDf is to demonstrate remote fabrication

technology and economics. The fuel types that were considered in the development of criteria for the facility were oxide and carbide; however, other fuels such as alloys, dispersions and beryllides could be accommodated. The facility is to be capable of handling full-size power reactor fuel elements. Because this facility is to be used for development and not for production, capacity figures are not especially significant, as the capacity will be a function of the complexity of the process and the design of the production equipment.

The facility is to be capable of processing and refabrication of fuel assemblies that have maximum lengths of 12 feet and that have decayed for 90 days. Shielding is to be sufficient to permit refabrication of fuel which has undergone little or no decontamination. Normal source size will be limited to 35 kg irradiated to 25,000 Mw $\cdot$ d/tonne; however, larger sources could be handled without overexposure of personnel to radiation.

The desirability of a heavily shielded fuel cycle facility for either experimental or production purposes derives from two factors. The first is that the material to be refabricated will, to an appreciable degree, be radioactive and will require confinement in a closed, sealed and shielded space; in addition, operations on a significant scale most probably will be carried out by automatic equipment or by use of manipulators. The second factor is that some saving can probably be made in capital expenditure for and operating cost of reprocessing equipment by a reduction in the fuel decontamination requirement.

Instead of using a high-decontamination multicycle process, some simpler single-cycle process yielding relatively low decontamination factors could be substituted. Because both capital cost of the shielded space and operating cost for the fabrication equipment will obviously not be strongly influenced by reasonable shield thickness, a heavily shielded facility may yield an overall lower fuel cycle cost than can a facility with shielding adequate only for the U^{232} decay products at short times after complete decontamination.

Design of the TUFCDP

To accomplish the objectives, four operating cells and two service cells are required, as shown in Figure 22. The four operating cells are arranged in a line with one of the service cells which is to be used for decontamination and as a radiation lock, teeing off from the line at the point where the two large central cells join. Another service cell, to be used for storage of contaminated equipment, is located at the basement level and joins the decontamination cell via a hatch in the decontamination cell floor. All cells, except the storage cell, are to have the equivalent of 5-1/2 foot normal concrete shielding. The storage cell will have a 1-1/2 foot normal concrete shielding. The four operating cells are to be used for chemical processing, mechanical operations incident to irradiated fuel recovery, and to reconstitution of fissile and fertile materials into forms suitable for use in fuel element manufacture, fabrication operations through the point at which fissile and fertile material are contained in fuel

elements, and final fabrication operations such as inspection and assembly. All operating cells will have a common roof line, but the floor levels are different.

Three of the four operating cells either are, or can be, maintained entirely by remote devices. The clean fabrication cell is the exception because it is to receive fuels shortly after they are encapsulated in tubes or other containers. In this cell the installation and repair of equipment will be accomplished by contact methods (i.e. in gloveboxes). Either remote or contact maintenance may be used in the chemical cell. A doorway and shielding are to be provided such that it can be either isolated from or joined with the mechanical processing cell. If the door is open and the shielding removed, the overhead crane and mechanical arm bridges can enter the chemical cell.

The lifeline of the cell complex is the transportation system. This consists of a pair of overhead bridge cranes that can travel over essentially all the area in the glove maintenance room and the decontamination, contaminated-fabrication, mechanical-processing, and chemical cells. A special transfer bridge system, to be provided in the decontamination cell, will be able to move in three planes and will provide for easy movement of a hoist from one area to another and will also allow removal of the operating cell bridges to the glove maintenance room for repair. Bridge-mounted mechanical arms will be provided for the cell complex.

The operating cells and the decontamination cell are laid out on a modular pattern of approximately 8 x 10 feet. With some exceptions, each module is provided with a window liner, holes for master-slave manipulators, five one-inch stainless steel pipes leading to the service area, ten bent-tube service access sleeves and three stepped plugs for passage of replaceable service lines, two 1500-w iodine-quartz lamps, plus a number of precisely located foundation pads in the floor for mounting of equipment. At alternate modules, stations are provided for waste collection, hot off-gases, and periscope installation.

The remotely maintained portion of the cell complex is to be exceptionally well sealed in order to adequately confine radioactive materials and to allow for future conversion to an inert atmosphere. All openings, whether they are for viewing windows, doors or service access, will be tightly sealed. This seal is to be maintained at all times. In order to maintain a constant seal, somewhat special designs are being used for windows, service access sleeves, manipulators and other devices.

Also provided is a fuel storage basin connected to the decontamination cell by a canal. The building will provide space for operating areas, service equipment, offices, change rooms, small development laboratories, and an equipment receiving area.

Approximately 30 percent of the design work on the TUFCDP has been completed.

Fabrication Processes in the TUFCDP

(Thorium-Uranium²³³) O₂-Bearing Fuel Elements

The process equipment to be initially installed in the TUFCDP is to be designed especially for preparation of metal-clad oxide-filled rods that are to be assembled into complete reactor fuel elements. The sol-gel process is to be used for preparation of dense Th-U oxide, and vibratory compaction is to be used for densification of graded oxide fuel solids within metal tubes.

As the facility is to demonstrate remote fabrication technology and economics, the design of the process equipment is based on the scale-down of equipment concepts that might be used in full-scale production plants. Since operations in a full-scale production fabrication plant would very probably be performed by semiautomatic or automatic equipment, the objective of the TUFCDP process equipment is to demonstrate on a unit basis the feasibility of remote operation and maintenance of that type of equipment. This objective does not require that means be provided for automatic conveyance between all process steps or for programed control of the complete process.

The equipment is to be sufficiently flexible to permit the fabrication of rods ranging from 1/4 to 3/4 inch in diameter and from 2 to 10 feet in length. In actual practice, this objective will be met by designing equipment that can be retooled by replacing chucks, adapters, seals and other parts.

In addition to this basic design criteria, there are other criteria which are dictated by the facility design itself and by the radiological hazard presented by the materials that are to be processed. These criteria fall under the following categories:

Installation, Maintenance and Removal of Equipment

All equipment to be used within the mechanical processing and contaminated fabrication cells is to be suited for remote installation, maintenance and removal within the capabilities of the remote handling equipment. Insofar as practicable, motors, switches, complex mechanical components, etc., are to be designed to permit replacement within the cell without removal of the complete item of equipment. The equipment to be used within the clean fabrication cell is to be installed, maintained and removed by direct-contact means aided by the handling facilities of both the cell and the building.

Fuel Powder Containment

It is desirable to guard the fuel powder from the cell atmosphere in order to prevent the loss of valuable material and to prevent dust from the fuel powder unnecessarily contaminating the cells and equipment. The exposure of uncapped fuel-bearing tubes for short periods of time is permissible, however, because such transfers will be done after the fuel has been compacted, when the danger of dusting is at a minimum.

Materials of Construction

Most of the in-cell equipment is to be fabricated from mild steel

or aluminum. The use of stainless steel is to be limited to the following applications: (1) the parts of the process and transfer equipment that directly contact the process fluids and fuel; (2) containers of corrosive liquids or parts exposed to a corrosive atmosphere; and (3) isolated uses that warrant the additional expense.

All pneumatic systems used within the contaminated fabrication cell are to be capable of operation with helium, argon or air. Elastomers, or organic materials, are to be used sparingly within the cell, and then only in such cases where the elastomer can be easily replaced and is restrained by metal parts.

Design of the Reference Fuel Element

Because the design of the initial tooling for the fabrication and inspection equipment depends to a great extent upon the configuration of the fuel element to be made, it was necessary to use a reference assembly as a basis for the equipment design. The reference fuel element was chosen to be a modified Elk River Reactor element. This element is being redesigned so that it can be mechanically assembled.

Refabrication Process

The fuel is to be reconstituted by the sol-gel process.

The fuel-element fabrication and inspection process involves generally five categories of operations: (1) the conditioning of bulk oxide to render it suitable for vibratory compaction; (2) the vibratory

compaction of the oxide in fuel tubes and their end capping; (3) fuel-rod cleaning; (4) inspection; (5) fuel-element assembly and inspection. The operations are depicted in the flowsheet (Figure 23) and the equipment layout (Figure 24).

Oxide Conditioning

The fuel material from the sol-gel process in the mechanical processing cell is deposited into a vibratory feeder trough that transfers material to a vibratory spiral elevator. This elevator serves as a vertical transfer device and as a feed control to the jaw crusher. The material, which can be up to one inch in size, must be crushed to 10 mesh or finer. The crushing is accomplished in two operations: the first, jaw crushing, in which the one-inch particles are reduced to 1/4 inch or less and the second, roll crushing, in which the material is reduced to 10 mesh or finer.

The material delivered by the roll crusher is deposited into a second spiral elevator that transfers the material at a controlled rate to the first, or No. 1, classifier. This classifier is a three-screen, four-deck continuous machine that separates the material into four fractions and deposits them into storage hoppers (not shown in Figure 24). Below each of these hoppers is a shut-off valve and a flowmeter that will indicate the amount of each fraction of material that is being used in the ensuing process.

The material from the first classifier is distributed as follows:

the coarsest fraction is transferred back to the crusher via the first spiral elevator; the next material fraction, which is acceptable as the coarse fraction of the fuel rod material, is fed to the weighing machine; the remaining two fractions are fed independently to the ball mill.

The two fractions fed into the ball mill are milled for a predetermined length of time. Most of the coarser fraction after milling is the correct size for the intermediate fraction of the fuel-rod material, while the major portion of the finer fraction after milling is suitable for use as the fine fraction of the fuel-rod material.

The ball mill discharges into a third spiral elevator that discharges to a second classifier that separates the material by size into four fractions. The material of two of the size fractions is fed into the weighing machine and the other two fractions are recycled to the ball mill for further processing.

The weighing machine dispenses a predetermined weight of each of the three material size fractions so that their combined weight is the correct amount to load into a fuel rod, and dumps them into a common container. The material in this container is transferred by the fuel-transfer unit to the blending operations.

Fuel Rod Fabrication

In general, the fabrication equipment is in the form of a multi-station system with the electromechanical manipulator used to move the fuel rods from station to station.

The empty fuel tubes are brought into the cell in a tube magazine by means of the in-cell crane and placed into the fabrication process line at position No. 1. From position No. 1, the manipulator moves an empty fuel tube to the Blender-Fill-Vibrate Machine at position No. 2. The fuel material that was deposited into the blender of this machine by the fuel-transfer unit is blended and fed into the fuel tube. The tube is vibrated until the desired fuel density is obtained.

The tube is transferred to position No. 3, the gamma scanner, where the density of the fuel in the tube is inspected. Fuel rods rejected by the gamma scanner inspection are transferred to the reject fuel rod basket at position No. 4, and those accepted are transferred to the cap-and-welding machine at positions Nos. 5 and 6. At position No. 5, the Al_2O_3 plug, spring and end cap assembly are inserted into the fuel rod; and at position No. 6 the cap assembly is pressed into the fuel tube and welded. From the welder, the rod is inserted into the fuel rod basket, position No. 7.

Cleaning and Intercell Transfer

The cell crane transfers the basket of approximately ten fuel rods from its position in the fuel-rod fabrication line into the cleaner tank. There the fuel rods are subjected to a complete cleaning cycle of washing, rinsing and ultrasonic cleaning and then transferred horizontally on the carriage to the clean fabrication cell. The basket of fuel rods is removed by the crane in the clean fabrication cell and placed on the surface-smear indexing unit, position A, which is the first piece of equipment in the inspection process.

Fuel Rod Inspection

The arrangement of the fuel rod inspection process is similar to that of the rod-fabrication process; that is, a multistation system with an electromechanical manipulator to move the fuel rod from station to station. After the fuel-rod surfaces are checked for transferrable contamination at position A, the fuel rods are taken from the basket and placed into the helium-leak inspection unit, position B, by the transfer unit. At this position, the fuel rod is subjected to a vacuum to check for leaks in the end-plug weld area.

The fuel rod is transferred to the radiography unit, position C, where the end-plug weld area is X rayed to inspect for detrimental inclusions, porosity and void areas in the weld. The fuel rod is transferred to position D, where its diameter and length are inspected; and then it is placed in the storage magazine of the assembly machine, position E.

Fuel Bundle Assembly and Inspection

The fuel rods are inserted, one at a time, into the fuel bundle casing, after which the end fittings of the fuel bundle are welded to the casing. The assembled bundle is then dimensionally inspected for compliance with the tolerance on rod-to-rod spacing and fuel-element bow. The completed fuel bundle is moved by the cell crane to a location directly under the fuel-bundle transfer port and is elevated through the port into a shielded cask by the devices provided with the cask for that purpose.

Thorium-Uranium²³³ Fuel in Graphite

The development of processes for refabrication of fueled graphite fuel elements is being pursued at ORNL. This development involves the use of the sol-gel process to simplify and shorten flowsheets for making microspheres (nominally 200 μ) of (U-Th)C₂ and refinement of devices for coating the spheres so that such devices can be operated and maintained remotely. As soon as practicable, a complete line of equipment for demonstration of remote-fabrication technology on fueled graphite will be constructed and tested.

SECTION IV
THE EXPERIMENTAL BREEDER REACTOR II
FUEL CYCLE

One of the purposes of the second Experimental Breeder Reactor (EBR-II) is to demonstrate an integrated system for fuel recycle. The EBR-II plant includes a facility for recovering the radiation-damaged fuel and for refining it to remove the damaging fission products. No attempt is made to decontaminate the refined product to biologically safe levels. For this reason the fuel must be refabricated into fuel elements by remote controlled processes.

The plant, which recovers and refines the fuel and then manufactures it into fuel elements for return to the reactor, is named the EBR-II Fuel Cycle Facility.

The EBR-II is a small high-performance reactor. It is designed to produce 62.5 Mw of heat. Its core volume may be varied to allow use of a variety of core compositions and configurations.

The reactor, coolant pumps, fuel-changing mechanism and fuel-cooling rack operate submerged in a large tank of sodium. The fuel-changing mechanism is designed to load and unload individual fuel elements on a regularly scheduled basis. The fuel elements are transferred out of the reactor core and cooled for 15 days in the sodium. At the end of this time, radioactive heating has diminished to a level that allows the fuel to be gas cooled. Fuel will be managed so that not more than three elements (273 fuel rods) need be processed per week.

The Core-I fuel element is shown in Figure 25. It was designed for remote disassembly and assembly. At present the lower adapter and 18 lower blanket rods are preassembled from outside the process cell. A second preassembly consists of the upper blanket, hexagonal tube and handle fitting. The fuel bundle is constructed and assembled with the lower and upper blanket sections by remote control.

The fuel section contains 91, 3.66-mm-diameter by 36.0-cm-long, uranium alloy pins. These pins are sodium bonded in 0.23-cm wall st. steel jackets. The bond is nominally 0.15-mm thick. The bottom of the jacket is closed by a T-slotted fitting by which the rod is anchored in the fuel element. The fuel rod is restrained from ratchetting or growing vertically in the jacket by an internal strut that is part of the top weld plug. This component is termed the "restrainer". The individual fuel rods are spaced one millimeter apart in the fuel element by means of spiral wires.

Lateral control of the fuel bundle is important to prevent motion and chafing together from the hydraulic forces of the flowing sodium. This is achieved by a series of lateral beads on the inside of the hexagonal tube compressing the fuel bundle. The finished assembly must be straight within one millimeter and must be proof tensile tested at loads beyond those that might be imposed by the fuel-handling and-loading machines.

The initial Core-I loading is a 95 w/o-uranium-5 w/o fission alloy. Fission is a name given to the mixture of fission products that

are not removed in the refining process. In the initial loading, the alloy was simulated by an alloy of nonradioactive natural elements.

With multiple recycle, the concentration of fission will depend upon the quantity of uranium (or plutonium) added per cycle to replace that burned out and upon the process losses. The analysis of fission will change somewhat as plutonium is added or builds into the fuel. Table VIII shows the initial composition of the Core-I fuel and calculated equilibrium compositions for the uranium based fuel alloy.

The Fuel Cycle Facility⁽²⁶⁾

The EBR-II Fuel Cycle Facility, a building with a floor area of 19,000-square feet, houses two large shielded cells. A sectional view of the Fuel Cycle Facility is shown by Figure 26. The rectangular cell encloses a shielded volume 15-feet wide by 47-feet long by 21-feet high. Air is changed every three minutes by 5000-cfm blowers. Access is by a circular six-foot diameter floor port from the basement, by shielding doors in the south wall, and by a 12-inch diameter shielded pass-lock in the north wall.

The second cell is a 16-sided regular polygon measuring 62 feet inside of flats (the inner diameter normal to two opposite sides). The center of this area is occupied by a shielded control room of the same shape. The control room measures 30 feet across flats by 10 feet high outside the shielding. This leaves an annular space 16 feet wide for process equipment.

TABLE VIII

Predicted Equilibrium Compositions
and Core-I Compositions

Elements	Predicted Fission Range 3.7 - 8.8 w/o Fs	Core I Nominal Composition 5 w/o Fs	Core I Analytical (a) Composition w/o
Molybdenum	1.6 - 3.4	2.46	$2.56 \pm 0.12^{(b)}$
Ruthenium	1.2 - 2.6	1.96	2.14 ± 0.07
Technetium	0.5 - 1.0	--	--
Rhodium	0.2 - 0.5	0.28	0.27 ± 0.03
Palladium	0.1 - 0.3	0.19	0.19 ± 0.02
Zirconium	0.1 - 1.0	0.10	0.11 ± 0.03
Niobium	0.01	0.01	$0.01^{(c)}$

(a) Emission spectrographic data on cast fuel pins.

(b) All deviations were determined from the averages by

$$\sigma = \sqrt{\frac{\sum x^2}{n} - \bar{x}^2}$$

(c) No analysis was obtained for niobium; quantitative alloying assumed.

Shielding walls and windows are five-feet thick. The windows and the concrete walls have a density of 3.5 g/cc. They were designed to attenuate radiation from a 10^6 -r/hr one-Mev source, at a distance of one foot from the inside wall, to less than 0.1 mr/hr at the outer surface. The inner wall of the cell is sealed by a zinc-coated steel liner.

Work upon irradiated metallic fuel and sodium requires an inert atmosphere to prevent excessive oxidation and fire. The 16-sided "circular" cell is provided with a recirculated, cooled and repurified argon atmosphere⁽²⁷⁾. The total volume of the cell and atmosphere system is about 60,000 ft³ (1700 m³). The atmosphere is recirculated by two 14,000-cfm (400 m³/min) blowers across heat exchangers capable of removing 270 Kw of heat. Because of possible metal reactions and nuclear hazards, no water may be used for cooling process equipment. The high velocity of the argon atmosphere materially assists in cooling furnaces and the radioactively heated fuel.

About 2200cfm (62 m³/min.) of the argon is filtered and passed thru a catalytic reactor. The oxygen is reacted with hydrogen. The resulting water vapor is absorbed by a synthetic zeolite drier. Nitrogen is not removed and will gradually reach a value limited by the argon makeup additions. Oxygen is reduced to a few parts per million. After a period of operating with a very low water vapor content, the humidity of the atmosphere was deliberately increased to improve sodium handling.

Cranes, manipulators and much of the process equipment have dual controls: one set in the central control room and one set in the operating annulus. Auxiliary equipment, connected by piping to the process machinery, is housed in a shielded subcell directly below the argon cell. This includes vacuum pumps, pneumatic controls, the argon purifying system, etc. Although filters between the process and subcell equipment collect much of the radioactive contamination, eventually the radioactivity in the subcell will limit personnel access in this area. Subcell equipment is installed with quick disconnects and mounted on skids so that it may be replaced with minimum personnel exposure.

Connection between the subcell and argon-cell equipment is made thru standardized prefabricated feed-thru shield plugs. Standard electrical, vacuum line, pneumatic and instrument feed-thrus are interchangeable by crane and manipulator from within the argon cell.

Materials and equipment are transferred between the argon and air cells thru vacuum locks. Two of these locks, 13-inches wide by 23-inches high, are one-way passages thru the common wall. Four-wheel bogies move down inclined tracks toward the air cell in one lock and toward the argon cell in the second lock.

Large items and equipment are transferred both ways thru a vacuum lock in the argon cell floor, thru a passage beneath the common wall and thru a trap door in the argon cell floor. The vacuum lock is a six-foot (1.8-m) diameter by an approximately 5-1/2-feet (1.7-m) high cylinder. The upper end of this lock extends into the argon cell. A

hydraulically elevated platen seals the lower flange of the vacuum lock. When lowered, the platen is positioned on an electrically controlled shuttle car which moves beneath the trap door. The load is picked up by the argon cell crane.

Cranes and Manipulators

The annular plan of the argon cell has many advantages. Radial cranes are used for the six electrically-controlled manipulators and two hoists. The cranes and hoists are powered from slip rings on a central column. The manipulator cables are short and connected near the center of the cell. They are designed so that the manipulator cranes can make more than one circuit of the cell. Thus, all the general-purpose manipulators and hoists are available to all operating locations in the cell.

The general-purpose manipulators are of special design to reduce radiation damage to motors⁽²⁸⁾. They are used with interchangeable tongs, a single-hook grip, or a double-hook grip attached to the bottom of a vertical telescoping tube. Grip, rotary and x, y and z motions are controlled from motors located in a shielded box above the cranes. Normally the manipulator tools are attached directly to telescoping vertical tubes. For nonroutine applications, a conventional articulated manipulator arm with elbow and wrist movement can be attached to the lower end of the telescoping tubes. Since the conventional arms have a limited operating life under high radiation and in a very dry atmosphere, their use is reserved for emergencies.

The general-purpose manipulators can be lifted from their cranes by means of a hoist. This hoist is located in a "blister" or cupola on the roof of the argon cell. The manipulators are interchangeable with others in the argon cell and with those in the air cell. The air cell cranes are of the more conventional bridge type.

Model-8 manipulators are installed over each window in the air cell. Sealed master-slave manipulators are used at three locations in the argon cell.

Fuel Cycle Processes

A simplified flow diagram of the EBR-II Core-I Fuel Cycle is as shown in Figure 27. For purposes of this report, refabrication operations are detailed, less detail is given on fuel recovery and reprocessing⁽²⁹⁾, and no detail is given on blanket processes or slag processing⁽³⁰⁾. The equipment floor plan of the Fuel Cycle Facility is shown in Figure 28.

After 15 days' cooling in the primary sodium tank of the reactor, the fuel element is removed from the tank by the reactor loading machine and placed in the interbuilding transfer coffin⁽³¹⁾. The coffin is top loaded thru a sealed slide gate. It is equipped with a recirculated atmosphere to remove heat from the fuel elements. The cooling blowers may be powered by self-contained batteries or by an external power source.

The interbuilding coffin moves thru a corridor between the reactor and Fuel Cycle Facility (FCF). Sodium is removed from the fuel element at a station in this corridor. This is accomplished in the coffin by oxidizing the sodium with a recirculated air-argon mixture followed by reaction with moisture-saturated air. After the sodium reaction is complete, the element is rinsed with water and dried with warm air. During the rinsing cycle the blower is isolated to prevent loading it with water.

The coffin moves into the FCF. A crane lifts it from its carriage and lowers it thru a hatch onto a similar carriage in the basement. The coffin is moved below the air-cell floor port. The slide gate is

opened and a grapple with a self-contained blower is lowered onto the fuel element. The grapple engages the handle of the element and it is lifted into the air cell by the crane.

Fuel Recovery

The element is loaded into the fuel-element dismantling machine⁽³²⁾. As the element is rotated, the dismantling equipment cuts the hexagonal tube by means of rolling cutters. Cuts are made at the lower adapter and near the handle. The ends and the hexagonal tube are drawn from the fuel and blanket bundles. If this operation is not successful, the dismantling machine is equipped with longitudinal cutters that can be used to split the hexagonal tube.

The blanket sections are dismantled by twisting off the stainless steel bolts thru the end grids. The grids are pulled off leaving the blanket rods free. The blanket rods are removed by Model-8 manipulator. The fuel bundle is restrained in its original configuration by constraining clamps. One row of fuel rods is separated from the bundle at a time by a wedge. A feeder separates single rods for inspection and loading into decanner magazines.

The magazines, loaded with fuel rods, are transferred thru the vacuum locks into the argon cell. The decanner⁽³³⁾ and fuel-pin chopper are used to recover the fuel for melt refining. The rods cropped from the fuel rods at a point just inside the spot welds that attach the spiral wire; the wire separates and drops free. The stainless steel

tube with fuel pin is pushed thru a motor-driven three-roll spiral rotary shear that cuts the stainless steel into a continuous 1/8-inch wide spiral ribbon. The fuel pin is pushed thru a chopper that progressively breaks it into one-inch to 1-1/2-inch lengths. The fuel pieces are loaded into an extended-surface hopper, which is convectively cooled.

Melt Refining

The purpose of melt refining is to remove metallurgically or neutronically undesirable fission products from the fuel. The fission products that form gases at reactor temperatures probably are the most undesirable since they cause the fuel to swell. The melt-refining step is also used for re-enrichment of the fuel and for addition of fertile materials to compensate for burnup and process losses.

Melt refining is accomplished by slowly heating chopped irradiated pins to about 1400°C in a zirconia crucible. The melt is liquated at this temperature for about three hours. Argon gas at about one-atmosphere pressure is used over the melt during much of this period.

The volatile elements, bromine, krypton, rubidium, cadmium, iodine, xenon and cesium are released^(34, 35, 36). A fibrous aluminum-silicate fume trap over the crucible condenses and traps cadmium, cesium, rubidium and adhering sodium. Bromine and iodine tend to condense on cold parts of the furnace and piping. An activated carbon trap and silver nitrate scrubbing tower remove the iodine and bromine in the

exhaust to tolerable levels. The noble gases, xenon and krypton, and residual halides are pumped to a retention tank for decay and favorable meteorological conditions to discharge to the atmosphere.

Tellurium, strontium, barium, yttrium and the rare earths react with the zirconia crucible forming an adherent oxide slag⁽³⁵⁾. This remains in the crucible when the melt is poured. These elements are removed with an efficiency of over 95 percent.

Zirconium, niobium, molybdenum, technetium, ruthenium, rhodium and palladium are not removed by melt refining^(37, 38). There is also little oxidation of the uranium and plutonium, although at 1400°C some volatilization of the plutonium may be expected. The fission products, which are not removed by melt refining, build into the fuel with multiple recycle. They are diluted by additions of uranium and plutonium added to replace burnup and process losses. If reactor fuel management and operation is consistent and make-up additions are constant, an equilibrium composition will result.

Melt refining is carried out in the induction furnace shown in Figure 29. A prototype of this furnace was used for preparation of Core-I alloy⁽³⁹⁾. The induction coil is wound from a solid 1/2-inch diameter copper rod. A graphite mold in a steel shell is used. The furnace chamber is of the bell jar and flange type and is made of electroless nickel-coated steel. A fusible metal seal is used to seal the bell jar to the furnace-base flange. Power is supplied from one of two 30-kw 9,600-cycle/sec motor-generators. It should be noted that, owing to radioactive heating, very little power is required.

The normal melt-refining charge is six to ten kilograms and is composed of fuel pins and recycle shards. The refined metal is poured into a 3" x 3" x 4-1/4" ingot. Melt refining removes about two-thirds of the fission product by weight. It also reduces radioactive heating to one-third that before refining.

The EBR-II Fuel Refabrication

The six to ten kilogram melt-refining billets of radioactive fuel must be refabricated into fuel pins. The fuel pins must be jacketed and bonded to make fuel rods. And the fuel rods must be assembled by remote control with upper and lower blanket preassemblies to make the fuel elements.

The uranium-5w/o to -10w/o fissium alloys were very hard and tough. The original rolling tests were discouraging. After two or three passes in the rolling mill, the material work hardened excessively and further rolling required heating to above the gamma-phase transition. The cast material was of variable hardness. When chill cast, thin sections measured as low as Rockwell-C-35. After heating or working, the hardness increased to Rockwell C-55 or above.

Zeigler and Nevitt studied the metallography of three-to-ten weight-percent fissium alloy⁽⁴⁰⁾. They demonstrated that these alloys quenched from above the gamma transformation temperature contain a large percentage of the retained gamma phase. The hardness and density of this material were low and the gamma phase was metastable. When heated

to above 400°C, it is converted by martensitic transformation to the alpha-uranium structure. Similar gamma phase retention occurred in the chill castings. Heating and working caused transformation of the structure and resulted in increased density of the metal.

The fluidity and castability of the alloy were very good. It replicated the minute machine marks and defects of the molds in which it was cast. With sufficient superheat it was possible to cast the fissium alloy ^{IN}is very thin sections.

The unusual properties of the alloy, the high radiation levels and the inaccessibility to normal operating and maintenance precluded use of conventional commercial fabricating machines. The high radiation levels, in the range of 10^6 -r/hr, were such that ordinary lubricants, electric insulation, rubber gaskets and hydraulic fluids would be damaged within a few weeks' operation. Radiation heating made cooling rather than heating necessary for most operations.

As a result of the above considerations, a program to develop a new fabricating method was initiated. The program was based upon the following requirements:

1. The process should have a minimum number of steps.
2. It should handle a range of alloy compositions and should be adaptable to uranium-base fuel and to plutonium-bearing fuel.

3. It should be adaptable to various shapes and sizes of fuel rods.
4. Repeating operations should be mechanized.
5. The materials used in constructing the equipment should be good for at least 10^9 -r total dose.
6. No materials should be used which, upon irradiation, would poison the catalysts in the atmosphere purifying system.
7. Process equipment should be designed for manipulator and crane assembly, installation and replacement.
8. Argon cell equipment should disassemble into components that will pass thru the vacuum transfer locks.
9. The equipment should be built up of prealigned sub-assemblies that would plug together with simple vertical and vertical-axis rotary motions.

Precision Injection Casting

Of the several methods considered, it appeared that precision casting could meet these requirements. After trying several methods of precision casting, gas-pressure injection casting was selected as the most suitable method⁽⁴¹⁾. Basically, injection casting consists of suspending a number of impermeable precision-bore mold tubes vertically,

with the open ends down, above a crucible of molten metal. The furnace and molds are evacuated. The crucible is raised to immerse the mold ends and the furnace is rapidly pressurized with inert gas. The pressure on the surface of the metal in the crucible causes the evacuated molds to fill. As soon as the metal in the molds solidifies the crucible is lowered. Neither sprues nor runners are required.

Vycor glass was selected as the most suitable mold material. It will withstand the thermal shock of casting 1350°C metal. It may be formed to extremely close tolerances. Glass fabricators produced 0.1480 ± 0.001 -inch (3.75 ± 0.025 mm) diameter by 18-inches (45.7-cm) long molds. One end of the molds was flattened and fused closed. The opposite end is open but cut at an angle of 60° to the axis to form a drip tip.

The molten fuel reacts with the glass leaving the castings coated with a brittle silicon alloy. This reaction is prevented by a thin coating of 5-10 micron thoria. The coating is applied to the inside of the mold, as a 25-gram thoria suspension in 25 ml of ethyl alcohol, by means of a short length of pipe cleaner on a wire handle. The application is kept very thin in order not to destroy diametral precision. The lower outside portion of the mold is also coated. After coating, the molds are air dried and then heated to 800°C in a muffle furnace to "set" the thoria on the surface of the Vycor. The molds were usually stored in a 160°C oven to prevent adsorption of atmospheric moisture.

A sectional view of the injection-casting furnaces used in the

Fuel Cycle Facility is shown in Figure 30. A thoria-washed graphite crucible of 16-kg capacity sits upon a compressed argon-powered vertical actuator. When the actuator is in its lower position, the crucible is centered in an induction heater. The crucible actuator is a plug-in assembly and connects to the compressed argon line by a small metal freeze seal. Temperature is read by a base-reference thermocouple against the bottom of the crucible.

The induction heater consists of a six-turn internal coil, a lava and spun-alumina external insulator, and alumina and Inconel structural members⁽⁴²⁾. The coil is wound from a 3/8-inch diameter solid molybdenum rod. The use of an internal coil improves coupling and reduces temperatures of the furnace shell. A double door Inconel furnace cover, which is a part of the heater assembly, is pushed open when the crucible is raised.

As many as 160 molds can be placed in the mold pallet. This requires a furnace charge of 16 kg. A more normal load is 12 kg of metal and 120 molds. The pallet consists of two perforated stainless steel plates on a central column. The lower plate may be lifted into contact with the top plate to make mold loading by manipulator more easy. The center column is a perforated tube that helps to distribute quench gas. Provision is made in the pallet for a central dipping thermocouple for calibrating the crucible thermocouple and for programming crucible retraction.

The mold pallet is supported on a combination baffle, shield

and stand. After casting, the furnace atmosphere is circulated thru a filter and a cold exchanger by a turbocompressor and returned to the furnace. The gas circulates up around the outside of the mold support and down thru the mold cluster to accelerate its cooling.

The furnace shell is of the bell-jar type. The bell jar is sealed to the furnace base by means of a fusible metal trough into which the lip of the bell jar dips. The freeze seal is electrically heated. Cylindrical resistance heaters surround the mold zone. These are used to preheat the molds before casting.

All components of the furnace are of plug-in design held together by gravity. Manipulator trunions are provided so that many of the subassemblies can be picked up directly by a double-hook grip on the manipulator. The furnace auxiliaries consist of two vacuum pumps, an accumulator tank for pressurizing the furnace, a seven stage turbocompressor, cold exchanger and filters. These are located in the subcell.

Injection casting depends upon a rather involved set of conditions. The parameters of the following conditions were investigated: (a) melt size, (b) melt superheat temperature, (c) number of molds, (d) mold temperature, (e) pressure (vacuum) before casting, (f) pressurizing delay after crucible elevation, (g) pressurize rate, (h) ultimate pressure, and (i) timing of crucible retraction.

Several conditions were found to be interdependent. The number of molds can be determined by subtracting the weight of the heel (about

1400 grams) from the charge weight and dividing by the weight of the charge times 89. The pressurizing rate, controlled by a throttling valve in the line to the accumulator, was determined to be more important than ultimate furnace pressure after casting.

Timing was found to be important. If the furnace is pressurized immediately after crucible elevation, frozen metal plugs the mold gates and the molds do not fill properly. If pressurizing is delayed for about five seconds after raising the crucible, the lower ends of the molds are preheated and a much better yield of acceptable castings results. If the crucible is lowered before the metal in the molds freezes, some will run out of the molds producing hollow castings. On the other hand, if crucible lowering is delayed too long, the metal heel in the crucible will freeze to the castings. Automatic program controllers were provided so that casting conditions may be repeated.

The 12,000 fuel pins, made by injection casting for the Core-I initial loading, were used to establish casting parameters on a statistical basis^(43,44). Once the casting variables were controlled, the overall yield of good fuel pins was 84.5 percent. The following defects were noted and causes of defects were established.

1. Drip back was caused by lowering the crucible before metal solidified. It was corrected by addition of timed program controls and use of forced gas cooling.
2. Hot tears were caused by lowering the crucible too late, also by castings sticking to molds. This defect was partly corrected by program controls.

3. Surface defects were caused by improperly applied mold wash or incompletely outgassed molds.
4. Short castings or misruns were caused by cold molds, cold metal, plugged molds. Corrective measures were close control of temperatures, the use of clean metal and a five second delay after elevating crucible before pressurizing. Isolated instances of short castings remain unexplained.
5. Undersized castings were usually caused by a defective mold.

Fuel Pin Process and Inspection

After cooling, the pallet of injection-cast fuel pins is removed from the furnace. The molds are removed from the pallet by means of a master-slave manipulator and loaded into a magazine feeder. The magazine of gravid molds is installed on the first station of a pin process and inspection machine. The pin process and inspection machine has the following functions:

1. Remove the molds from the castings.
2. Crop both ends from the casting leaving a 14.22-inch (36.12-cm) long fuel pin.
3. Gage pin length to an accuracy of ± 0.01 inch (± 0.25 mm).
4. Weigh the fuel pin to an accuracy of ± 0.01 grams.
5. Measure and plot diameter vs. pin length.

6. Measure and plot a trace of impedance from an eddy-current sensing coil vs. pin length.

The pin process and inspection machine consists of four work stations on a modular five-platform, stair-step frame⁽⁴⁵⁾. Each platform consists of two rails to which the work station is locked. One rail of each step has four pneumatic disconnects; the other rail is equipped with two multipin electrical receptacles. The steps on the frames are standardized so that the work stations fit interchangeably between the steps on the base frame. The frame and plug-in stations are shown in Figure 31. The functions of each station are as follows:

Demolder

The demolder is located on the topmost step. Fuel pins are fed, one at a time, onto two closely spaced horizontal rails. The rail spacing will allow a fuel casting to drop thru, but the glass mold will not pass. A long hardened-steel blade is driven against the gravid mold by an argon-powered cylinder. The glass is broken and the casting is driven thru the space between the rails. The glass fragments fall down a chute into a hopper. The fuel casting rolls on inclined rails to the shear station.

Shear

The fuel pins are deposited singly by a feed gate into the shear. A pneumatic positioner adjusts the pin so that 3/4-inch (2-cm) is sheared from the bottom. The shear consists of two fixed tools spaced 14.24

inches (36.2-cm) apart and two opposing moveable tools mounted 14.20 inches apart. As the shear is opened the casting falls between the blades. The shear is closed and the casting is gripped over its length by spring-loaded clamps. As the shear stroke continues, the moving blades push the center portion past the stationary blades. The end shards drop into collector shutters while the 14.22-inch center section is released onto an incline and rolls to the length and weight measuring station.

Length Comparison

The fuel pin rolls against a stop on the inclined feeder. Here length is measured by the following operation. A pneumatic plunger pushes against one end of the pin until the plunger anvil engages a stop fixing the position of that end. The other end of the pin is pushed against a spring-loaded gaging anvil. The position of this anvil is sensed by a linear-variable-differential transformer (LVDT) which provides a signal that is calibrated in terms of pin length.

Weight

The pin is lowered onto a balance. This is adapted from a Mettler K5-T balance beam and suspension. The sensitivity of this beam is calibrated and beam movement is measured by a null-balancing LVDT.

Diametral and Eddy-Current Gage

The pin is lifted from the balance and rolls down an incline into a linear actuator. This actuator is powered by a ball-screw driven

by a synchronous motor. It pushes the pin thru an eddy-current coil and an argon-jet ring gage. The synchronous motor is powered by a variable-frequency oscillator which also powers a second synchronous motor on a chart drive in the data processor. The chart drive is geared so that each position along the length of the pin corresponds to the same position on the diametral and eddy-current traces.

Data Processing

Electrical signals from the length, weight, diameter and eddy-current sensing elements are fed into a data processor. This unit, located in the operating annulus, converts the electrical signal to numerical values of pin weight in grams. It mechanically integrates diameter over pin length and computes pin volume in cubic centimeters. The pin weight is divided by the volume resulting in density in grams per cubic centimeter. Pin diameter and eddy-current traces versus pin length are plotted on the strip chart recorder. The computed values obtained by the data processor are fed thru an encoder to an automatic data card printer. A separate data card is printed and punched for each fuel pin.

The data process equipment has limit alarms for out-of-tolerance conditions. The alarms assist the operator in making an accept or reject decision on each fuel pin. The fuel pins are pushed from the diametral gate onto a selective two-way diverter. Upon command from the operator the fuel pin is directed into accept or reject magazines.

Injection casting and fuel-pin processing and inspection complete fabrication of the radioactive fuel. The cell area in which fuel fabrication takes place is shown in Figure 32.

Jacket Preparation and Sodium Loading

Figure 33 shows the components of the EBR-II Core-I fuel rod. The quantity of sodium in the fuel rod must be closely controlled. If there is too little sodium, the fuel pin may not be fully immersed. If there is too much, there will be insufficient expansion space to accommodate volumetric changes of the sodium, fuel-rod components and fission products.

Preassembled jackets, each consisting of the tube, spiral wire and T-slot tip are supplied. Restrainers are furnished separately. The jackets are leak detected and 10-point bore gaged. The jackets are grouped by average bore diameter into ten, 0.0001-inch internal classes between 0.1555 and 0.1565 inch. The groups of jackets are transferred to an inert-atmosphere glovebox.

The weight of sodium loaded into each jacket is compensated for the jacket size. Clean, low-oxygen sodium is extruded as a 1/8-inch (3.2-mm) diameter rod. This rod is cut to a measured length and adjusted to within two mg of the predetermined weight. The weighed Na rod is inserted into the jacket thru a funnel which protects the lip of the jacket from sodium contamination. The loaded jackets are heated to 150°C to melt and outgas the sodium.

Sodium level caused a 15.8 percent inspection rejection in Core-I production⁽⁴⁶⁾. A statistical study showed the inconsistency of the relationship between fuel pin and jacket dimensions and sodium level⁽⁴⁷⁾. The problem was further complicated by an irregular volume change in the fuel pin resulting from transformation of retained gamma phase uranium. Sodium level tolerances were increased from 0.65 ± 0.10 inch (16.5 ± 2.5 mm) to a more realistic 0.65 ± 0.15 inch (16.5 ± 3.8 mm).

Fuel Rod Assembly

The jackets are capped with plastic seals and transferred into the argon cell to the assembly station. Fuel-rod assembly is a master-slave manipulator operation. The jackets are placed in a 20-rod rotary welding magazine. A guide fixture is installed on the magazine. Each jacket engages a funnel-shaped bushing that protects the weld lip of the jacket as the fuel pins are inserted. The bottom of the pin rests upon the sodium while the top protrudes about $3/4$ inch (2 cm). After the guide fixture is removed the magazine is inspected to see that all jackets have been loaded.

The magazine is transferred to the "settling" machine where it is heated to melt the sodium. The jackets are gently tapped from the bottom to settle the fuel pins into the sodium. When all pins have settled, a second guide fixture is placed over the magazine and a restrainer is dropped into each jacket. When these have settled into position, the assembled fuel rods are ready for welding.

Fuel Rod Closure Welding

The restrainer and jacket are fusion welded by discharging a capacitor across a gap between a thoriated-tungsten electrode and a projection on the restrainer.

The stored-energy, or capacitor-discharge, welding method was developed by C. C. Stone and R. A. Noland at ANL to circumvent problems associated with conventional TIG welding closures in small fuel tubes⁽⁴⁸⁾. These problems included current control, weld bead sagging, lack of fusion at low arc currents, overheating of the restrainer, and sodium vaporization at high arc currents.

By use of a welding current in excess of 500 amperes for a few microseconds, fusion of the restrainer plug and jacket tube may be accomplished before heat is transmitted down the tube and restrainer stem to the sodium. The entire top of the restrainer and jacket are fused in a hemispherical bead. The high current produces electromagnetic forces that tend to hold the weld bead in position.

Reproducible quantities of electrical energy may be stored by charging a capacitor to a given voltage under carefully controlled conditions. This energy is discharged through switches and power lines across a gap formed between a tungsten electrode (anode) and the fuel-element restrainer (cathode). Only a portion of the energy is available in the arc. The rest of the energy is expended in resistively heating the conductive elements of the circuits and in overcoming the

impedance to the rapid changes in current. With the 0.17 farad capacitor charged at 150 volts, the stored energy is 1900 watt-seconds. Between 500 and 700 watt-seconds of this energy is available in the arc. Both helium and argon arc plasmas were tried. Both were found to work although somewhat more effective arc energy was available from the helium arc.

Radio-frequency current from an oscillator tank circuit is used to start the arc. The functions of the high-frequency current are threefold: (1) to ionize the shroud gas between the restrainer and electrode, (2) to preheat the electrode and restrainer, and (3) to spark clean the electrode and restrainer top. Once the arc is initiated, a current-sensitive relay interrupts the high-frequency circuit.

The fuel rod welding and settling machines are shown in Figure 34. The function of the welding mechanism is to sequentially position fuel rods below a nonconsumable, inert-gas-shielded weld gun. Sensing functions, built into the mechanism, detect the absence of a fuel rod, the absence of a restrainer, or malposition of the fuel rod. The sense function is interlocked with the welder control to prevent firing in these cases.

The fuel rods are transferred from the settling operation in a rotary magazine. This magazine holds 20 fuel rods vertically on an eight-inch circle. A notched beryllium-copper chill plate at the top of the magazine positions and electrically grounds each rod.

To facilitate loading, the welder spindle, magazine and indexing mechanism are mounted on a pivoted arm. This arm is moved to either of two positions by a packless cylinder. Pressure is maintained on the cylinder to hold the magazine in either position, and in the weld position, to furnish the force that grips the fuel rod between the magazine chill plate and the idler wheel.

The spindle and magazine are indexed by an unconventional cam plate operated by a double-acting cylinder. The cam plate consists of two concentric ten-lobe cams inside a rigid housing. The cams are shaped so that each stroke of the cylinder imparts 18 degrees of rotation to the spindle. At the end of each stroke, the roller seats in the rigid portion of the cam for positive positioning. At each stroke the two lobe plates shift slightly in angular relationship preventing reversal of rotation. While a rod is welded, angular position is held by maintaining cylinder pressure.

The weld gun consists of an electrode-holding and clamping device and a cam shoe that depresses the fuel rods to the welding location as they pass below it. A multiple-leaf spring counteracts this depression. As the fuel rod passes below the shoe, it is gripped between the notched chill plate on the magazine and an idler wheel on the frame of the machine and held in vertical position. The chill plate forms a heat sink to localize the weld zone. It also provides an extended-contact surface electrically grounding the fuel rod.

Leak Detection

Leaks were found in Core-I fuel rods by mass-spectrometer leak detection⁽⁴⁴⁾. This was done by placing the rods in a pressure chamber and impregnating the expansion space in the rods with helium thru the leaks. This was followed by transferring the rods quickly to a second chamber that was evacuated as a sample was taken by mass spectrometer. With the long sensing lines required for remote operation, the method lacked both sensitivity and speed of response. Large leaks passed undetected because the expansion spaces in the fuel rods were evacuated before the mass spectrometer could respond.

A second method was developed in which the upper weld is enclosed in a close-fitting chamber⁽⁴⁹⁾. The test chamber is filled to 1000 psig (68 atmospheres) by pulsing an O-ring valve from a pre-filled chamber. The chamber is immediately isolated and pressure decay is recorded from a transducer within the test chamber. A large leak is detected by a rapid pressure drop to a pressure fixed by the volume of the fuel rod expansion void, while a small leak is detected by a more gradual decay in pressure to this value. Because of the high pressure used, the response period is rapid -- less than five minutes for a leak of 5×10^{-6} std cc per second. The method is self checking for system leaks since the pressure then drops below the predicted value. It was also found that, with the high-pressure leak detection, leaks are evident which can not be detected by vacuum leak detection.

Bonding

The purpose of bonding is to establish a void-free, heat-conducting sodium filling between the fuel pin and jacket. The bonding operation must also provide a measurable sodium level. The level must not be deeply indented by shrinkage and the low-density gamma uranium structure must be converted to the stable alpha uranium structure.

The sodium must wet both the fuel pin and inside jacket surfaces. High temperature promotes wetting and, by reducing both surface tension and sodium viscosity, assists void elimination. The temperature must be kept below the 560° alpha-gamma transformation temperature.

Force must be imparted to the fuel rod to move gas-filled voids thru the annulus to the expansion space. Gravity alone was insufficient. Gravity forces were assisted by coupling a 60-cycle-per-second vertically acting vibrator to the bottom of the fuel rod. Later a somewhat more random bouncing action was imparted to the fuel rod by resting it upon a tappet which was loosely coupled to the 60-cps vibrator.

The method was used to bond about 11,000 Core-I fuel rods and several thousand experimental rods. The random vibration failed to bond about ten percent of the rods even after repeated three hour rebond cycles.

The application of directional force assists in eliminating gas-filled voids. Various methods were tried including centrifuging, application of induced magnetic forces and jolting. Some of the reject Core-I

rods were bonded by transferring them to a centrifuge and spinning them while hot at 1000 RPM.

Cameron studied the effect of a directional jolting action⁽⁵⁰⁾. When applied at a frequency of about 120 shocks per minute, this was effective in moving gas-filled voids. The height to which the fuel pin would bounce was a rough measure of the imparted acceleration. A sharp axial shock that will bounce the fuel pin about 16 mm was effective without damaging the lower fitting or weld. The time required was greatly reduced over that needed with random vibration.

Two jolt bonders shown in Figure 35 were designed for the FCF. The fuel rods are held in a 50-cavity rotary magazine. The magazine is placed over a central heater and is covered by an insulated bell jar. A spring suspended mass, or hammer, is oscillated vertically at its natural frequency by a pulsed magnet. On its up-strokes, the hammer strikes tool steel tappets which impart the shocks to the fuel rods.

Sodium Bond and Level Inspection

Pulsed differential eddy-current techniques are developed to examine the fuel rods for voids and to measure sodium level⁽⁵¹⁾. The tests are made at about 150°C on the molten sodium to eliminate shrinkage porosity and to obtain a more distinct sodium level than obtained with solid sodium.

Equipment used for sodium-level testing, also shown in Figure 35, consists of a 50-station rotary index mechanism, the bonding magazine

and a heater, the eddy-current coil assembly and an elevator mechanism. The elevator mechanism passes the rod slowly thru the eddy-current test coils. Heaters on the elevator maintain the fuel rod at about 150°C during the test. Three closely spaced, air-cooled flat encircling coils are used. One acts as a driving coil. The other two act as sensing coils and are connected differentially.

The eddy-current test circuit consists of a square-wave oscillator and pulse-forming circuit that produces a sawtooth signal of about 2250 cps. This signal modulates the output of a 50 to 150 Kc variable-frequency oscillator. The resulting alternately pulsed and damped signal is supplied to the driving coil. Eddy currents are induced in the fuel rod under test. The path of the eddy currents is distorted by the presence of defects or inhomogeneity near the surface of the test rod. The effective depth of penetration of the eddy currents may be adjusted to the sodium depth by selection of the proper driving frequency.

A voltage is induced in the sensing coils by the eddy currents in the test piece. When a homogeneous rod is in both coils, the differential voltages balance producing a null signal. When a flaw enters one sensing coil, but is not yet within the field of the second, the voltages do not balance. This produces a current that can be rectified, amplified and recorded as deflection on a recording galvanometer. As the flaw passes from the first coil to the second, the recorder pen is deflected in the opposite direction. The amplitude of the signal is

influenced by the size of the defect. The location of the defect is duplicated on the trace by synchronizing the strip-chart drive with the elevator drive.

Signals are produced as the end of the fuel pin, the tip of the restrainer, and the upper sodium level pass thru the coil. Sodium level is measured directly from the strip chart as the distance from the top of the pin to the sodium level. Sodium lodged or trapped in the expansion space also produces a distinct signal.

The interpretation of eddy-current traces requires considerable experience on the part of the chart readers. Spurious signals caused by the spiral wire and the fuel pin can usually be discriminated. Void size can be calibrated against known standards. The sodium-level signal is masked by the restrainer tip when the level is low. A "smeared" signal results when the sodium level is irregular.

Fuel-Element Assembly

Fuel-element assembly is carried out by master-slave manipulators and the equipment shown in Figure 36. Two nonradioactive preassemblies are supplied to the assembly operation. One of these consists of the lower blanket section, adapter and T-bar grid. The second preassembly is made up of the upper blanket section, top fitting and hexagonal tube (see Figure 25). At present these preassemblies are constructed and inspected before introduction to the air cell.

Interchangeable tooling adapts the fuel-element assembly machine

to the 91-rod core and inner blanket elements and to the 61-rod control and safety elements. Because of self-heating, sodium will melt in the fuel rods as the bundle is assembled, so that construction must be done with the rods held vertically.

The lower preassembly is placed in its positioning socket by means of a crane. An elevator mechanism is used to raise or lower the various elements to register the T-bar grid with the corresponding guide bars on the fuel-bundle assembly platform.

The fuel section of the element is assembled with the aid of the guide mechanism shown in Figure 37. The fuel rods have 11 T-bars on the grid while the smaller control and safety rods have only nine T-bars. Assembly is facilitated by the funnel-shaped gates into which the lower tips of the fuel rods are inserted. The gates are electrically controlled and interlocked in such a manner that they will accept fuel rods only in correct sequence and orientation. If both sequence and orientation are proper, the rod may be slipped along the guide wire onto the T-bar grid.

As each row of fuel rods is assembled, it is pressed into position and held while the succeeding row is constructed. A blower draws air thru the bundle to prevent overheating during assembly. When the last row of rods is in place, clamps are moved in to form the bundle into hexagonal shape.

The upper preassembly held in a blower-cooled transfer grapple

is placed in the force bridge. The grapple remains over the top of the element during assembly providing cooling. A sensitive load cell between the grapple and force bridge transmits a remote indication of the forces required to insert the fuel bundle in the hexagonal tube.

The lower end of the hexagonal preassembly is aligned with the fuel bundle by means of a roller guide. The fit of the hexagonal tube is such that the fuel bundle is compressed slightly during assembly. This can only be done by distorting the jackets of the fuel rods while the sodium is molten. Electric heaters expand the hexagonal tube slightly and also prevent chilling the outer row of elements during assembly. The force required to bring the hexagonal tube over the fuel bundle varies from 125 to 250 pounds. The force limiter is set at 300 pounds. Forces in excess of this amount usually indicate improper assembly of the fuel bundle.

When the hexagonal tube has been properly positioned, it is welded to the adapter by six TIG spot weld guns. Opposite weld guns are fired alternately around the tube to balance welding stress and prevent distortion.

Fuel-Element Gaging and Test

The assembled fuel element is transferred to a straightness and tensile-test fixture. The lower adapter is held in a closely fitting socket in the same manner as in the reactor. Three, six-point gages are provided near the middle and both ends of the element. Electrical

contacts in these gages indicate remotely when the fuel rod deviates more than 0.040 inch from straightness.

The same fixture is used to proof tensile test the welds made during fuel-element assembly. A forked beam engages the knob on the upper fitting, while a shot bolt is passed thru a hole in the adapter securing the element to the test frame. An axial force of 1600 pounds is exerted on the fuel element to test the welds between the hexagonal tube and adapter.

The refabricated fuel element is now ready for transfer back to the reactor. Return to the reactor is via the inter-building transfer coffin.

SECTION V

REMOTE FABRICATION OF

TRANSURANIUM TARGET ELEMENTS

A program aimed at producing in gram quantities the heavier transuranium elements for research purposes by successive neutron captures in Pu^{239} is underway at ORNL. The first part of the production path, conversion of Pu^{239} to Pu^{242} and Am^{243} to Cm^{244} , is being carried out at Savannah River. The Pu^{242} , Am^{243} and Cm^{244} will be recovered and fabricated into target elements in a glovebox facility. The target elements will be exposed to a flux of 3×10^{15} neutrons/cm²-sec in the flux trap of the High Flux Isotope Reactor⁽⁵²⁾ (HFIR) now under construction at ORNL. After irradiation, the target elements will be processed in the Transuranium Processing Facility⁽⁵³⁾ (TRU) to recover the product actinides, and there the curium isotopes will be refabricated⁽⁵⁴⁾ remotely into new target elements for irradiation in the HFIR. Many transplutonium isotopes of research interest (such as americium, curium, berkelium, californium, einsteinium and fermium) will be processed in the TRU. These

alpha-emitting, spontaneously fissioning actinides have created problems in plant design. The combination of fast-neutron flux and penetrating gamma radiation from fission products and spontaneous fission required shielding considerations normally associated with reactor shields. The high specific toxicity of the alpha-emitting actinides dictated a refined equipment design philosophy to ensure against the escape of airborne contaminants.

Design of the Transuranium Processing Facility

The TRU Facility will have nine heavily shielded cells served by master-slave manipulators.

The nine shielded process cells are arranged in line. Removable top plugs provide access to the cells. The top and back of the cell line are served by a bridge crane in a limited-access area of the building not normally occupied by operating personnel. The front face of the cell is provided with windows, master-slave manipulators and plugged ports for installation of periscopes.

Of the nine radioactive cells, four will contain chemical processing equipment for dissolution, solvent extraction and precipitation processes. Three will contain equipment for the remote preparation and inspection of recycle targets. Two cells will be used for remote analytical operations. The cells are shielded by 54 inches of magnetite concrete.

Within the shielded cells, process equipment will be enclosed in a cell cubicle.

Service lines enter through removable plugs in the back and top of the cell. Shielded pits behind the cell, in the limited access floor, house off-gas filters and a pipe tunnel for process lines.

Communication between cells is by a conveyor consisting of an 8-inch diameter x 8-inch high canister on a dolly drawn by double chains.

A 12 x 12-inch airlock in the walls separating the cells can also be used for transfer. The conveyor communicates with each cell and with the transfer area, where the canisters can be charged or discharged. The transfer area is provided with manipulators. A glovebox accessible through a rotary transfer port provides for removal of low-activity items. A door in the transfer-area shield accommodates a shielded carrier for transfer of highly active materials such as analytical samples and solid wastes.

A shielded caisson is provided for the introduction into the cubicle or removal of equipment. The rectangular caisson will accommodate equipment 1.5 x 3 x 6-feet high.

Fabrication of Target Elements for the HFIR

The HFIR target element, shown in Figure 38, consists of a 3/8-inch O.D. finned tube and a 5/8-inch hexagonal can, which is attached to the fins as a spacer and coolant channel. The target is 35 inches long with 1/4-inch diameter 0.571-inch long pellets contained in the 20-inch active length of the rod. The remainder of the 35-inch tube

consists of end caps and void space for accumulation of fission gas. The pellets will consist of actinide oxide and aluminum powder mixture with a density that is approximately 89 percent of theoretical. In the pressing operation, each pellet will be completely encapsulated in an aluminum can.

The fabrication and inspection of the HFIR target elements will employ a combination of powder-metallurgical, welding and chemical techniques. The various operations have been assigned to the three fabrication cubicles, or cells, according to the degree of contamination expected from them. To minimize the recontamination of the target elements, auxiliary enclosures of some items of equipment will be provided within the cubicles. To summarize the criteria and the operational mode selected as a basis for equipment design, all equipment is to be designed to operate semiautomatically, requiring only minimum recourse to the manipulators. To minimize the spread of contamination, special transfer arms or similar devices will be used to effect transfer of components between steps in the process. Sensitive parts of the equipment must be easily removable and of a size such that they can be transported by the intercell conveyor for discharge and replacement. Further, all equipment will be so mounted that it can be removed from the cubicle through a 35 x 18-inch equipment-transfer hatch located in the cell roof.

The target fabrication and inspection equipment for TRU, all of which are depicted in Figure 39, is currently being designed and constructed.

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FIRST FLOOR PLAN

**FUELS RECYCLE PILOT PLANT
HANFORD LABORATORIES**

REMOTE FABRICATION DEVELOPMENT FACILITY
HANFORD LABORATORIES

19 ROD
CLUSTER

NESTED
TUBE

INVERTED
CLUSTER

PRTR FUEL ELEMENT CONFIGURATIONS

PLUTONIUM FABRICATION PILOT PLANT
HANFORD LABORATORIES

INVERTED CLUSTER FUEL ELEMENT WITH
REPLACEABLE SPIKE RODS

G 102-716

FLOW DIAGRAM - CLOSE-COUPLED PLUTONIUM
RECYCLE SYSTEM

OXIDE FUEL PARTICLE PREPARATION EQUIPMENT

Transverse Cross Section

Longitudinal Cross Section

CROSS SECTIONS OF REJUVENATION TYPE FUEL ELEMENT

REJUVENATED FUEL ROD CROSS SECTIONS

REMOTE CLOSURE EQUIPMENT FOR REJUVENATION
TYPE FUEL ELEMENT

PRTR FUEL ELEMENT REFURBISHING OPERATION