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ENGINEERING CONSIDERATIONS FOR REMOTE REFABRICATION OF EBR-II FUEL ELEMENTS*

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The factors which have influenced the selection of processes for remote refabrication of EBR-II fuel are considered. These have included fuel element design and specifications, and throughput requirements. Limitations imposed by the process plant, levels of gamma radiation, self-heating effects and metallurgical requirements have also been discussed. Remote controlled, semiautomated equipment was designed to require a minimum of operational steps and to handle a range of compositions and fuel shapes. This equipment was also designed to allow remote maintenance or replacement and to meet the process cell environmental conditions with reasonable life expectancy.

I. INTRODUCTION

The economic recovery of valuable uranium, plutonium and alloying elements from spent reactor fuel is a major goal of any power reactor fuel cycle. This is particularly true for a fast breeder reactor which "burns" costly enriched uranium or plutonium. The breeder reactor is at an economic disadvantage when several fuel charges must be tied up out of the reactor while cooling for aqueous decontamination. Criticality considerations add to the cost of the aqueous separation of fission products from the enriched uranium or plutonium. Conventional refabrication in unshielded equipment requires that an extremely high efficiency of decontamination be maintained. But, with repeated recycle, heavy plutonium isotopes build up which give rise to gamma problems even with

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efficient fission product decontamination. Therefore, remote refabrication may become necessary even with aqueous fuel cycles.

Because of these factors, an unconventional fuel cycle involving non-aqueous pyrometallurgical refining and remote refabrication of the fuel elements has been developed for the EBR-II. The purpose of this paper and of the four companion papers is to outline the problems and requirements for remote refabrication and to describe the methods developed to refabricate the EBR-II fuel elements.

II. EBR-II FUEL ELEMENT

Remote refabrication is made easier by the design of the fuel element specifically for the purpose. The EBR-II fuel rod shown in Figure 1 consists of a cylindrical fuel pin which is bonded in a stainless steel jacket. The fuel pin measures 0.144 $\pm$ 0.001" in diameter by 14.220 $\pm$ 0.032" long. It weighs between 67 and 70 grams at an alloy density of 17.8 to 18.0 grams per cubic centimeter. The surfaces of the fuel pin must be suitable for sodium bonding and free from any refractory oxides which interfere with melting in the pyrometallurgical refining operation. A slight internal porosity is acceptable provided that (1) the cavities do not penetrate to the surface, (2) the maximum size cavity is 1/16" in diameter, (3) no cavity or cluster of cavities occupy more than 1/4 of the area of any cross section of a fuel pin, and (4) that the weight of the fuel pin is 67 grams or more.

(Figure 1)

The fuel tube measuring 0.1560 ± 0.0005" bore diameter by 0.009 ± 0.0005" wall thickness is supplied with the investment cast tip and spiral wire as a leak detected preassembly. The spiral wire serves as the spacer and sodium turbulator in the fuel element assembly. It is welded at the ends only. The plug restrainer is supplied as a separate unit to be welded to the tube in the final assembly of the fuel rod.

The sodium bond must contain no voids greater than 3/32" in the longitudinal direction nor greater than 1/16" in the peripherial direction. The sodium level of 0.65 ± 0.10" above the fuel alloy should be noted as this has given particular difficulty in the final inspection of the fuel elements. These components have been found to be quite delicate and easily damaged in handling.

The assembled fuel rods are supported in structurally strong subassemblies to preserve their integrity during handling in the reactor core and reactor loading machinery. The fuel subassembly, termed the fuel element, is shown in Figure 2. The lower adapter fitting engages the reactor grid structure and contains orifice holes for regulation of sodium coolant flow. Eighteen lower, depleted uranium, blanket rods are attached by a grid to the top of the bottom adapter fitting. These are sodium bonded and stainless steel jacketed as are the fuel rods. The upper ends of the blanket rods are held in a second grid. Eleven T-rails on the top of this grid engage the T-slots in the tips of the 91 fuel rods. The upper 18 blanket rods, hexagonal tube and handle fitting are made up as a preassembly and are slipped by remote operation

over the fuel section and lower blanket. The hexagonal tube is welded to the lower adapter fitting completing the fuel element.

(Figure 2)

The control and safety elements contain 61 fuel rods in a moveable internal sleeve. This attaches to the drive mechanism. Provision is made for two safety and 12 control rods in the reactor core.

While these elements are necessarily quite complex, they were designed (under H.O. Monson and E. Hutter of ANL Reactor Engineering Division) specifically for remote assembly and disassembly.[1] The use of a sodium bond rather than a solid bond facilitates the clean separation of the fuel from the jacket tubes.

At 2 w/o burn-up, 62.5 MW reactor power and operation six days per week, it is assumed that the average fuel element use rate will be 3.2, 91-pin fuel elements per week. Because the use rate will be somewhat irregular, the process should be capable of turning out at least 1/3 more than this figure. Equipment was therefore sized for a weekly throughput of 400 fuel rods per week. Batch sizes, cycle rates and equipment size was factored upward to take into consideration scrap recycle and use factors.

III. EBR-II FUEL CYCLE

(Figure 3)

Figure 3 is a flow diagram of the fuel cycle which has been developed for the EBR-II. It should be noted that this fuel cycle is

the result of cooperative work by several divisions at ANL. The Remote Control Engineering Division has been responsible for fuel element dismantling and the removal of the stainless steel jackets from the fuel pin. The Chemical Engineering Division has been responsible for the melt refining operation[2] and for most of the process cell design features. The Metallurgy Division has been responsible for fuel refabrication. Reactor Engineering Division personnel have been assigned to work with the Metallurgy personnel on the fuel element assembly problem. Liaison and direction of the program have been under M. Levenson of the ANL Chemical Engineering Division.

(Figure 4)

Figure 4 is a schematic drawing of the EBR-II Fuel Cycle Facility. After cooling, the fuel elements are transferred to the shielded air cell where the hexagonal outer tube and ends are cut away. The fuel rods are transferred to a machine which strips away the stainless steel sheath and breaks the fuel pin into 1-1/2" lengths. These are placed, in 9 to 12 kilogram batches, in the melt refining crucible. Melt refining consists of holding the molten fuel in contact with a zirconia crucible and evacuation to remove volatile fission products. Fission products which reduce ZrO_2 form a floating dross while uranium, plutonium and fission products which do not reduce ZrO_2 remain in the melt. Uranium or uranium and plutonium are added to replace that burned or lost in process. This results in an equilibrium of between 5 and 10 w/o fission products after

melt refining. This equilibrium alloy has been termed fissium. The compositions of Uranium Core I and Uranium-Plutonium Core II and predicted equilibrium compositions are as shown in Table I.

TABLE I

EBR-II REFERENCE FUEL ALLOYS

Element	Uranium Fissium		Plutonium Fissium	
	Core I	Recycle	Core II	Recycle
	w/o	5.0-10.0 w/o Fs.	w/o	7.0-12.0 w/o Fs.
Molybdenum	2.46	1.9 - 3.9	2.92	1.7 - 2.9
Ruthenium	1.96	1.5 - 3.0	4.20	3.5 - 4.3
Technetium	--	0.6 - 1.1	--	0.6 - 1.1
Rhodium	0.28	0.26 - 0.53	0.65	0.43 - 0.49
Palladium	0.19	0.17 - 0.34	2.17	1.4 - 2.5
Zirconium	0.10	0.5 - 1.0	0.07	0.5 - 1.0
Niobium	0.01	--- - 0.02	---	--------
Uranium(1)	94.90	94.8 - 89.0	Balance	Balance
U^{235}	45.64	45.0 - 46.0	15.0-18.0	15.0 - 18.0
Plutonium	---	------	18.0-15.0	18.0 - 15.0

(1) 48.13 Isotopic % U^{235}

Natural elements have been added to the initial fuel loading to simulate the radioactive equilibrium alloy which will result from repeated fuel cycles. After repeated recycle, the originally non-radioactive natural elements will be replaced by fission produced isotopes and will result in a highly radioactive material.

The in-put to the fuel fabrication operation will be the melt refined billet and return scrap consisting of pin cuttings and crucible heels. The melt refined billets are approximately 3-1/4" square in cross section with rounded edges and from 3 to 4" high. They weigh 9 to 12.5 kilograms.

IV. RADIATION STUDIES

An engineering analysis was made to estimate the levels of gamma radiation intensity from various fuel sources in the Fuel Cycle Facility process cell. This was done by calculation of radiation intensity from a number of fuel geometries and conditions versus distance from the source to the receptor. These calculations are plotted in Figure 5. From the information shown on this figure, a plot of isotropic gamma radiation curves was made on the argon cell floor plan as shown in Figure 6. Consideration was given to overlapping gamma fields. The assumption is made that the argon cell processes are functioning at their maximum rated capacity. All machinery except one pin process machine is in operation and a mold pallet is being depalleted for loading this machine.

(Figure 5 and Figure 6)

Within the limits of practicality, materials resistant to damage by high-level gamma activity should be employed in the in-cell equipment. This limits the use of conventional electrical components because

of radiation damage to insulations. Where it was felt that electrical equipment was far superior to mechanical devices for process control, testing and development of special units was felt justified. A testing program was initiated and performance information on electrical apparatus in a 10^6 R/hr. gamma environment was obtained. Figure 7 shows one test apparatus which was irradiated in the ANL Gamma Irradiation Facility. The results of such tests have indicated choices of linearly variable differential transformer, eddy current coil,[4] switches, motors, and pressure pickups[5] for successful application in the high level radiation environment.

(Figure 7)

V. SELF-HEATING STUDIES

One of the problems of processes involving the refining and refabrication of irradiated reactor fuel is self-heating of the fuel. This is due to absorption of beta and gamma energy from the fission products. Self-heating may be such as to significantly influence the design of processes and equipment and to require induced cooling. To resolve this problem and to rationally design equipment for the processing of partially decontaminated fuel, it was necessary to know with fair reliability the temperatures which various configurations of radioactive fuel will reach. The self-heating effects were calculated and data were developed by N. Lazar and M. Feldman[3] for the cooling requirements through various fabrication and reassembly operations of the

proposed EBR-II fuel cycle. In this study the heating effect resulting from self-absorption was considered for a number of cases which occur during the operation of decanning the spent fuel elements and of refabricating the active material in the new fuel elements. The results of this study are summarized in Table II.

TABLE II

TEMPERATURE AND COOLING REQUIREMENTS -
VARIOUS ARRAYS OF EBR-II FUEL

Fuel Array	Temperature in °C	Cooling Method and Flow Rate
15 Day Cooled Fuel Element	120	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 & free convection argon
160 Close-packed Gravid Molds	390	free convection argon
160 Close-packed Gravid Molds	110	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	10 ft/sec. air
Reprocessed Fuel Element	100	10 ft/sec. air

VI. ENVIRONMENTAL LIMITATIONS

The hot fuel alloy and sodium will be easily oxidized and present a significant fire hazard in air. An inert atmosphere must be employed when the exposed fuel is handled. The process cell must be tightly sealed to maintain this atmosphere. This limits the penetrations which may be used through the cell wall to those which may be sealed gas tight. Until recently, master-slave manipulators which would meet this requirement were not available. Vacuum locks are employed to transfer materials and equipment into and out of the cells. This, in turn, limits the largest items of equipment which may be used to that which will pass the largest vacuum lock available (approximately 6' in diameter by 6' long).

In view of the foregoing conditions, conventional fabrication processes were surveyed for their suitability to the fabrication of EBR-II fuel elements. None of the conventional processes or equipment appeared to be adaptable for the following reasons.

1. The gamma radiation levels in the vicinity of the process equipment will range from 10^4 to 10^7 roentgens per hour. Conventional equipment requiring lubrication, or using organic seals, and insulators did not appear to be adaptable.
2. The process may be expected to spread contamination throughout the cell precluding human entry for manual maintenance and adjustment.
3. Manipulator service by high dexterity, master-slave-type manipulators will be limited.

4. Normal metal working practices were not readily adaptable to the complex hard alloy. This alloy was found to be easily fractured at elevated temperatures but at room temperature was very hard (approximately Rockwell C 50 to 55).

VII. REFABRICATION PROCESS REQUIREMENTS

The high radiation level, the inaccessibility of equipment for operation or normal maintenance and the unusual alloy gave rise to problems of considerable magnitude in the modification and adaptation of conventional fabrication machinery. Self-heating of the alloy made cooling rather than heating a requirement for many operations. The early studies of available processes and equipment indicated that the development of a new process offered the best solution to the problem. The following requirements were set forth.

1. The process should have a minimum number of steps.
2. It should be capable of handling a range of alloys and compositions.
3. It should match the capabilities of the Experimental Breeder Reactor-II to be adaptable to a variety of fuel shapes.
4. Repetitive operations should be mechanized.
5. Construction materials should be chosen for at least 20,000 hours exposure to prevailing radiation conditions or should be designed for semi-remote replacement of radiation damage components.

6. No material should be employed which upon irradiation would be poisonous to the catalytic beds of the atmospheric purifying system.
7. The equipment should be of componentized design, built up of plug-in sub-mechanisms. These should be readily replaced by manipulator or crane in case of breakdown or changing product requirements. These subassemblies must be of such size as to be transferable thru the vacuum locks.
8. The equipment must be designed to the limited capabilities of the process cell manipulators and cranes.
9. Replacement or adjustment should be accomplished by straight vertical or rotary movements about a vertical axis where possible.

While the fissium alloy was found to be refractory to metal working methods, it displayed excellent castability. It would reproduce molds into which the molten metal was poured precisely. Precision casting can be a very simple method. It was, therefore, chosen as the method around which the EBR-II refabrication would be developed.

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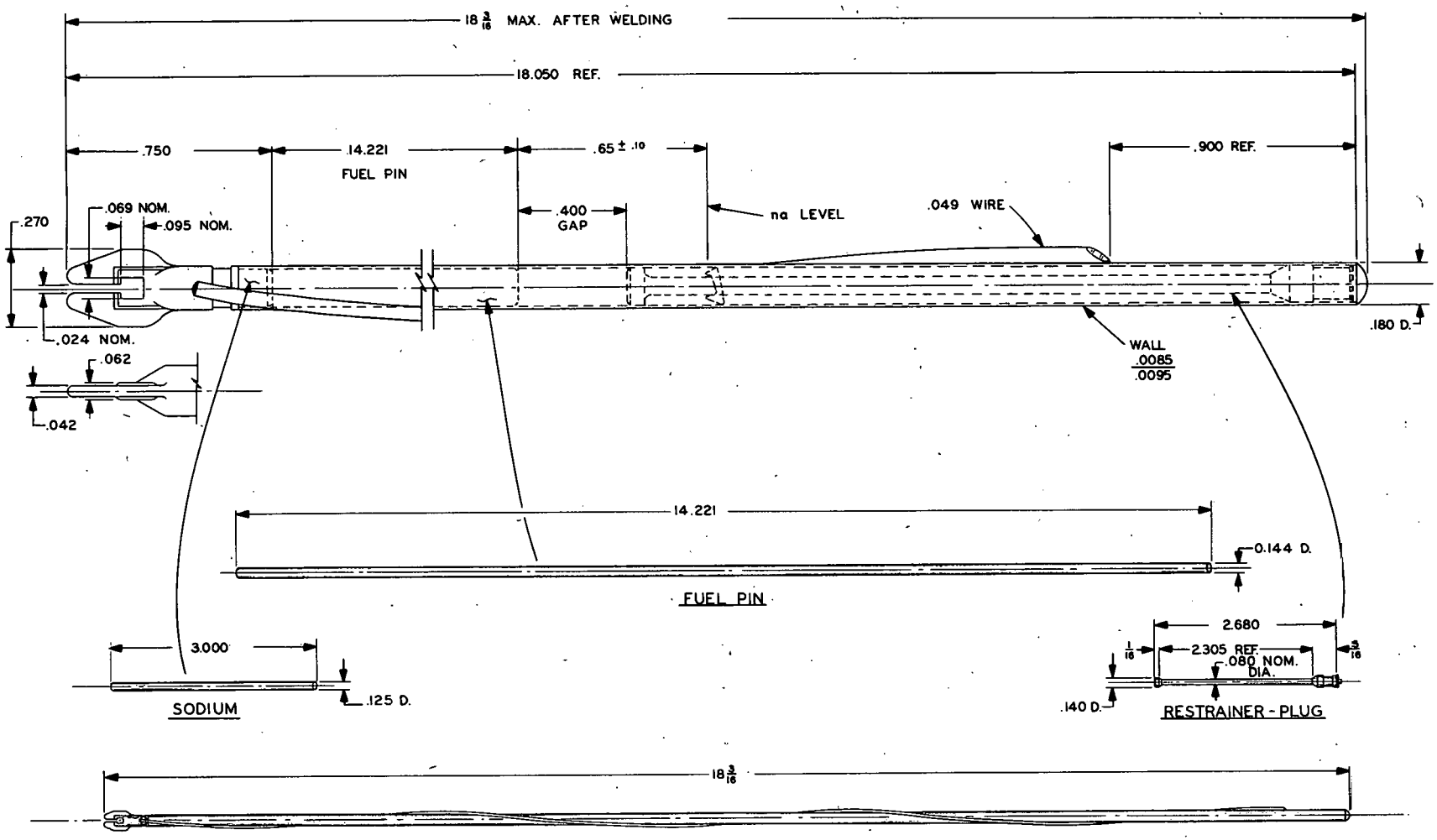

Figure 1. EBR II FUEL ROD

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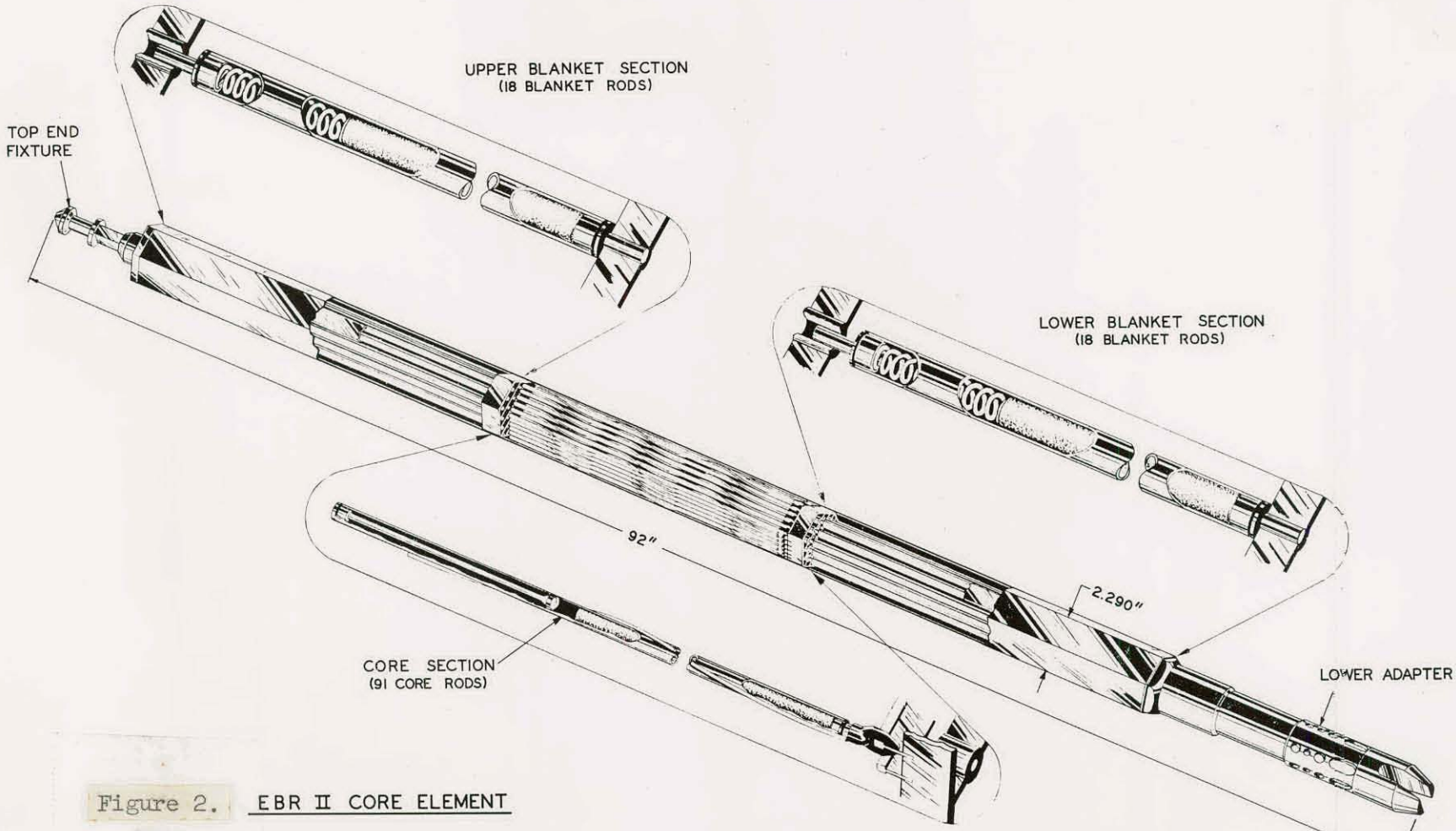
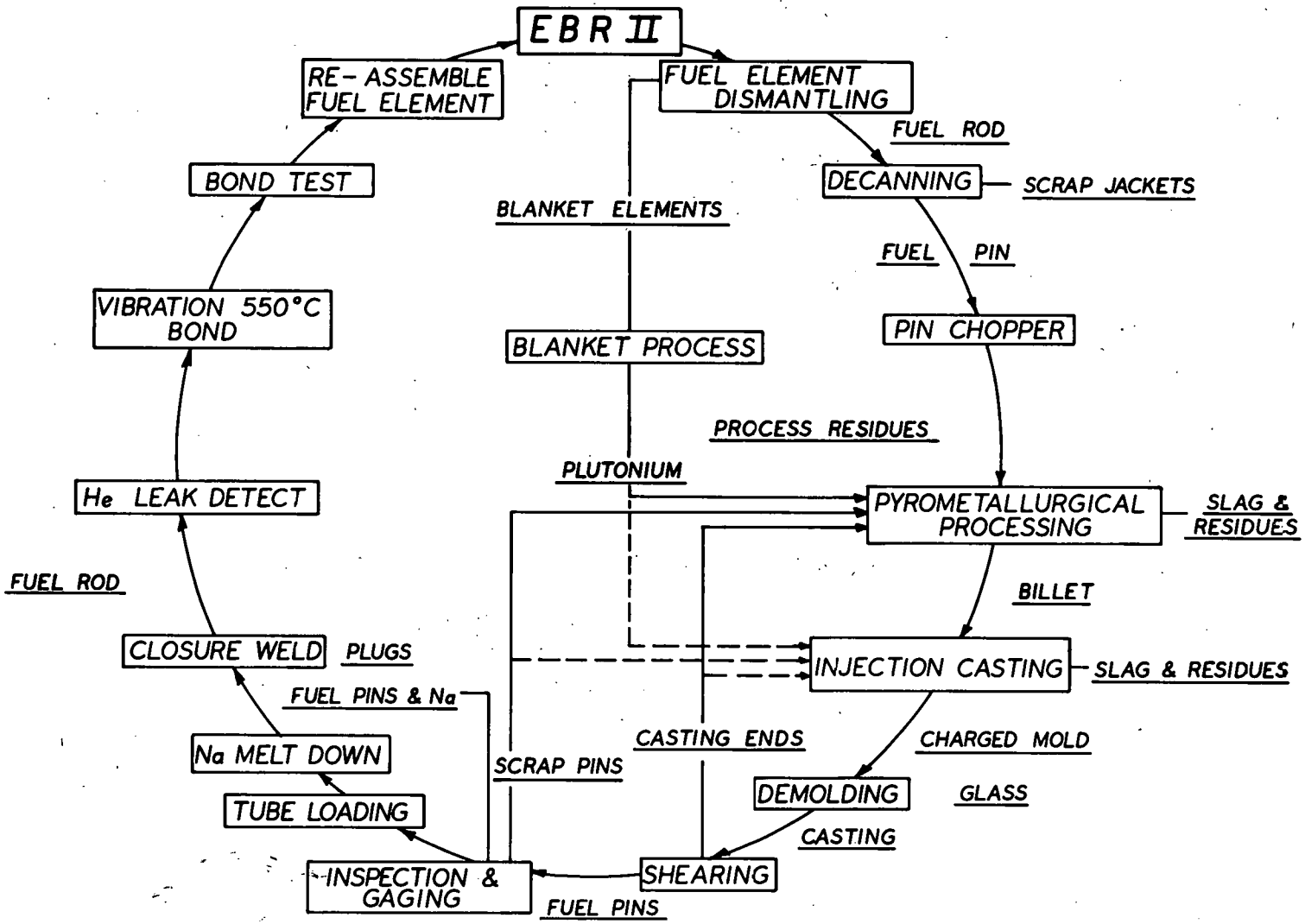


Figure 2. EBR II CORE ELEMENT



EBR II FUEL CYCLE FLOW DIAGRAM

Figure 3.

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PHOTOGRAPH

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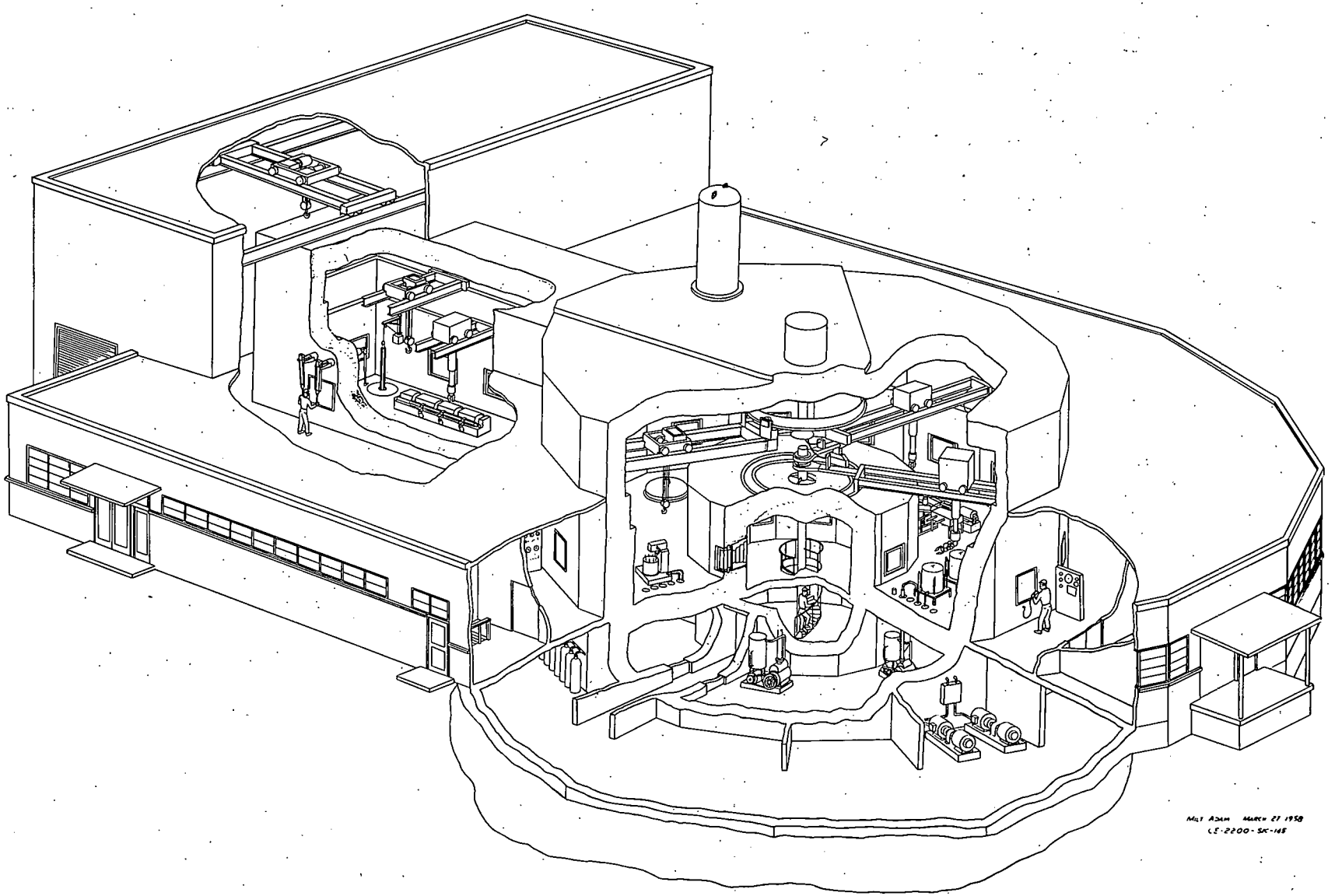

Figure 4. Fuel Cycle Facility Drawing

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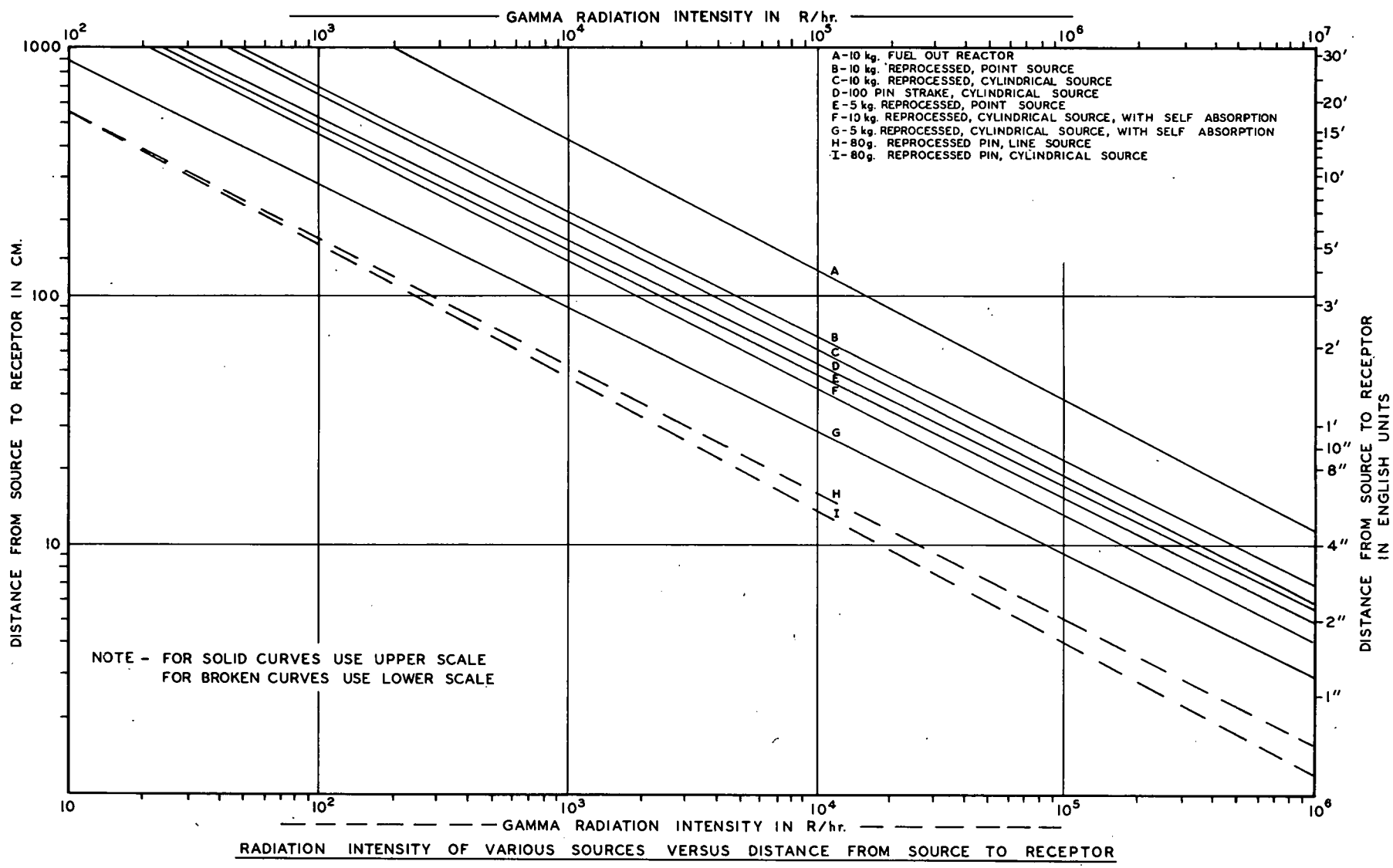

RADIATION INTENSITY OF VARIOUS SOURCES VERSUS DISTANCE FROM SOURCE TO RECEPTOR

Figure 5.

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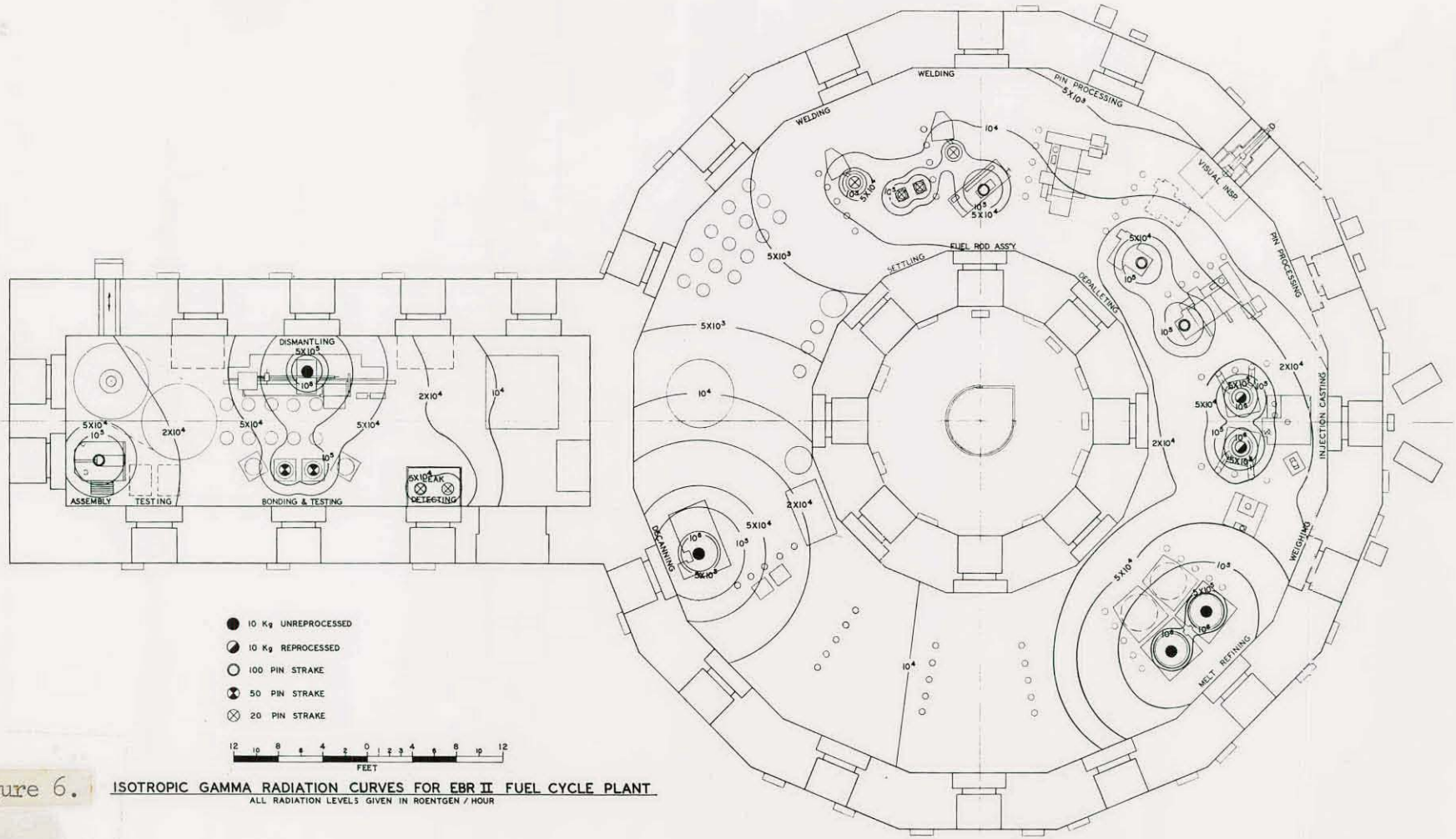

Figure 6. ISOTROPIC GAMMA RADIATION CURVES FOR EBR II FUEL CYCLE PLANT

ALL RADIATION LEVELS GIVEN IN ROENTGEN / HOUR

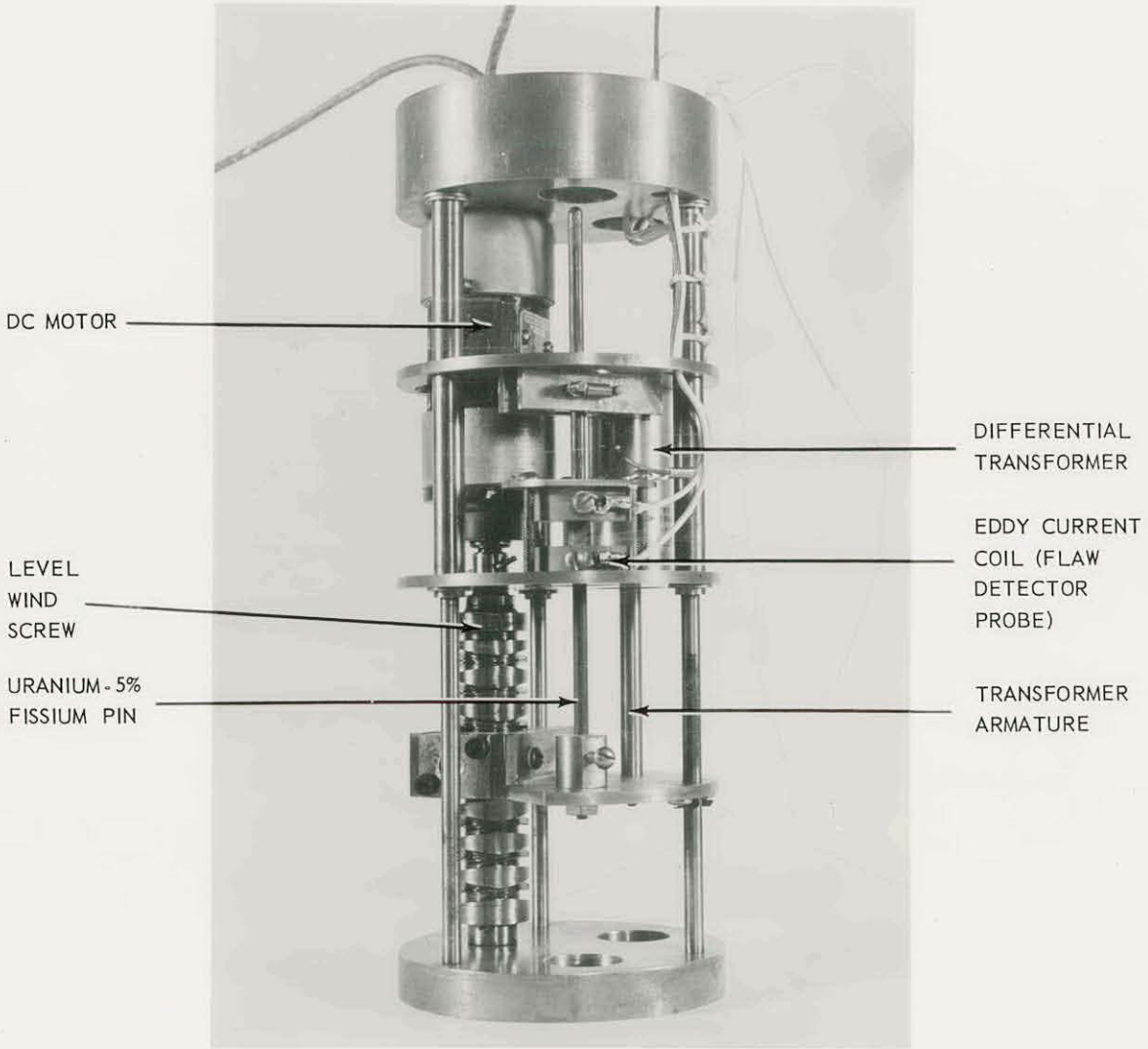

Figure 7. Test Apparatus for Determination of Effects of Gamma Radiation upon a Special Differential Transformer and an Eddy Current Coil.