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FUEL ELEMENTS
FOR THE
ARGONNE ADVANCED RESEARCH REACTOR

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The Argonne Advanced Research Reactor (AARR) is a general purpose high flux facility planned for construction at Argonne National Laboratory. The multiplicity of beam tubes and irradiation facilities provided in the reactor will greatly extend the current capabilities of the Laboratory in its program of basic research in nuclear physics, nuclear chemistry, and solid state science. The general design of the facility has been described in another paper.*

A preliminary feasibility and cost study on AARR has been completed by United Nuclear Corporation. As part of this study, a reference core design for the reactor was developed which utilizes stainless steel clad, UO_2 -stainless steel dispersion type fuel plates. The core is cooled and moderated by light water and utilizes beryllium as a reflector. At its initial power level of 100 MW, the core has a life of 90 days, and generates a thermal neutron flux in a central thermal column in the range of $3 \text{ to } 5 \times 10^{15} \text{ n/cm}^2\text{-sec}$.

The physics benefits which accrue to steel-water cores have been discussed in another paper.† The present paper reviews the core design and the fuel element concept that has been proposed to meet the experiment needs of the Laboratory. The design is not intended to be final, and, in fact, improvements and modifications are to be expected when the detailed design of the reactor is undertaken.

*L. W. Fromm, "General Design of the Argonne Advanced Research Reactor," Proceedings of Gatlinburg Conference on Research Reactor Fuel Elements, September 17-19, 1962 (in press).

†C. N. Kelber, "Physics Advantages of Stainless Steel Cores," Proceedings of Gatlinburg Conference on Research Reactor Fuel Elements, September 17-19, 1962 (in press).

Mechanical Design

The general arrangement of the core is primarily governed by the types of experiments and research that are to be conducted by the Laboratory. Thus, a design requirement has been an annular fuel region surrounding a central water-filled thermal column. However, large variations in local power generation are customarily encountered in fueled regions that surround such a centrally located flux trap. These variations, expressed as maximum /average power ratio, are emphasized when the boundary between the fueled region (core) and flux trap is characterized by sharp corners such as are found in a square geometry. Estimates made on early square core designs for AARR, using a uniform distribution of UO_2 -stainless steel fuel, indicated a peripheral power variation of about 1.35 at the core inner boundary over and above all radial and axial power variations. Ideally, a circular central hole is preferred as this tends to eliminate power peaking along the circumference of the interface. Although fuel elements have been designed which are adaptable to a circular geometry, they are expensive to fabricate (especially with a variable fuel loading), and their performance characteristics are not as well known as the more conventional flat plate box type.

The AARR core configuration, shown in Fig. 1, achieves a compromise between the square and circular geometry by providing a hexagonally shaped flux trap facility 4 inches across flats. This design permits the fuel region to consist of geometrically similar fuel elements, rhomboidal in shape, and composed of flat fuel plates. Three rings

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Fig. 1 — AARR reactor plan at midplane

totalling 45 fuel elements surround the thermal column; they form an annulus with hexagonal inner and outer boundaries. Across the outer flats of the hexagon, the core measures 17.4 in.; its active height is 18 in.

Twelve hafnium blades are provided for operating and safety reactivity control. Six blades blanket the outer surface of the fuel region, while six blades (three radial and three offset) are provided between the fuel elements in such a way that the uniform geometric dimensions of the fuel elements are not perturbed.

A 12 in. thick beryllium reflector surrounds the core in the radial direction and extends 2 in. above and below the 18 in. active fuel height. The reflector is shaped so that it is in the form of a right hexagonal prism, about 42 in. across flats, with a central hexagonal opening for the core. The inner 3 in. of reflector are in a region of high neutron flux and high heat generation. Since the beryllium in this region may be susceptible to damage, the individual pieces have been designed so that they may be easily replaced. The outer 9 in., which are penetrated by holes for beam ports, vertical thimbles, and rabbits, are installed in a more permanent manner, although replacement is still possible.

The inner row of beryllium pieces consists of rhomboidal shapes which continue the geometric pattern established by the fuel elements in the core. These pieces are penetrated by a central hole, 1.33 in. in diameter, and by two $1/4$ in. holes located in the thicker section of the

rhomboid. The central hole is filled by a 1.25 in. diameter beryllium plug. This configuration keeps thermal stresses within allowable limits in the region of highest heat generation. The rhomboidal shape of these replaceable pieces also allows the possibility of replacement of beryllium by standard fuel elements for special purposes. The outer reflector pieces are in the shape of slabs which become progressively thicker, from 3/4 in. to 2-3/4 in. The increasing thickness is permissible because of a decreasing heat generation rate. The coolant flow spaces between the beryllium pieces are 0.040 in. wide and are maintained by leaf-springs on the sides of the reflector pieces.

The fuel element assembly, shown in Fig. 2, is rhomboidal in cross section and consists of 27 plates fastened together at their edges by dovetailed locking keys, and at each end by end fittings. A 40 mil water gap between plates is maintained by spacers. The keys lock the individual fuel plates into a rigid cluster and eliminate the need for side plates; the resultant interchannel flow connections are intended to relieve pressure differentials between channels.* The upper and lower end fittings each consist of a hollow cylindrical section which develops into two short side plates, each cut out to accept the fuel plates and a locking key. The upper end fitting has an external thread on its cylindrical section which permits its fastening into an upper support grid.

*The open construction, keyed fuel plate assembly is patterned after a similar design originally proposed by ANL for aluminum plate elements, of square cross section, in an earlier AARR design study.

Fig. 2 — AARR fuel element

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The lower end fitting extends into a lower grid where a counterbored hole provides space for axial expansion of the element.

Each fuel plate is 40 mils thick and contains a uniform dispersion of highly enriched UO_2 particles, up to a maximum of 37 weight per cent, in a matrix of sintered stainless steel powder. A 5 mil thick stainless steel cladding is metallurgically bonded to each side of the fueled matrix. The fuel is high-fired uranium dioxide (UO_2) enriched to 93% U^{235} . The uranium dioxide powder is 44 to 88 microns, spheroidal and free of agglomerates, platelets, rods and surface fines. The matrix material is type 304 stainless steel powder; the particles have irregular shapes varying in size from 10 to 149 microns. The cladding and frame material is type 304 ELC wrought stainless steel.

One of the principal nuclear design problems in the AARR is to achieve a sufficiently flat power distribution to permit an average power density of about 1.35 MW/liter, necessary to yield fluxes in the desired range, while still not exceeding thermal limits at the core hot spot. As shown in Fig. 3, a uniformly fueled core has a power peak at the inner flux trap boundary of about 9 times the core average power, and a peak of about half this value at the beryllium reflector boundary. This power peaking has been reduced in the reference core to less than twice the average power at the core boundaries by using a nonuniform fuel distribution, attained by orienting fuel plates parallel to the boundaries, as shown in Fig. 4, and by specifying a reduced uranium content

Fig. 3 — Radial power pattern — uniform fuel loading

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in individual plates in a series of graduated steps.* Two fuel plate arrangements are shown. In Fig. 4a, the reference design, fuel elements occupy the entire core, except for control blades. However, power flattening by means of a graduated fuel loading in the plates near the outer boundary of the core is rendered difficult because the plates are not oriented parallel to the core boundary in all locations. An alternate arrangement shown in Fig. 4b, has been studied to ease this problem. Nine fuel elements comprising the No. 5 locations and the two No. 4 locations counter clockwise from each of them, are turned to make their plates parallel to the boundary. This reorientation makes the use of three filler pieces necessary to complete the core section in order that the fuel elements, which are not exactly equilateral parallelograms, remain all identical geometrically.

For both core arrangements, the symmetry of the design requires only 5 types of differently loaded fuel elements. The central row of the core, type No. 3, contains uniformly loaded fuel elements in which each plate carries the maximum normal concentration of 37 w/o UO_2 . In the inner row surrounding the thermal column, the first nine plates vary in concentration from 12 to 94% of the normal loading. In the outer row near the reflector, the last five fuel plates vary from 86 to 39% of the full loading. Fully loaded plates comprise 85% of the total number of

*An alternate method of reducing power peaking without varying the fuel plate loading is to poison the interfaces at the inner and outer core surfaces with a thermal neutron absorber. Although attractive because of its mechanical simplicity, this method tends to reduce the thermal flux in the central thermal column.

Fig. 4a — Reference design core configuration (showing fuel plate orientation)

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Fig. 4b — Alternate core configuration with fuel element location key (showing fuel plate orientation)

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plates. The total initial loading is 50.7 kg of U^{235} , a reduction of 5.3% from the uniformly loaded core, and this same reduction is accompanied by a decrease in reactivity of 5% in k .

The reference design fuel distribution yields the beginning-of-life radial power pattern shown in Fig. 5. The peak-to-average values for the innermost and outermost plates are 1.65 and 1.73, respectively. Some power peaking has been retained at the core edges for the following reasons:

1. The reduction in initial reactivity is not as severe as in a core having an initially flat power pattern.
2. A power pattern peaked near the reflector produces a higher thermal flux in the reflector than will a flat power pattern.
3. The initial power peaks at the core interfaces partially compensate the decrease of power generation as fuel is depleted in these regions. This decrease is caused by the higher fractional burnup of the fuel in these regions relative to that in the rest of the core. For example, in a core with an initially flat power pattern, the ratio of the power density in the fuel plate nearest the thermal column to the core average power density decreases to 0.21 after 90 days. For the reference core, this ratio is 0.35.

Fabrication of the fuel assemblies is expected to present no new or unusual difficulties. The open, nonwelded, nonbrazed construction designated is considered a distinct advantage for ease of assembly of

Fig. 5 — Radial power pattern distributed fuel loading

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the elements. Stresses under operating conditions are predicted to be high but not excessive, though experience with flow and thermal mock-ups is necessary for confirmation. The fuel plates, in uranium content, are within the presently accepted limits for confident production of UO_2 -stainless steel dispersion type elements. The irradiation-temperature-heat flux requirements on the plates are predicted to be within a range demonstrated to be satisfactory by reported experience on comparable elements, from the standpoint of metallurgical properties and radiation damage.

Operating Conditions and Performance

Operating and performance characteristics of the reference design AARR are summarized in Table 1. At 100 MW the core develops an average power density of 1.35 MW/liter at an average fuel plate heat flux of 560,000 Btu/hr-ft² and generates peak thermal neutron fluxes (unperturbed) of 3.5×10^{15} n/cm²-sec in the internal thermal column, and 7.2×10^{14} n/cm²-sec in the beryllium radial reflector. Higher fluxes may be attainable by minor alterations to the reference core geometry.

The initial fuel loading is 50.7 kg of U^{235} contained in 1,215 SS- UO_2 cermet fuel plates. The fresh core has an initial excess reactivity of 0.173 Δk , which is sufficient to yield a core lifetime of 90 days at a power of 100 MW; all excess reactivity is controlled by the movable control blades located in the core and at the core-reflector interface. For the first 75 days of core lifetime the reactor has full xenon override capability, permitting the reactor to be brought to full power at

Table 1 — AARR Core Thermal and
Nuclear Characteristics

Power, MW	100
Coolant	
Flow rate, lb/hr	7×10^6
Velocity, ft/sec	40
Inlet temp, °F	135
Outlet temp, °F	183
Inlet pressure, psia	450
Heat Flux, Btu/hr-ft ²	
Average	0.56×10^6
Nominal maximum	1.79×10^6
Hot spot	2.35×10^6
Critical (or burnout)	5.49×10^6
Power Density, MW/liter	
Core average	1.35
Nominal maximum	4.6
Hot spot	6.0
Fuel Loading, kg U ²³⁵	50.7
Core Volume, liters	74.2
Core Lifetime at Full	90
Power, days	
k _{eff} cold, clean	1.173

any time following a partial or complete shutdown. The last 15 days of core lifetime are obtained at the sacrifice of full xenon override capability as the core nears the end of its life.

To remove the energy generated in the compact AARR configuration requires operation at higher heat fluxes and higher temperatures than heretofore experienced in water-cooled-and-moderated research reactors. Hot spot heat fluxes may approach a significant fraction of critical or "burnout" heat fluxes. To preclude core operation in a region of uncertainty, a conservative approach to thermal design has been taken which insures that no boiling shall occur by limiting the maximum fuel plate surface temperature to values below the local saturation temperature of the coolant. Based upon this criterion, the reference design, at 100 MW power, is heat transfer limited when the inlet pressure is 290 psia. To provide a large assurance of successful operation at 100 MW, and to provide a reasonable margin to permit consideration of operation at higher power levels at some future date, a reactor inlet pressure of 450 psia has been selected. At this pressure, with allowance for all reasonable hot channel and hot spot effects, the maximum surface temperature of the reference design, 402°F, is about 45°F below the local coolant saturation temperature.

The critical heat flux was calculated for the reference design using the Zenkevich-Subbotin correlation* with a safety factor of 1.3.

*Zenkevich and Subbotin, Critical Heat Fluxes in Subcooled Water with Forced Circulation, J. Nuclear Energy, Part B, 1:2 (1959).

This correlation, which has been experimentally studied at ORNL and applied to the thermal design of the High Flux Irradiation Reactor, is also pertinent to the AARR. The minimum ratio of critical (or burnout) heat flux to fuel plate surface heat flux for the reference core was calculated to be 2.34. Since the surface temperature is always maintained below the local saturation temperature, burnout will not present any problem during normal operation.

The core and fuel element design described herein has been developed to permit the installation of a wide variety of experiment facilities useful for both long and short term research programs. The design has stressed reliability of performance wherein development efforts can be restricted to areas representing extensions of existing technology, without requiring fundamental development programs to achieve new technological "break-throughs."