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EXPERIENCES WITH BERYLLIUM SWELLING AND REPLACEMENT IN THE PLUM BROOK REACTOR

by William Fecych

Lewis Research Center

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ABSTRACT

A description is given of problems encountered from distortion and failure of major reactor core components in the high neutron fluence regions of the Plum Brook Reactor. Reactor material surveillance programs, the failure mode of the components, component replacement methods, associated health hazards, and the distortion of components against neutron fluence are described.

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SUMMARY

The swelling and fracture of beryllium reactor core components pose a challenging problem for the operators of high flux reactors which use beryllium as a reflector material. Neutron embrittlement and gas formation in beryllium result in distortion which may cause interference between movable components, such as the failure of the control rods to fall properly after a scram signal, or the fracture of highly radioactive major core components. Both of these problems are costly in reactor operating time and can be difficult to correct.

At the Plum Brook Reactor control rod drop time tests performed at every reactor startup, periodic measurements on the fixed and movable core beryllium components, and visual inspections were used to detect and monitor a potential safety problem. Beryllium component distortion rates against fast neutron fluence and the nuclear and physical environment are described. A description is given of the electrical discharge machining method used to remove the core box side plates. The techniques used to limit and control the health hazards are described. The mode of failure of the beryllium side plate is given.

INTRODUCTION

The Plum Brook Reactor (PBR) is a 60-megawatt (thermal) light water moderated and beryllium reflected high flux test reactor. The fast neutron ($E > 0.1$ MeV) reaction with the reactor core beryllium causes embrittlement and helium gas formation. This results in distortion and fracture of the core components. Distortion causes the pre-

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cisely machined and spaced control rods to fall in drop times outside the allowable limits. Embrittlement and swelling cause fracture of a core box beryllium side plate. A surveillance program was established to monitor and measure the effects of the distortion and swelling. Electrical discharge machining (EDM) was used to remove the fractured beryllium plate. A beryllium management program was established to rotate and replace the sensitive components to avoid interference problems and to extend the life of the components.

DESCRIPTION

The Plum Brook Reactor is operated by the National Aeronautics and Space Administration under AEC License TR-3. The reactor first achieved full power in March 1963 and has operated for a total of 37 256 megawatt days to February 1968.

The PBR reactor core is mounted in a 9-foot-diameter by 30-foot-high tank (fig. 1). The reactor core has a 9×3 array of aluminum clad plate fuel elements, and each fuel element contains 240 grams of U^{235} in an uranium-aluminum alloy. Removable beryllium reflector pieces $31\frac{1}{2}$ inches long by 3 inches square surround the fueled core on the north, east, and west sides (fig. 2). Five control rods with beryllium followers are in alternate positions with the north removable reflector pieces. Four rows of eight 4-inch-square beryllium pieces abut the south side of the fueled core and are separated from the core by a 1-inch-thick, $35\frac{3}{4}$-inch by 41-inch beryllium plate. A similar plate bounds the north side. These plates serve as hydraulic barriers for the primary cooling water flow. Each plate was fastened to the lower grid with five inaccessible bolts from below. The plates are also fastened to the east and west side plates with bolts which are accessible.

SURVEILLANCE OF REACTOR MATERIALS

The effect of neutron embrittlement and gas formation on beryllium has been described in various publications (ref. 1). Since its initial operation PBR has had test specimens of various reactor materials under irradiation in specific test locations. The test locations do not provide a neutron fluence equal to the maximum fluence on the south beryllium plate. Consequently other surveillance methods were used to monitor the distortion of the beryllium control rods, the beryllium reflector pieces, and the beryllium and aluminum core box plates. These consisted of frequent control rod drop time measurements; physical measurements on the removable beryllium pieces in the Hot Laboratory; underwater remote reading electronic micrometers to measure the spacing, squareness, and the profile of the north and south beryllium plates and the east and west aluminum plates; and visual inspections with optical aids.

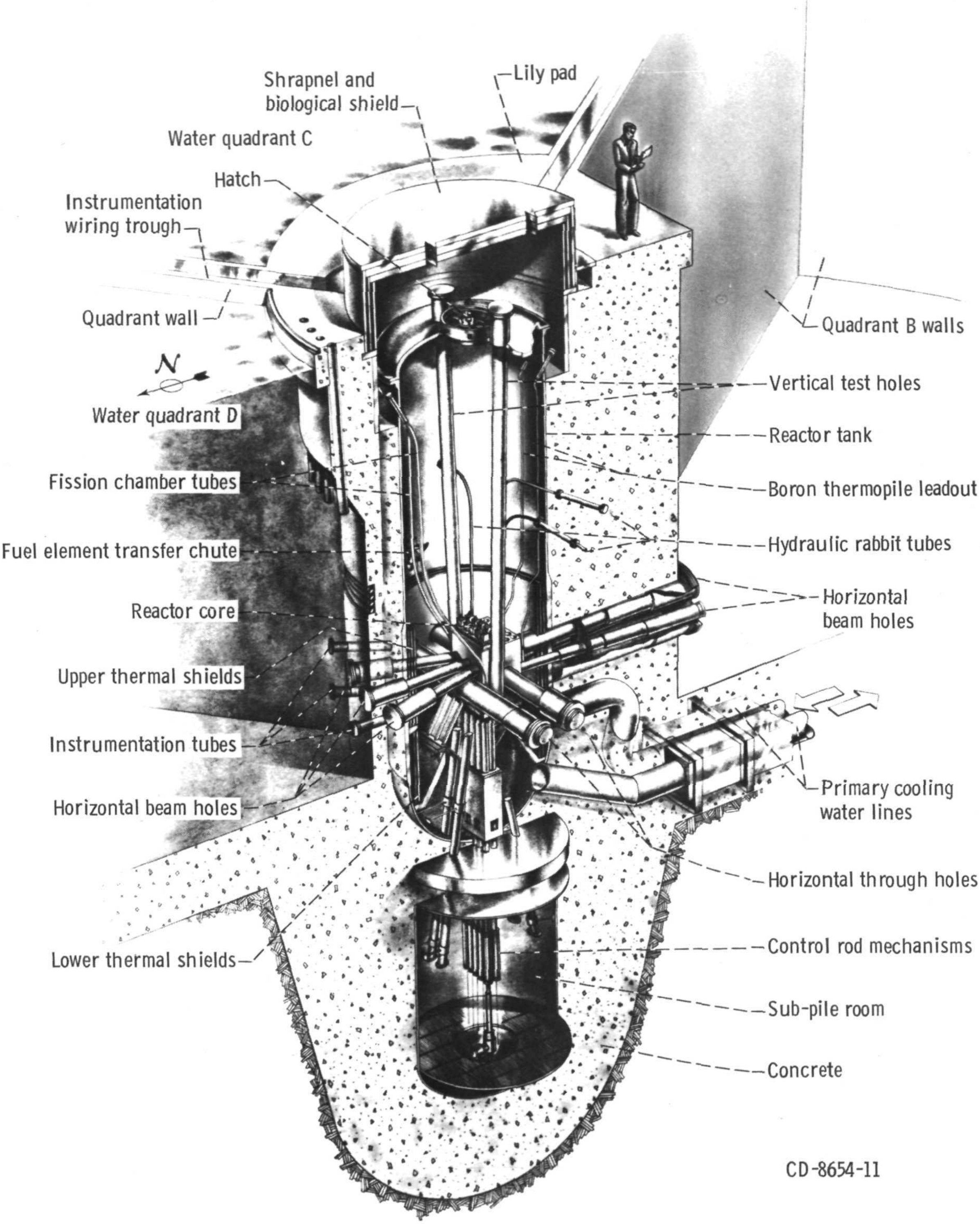
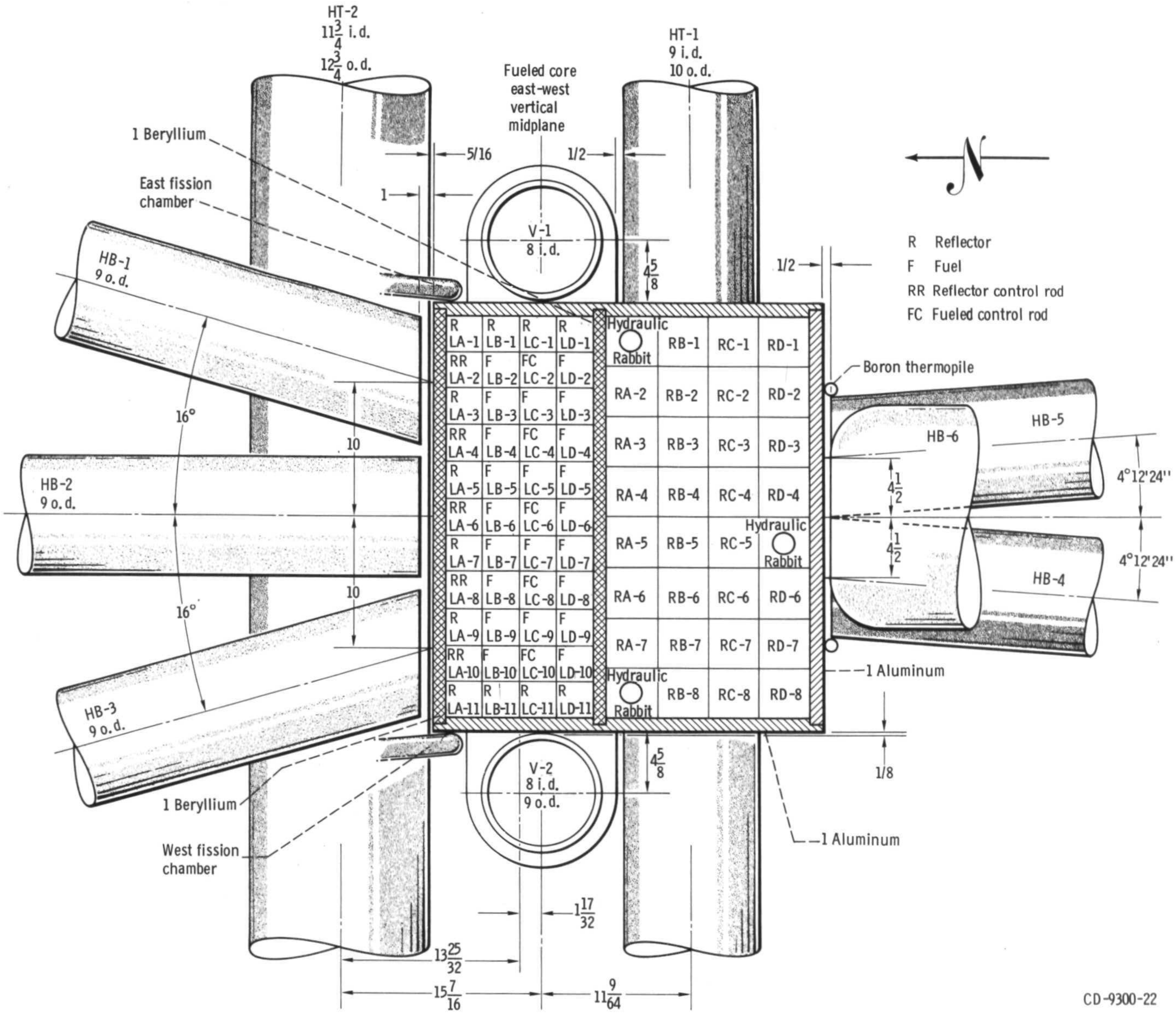
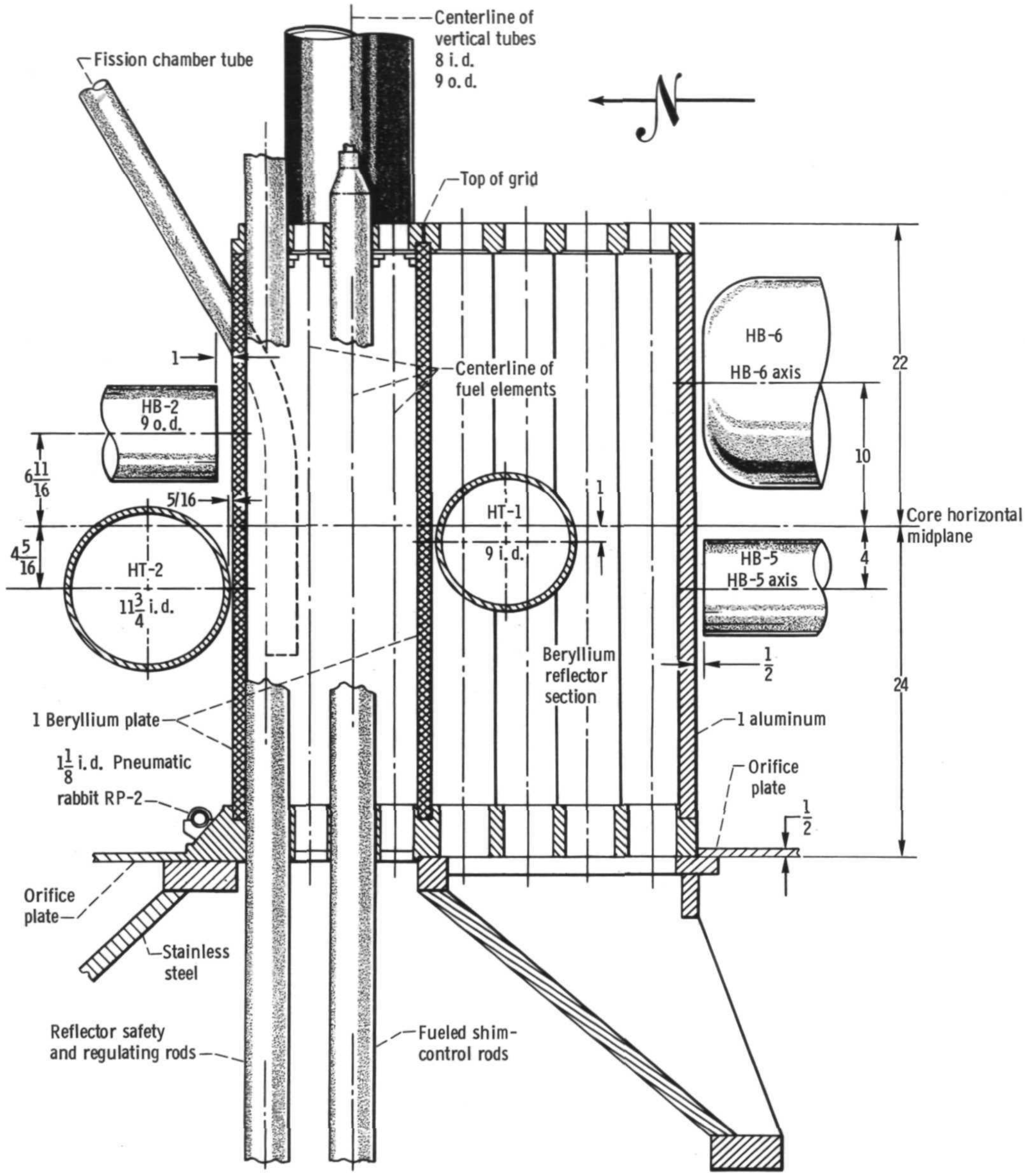


Figure 1. - Reactor tank assembly.



(a) Horizontal section.

Figure 2. - Reactor core. (All linear dimensions are in inches.)



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(b) Vertical section.

Figure 2. - Concluded.

REFLECTOR CONTROL RODS

From the surveillance program it was discovered that the bowing of the beryllium reflector control section caused the rods to bend. The control rod is made up of three sections: a stainless-steel poison section, a beryllium reflector section, and a lower stainless-steel guide sections. The three sections are tied together with one locking bolt. The lower section has two sets of bearings - a fixed lower bearing to center the drop of the control rod into a dashpot and an upper bearing with lateral float. The stainless-steel poison section is guided by a bearing block located on the core box upper grid.

During control rod drop tests in February 1967, the control rod, located in core position LA-8, would stop under no-flow conditions about 1 foot from its seated dashpot position. The rod would fall properly when the locking bolt located on the top of the poison section was loosened. This allowed the control rod sections to hinge.

A special alinement jig was made to measure the assembled control rods (fig. 3). Figure 4 shows the alinement jig in the Hot Laboratory with a bowed beryllium section installed. The bowed assembled rod is shown to be 3/8 inch away from the zero reference screw. Each beryllium reflector control rod section has an aluminum box at each end

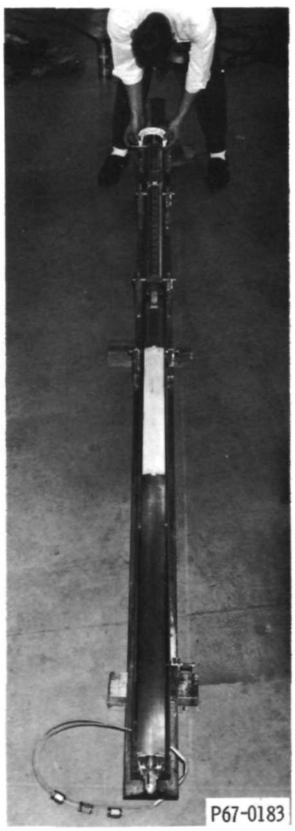


Figure 3. - Alinement jig with assembled control rod.

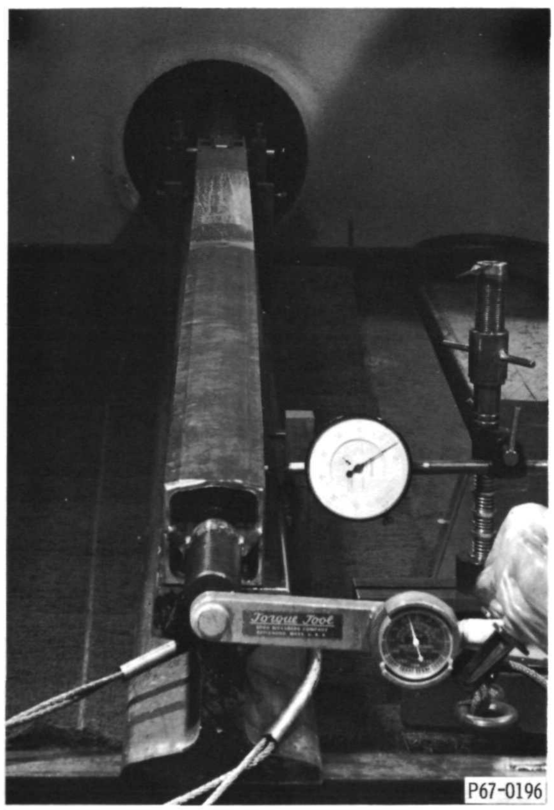


Figure 4. - Control rod in alinement jig with bowed beryllium section.

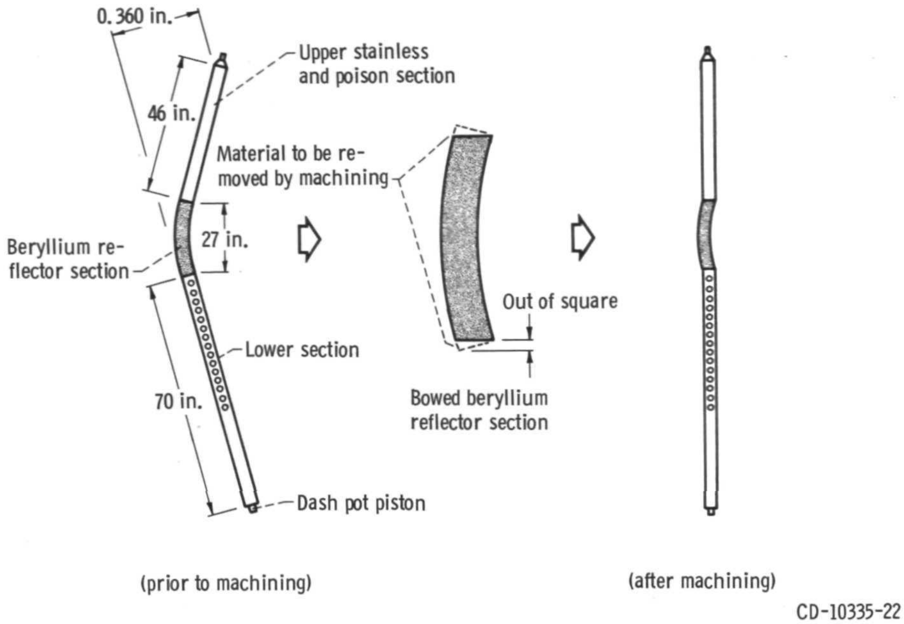


Figure 5. - Control rod (LA-8) with a bowed section installed and results with corrective machining.

which has the necessary mechanical devices for attachment. The beryllium section aluminum end boxes were mechanically machined parallel to provide proper alinement of the assembled control rods. Figure 5 graphically shows the results of this corrective machining.

BERYLLIUM PLATE

From the surveillance measurements on the south beryllium plate it was determined that the bowing rate towards the fuel elements was three times greater than expected. The plate, as it continued to bow, came into contact with the aluminum side plate of the fuel elements. Analysis and measurements indicated that the fuel elements could support the load. A visual inspection in February 1968 (37 256 MWD) indicated that the south beryllium plate had cracked during the cycle (fig. 6). A safety analysis had previously shown that reactor operations with a cracked plate would be safe and acceptable, and no abnormalities were observed during the cycle.

To mechanically remove the inaccessible bolts which anchor the side plates to the lower grid, the entire core box would have to be removed from the supporting structure. This also would require the removal of all the precisely alined beam tubes and through tubes. To avoid this major disassembly, the feasibility of using EDM was investigated. It had the following advantages:

Figure 6. - Top half of broken beryllium south plate.

(1) The bolts could be easily severed.

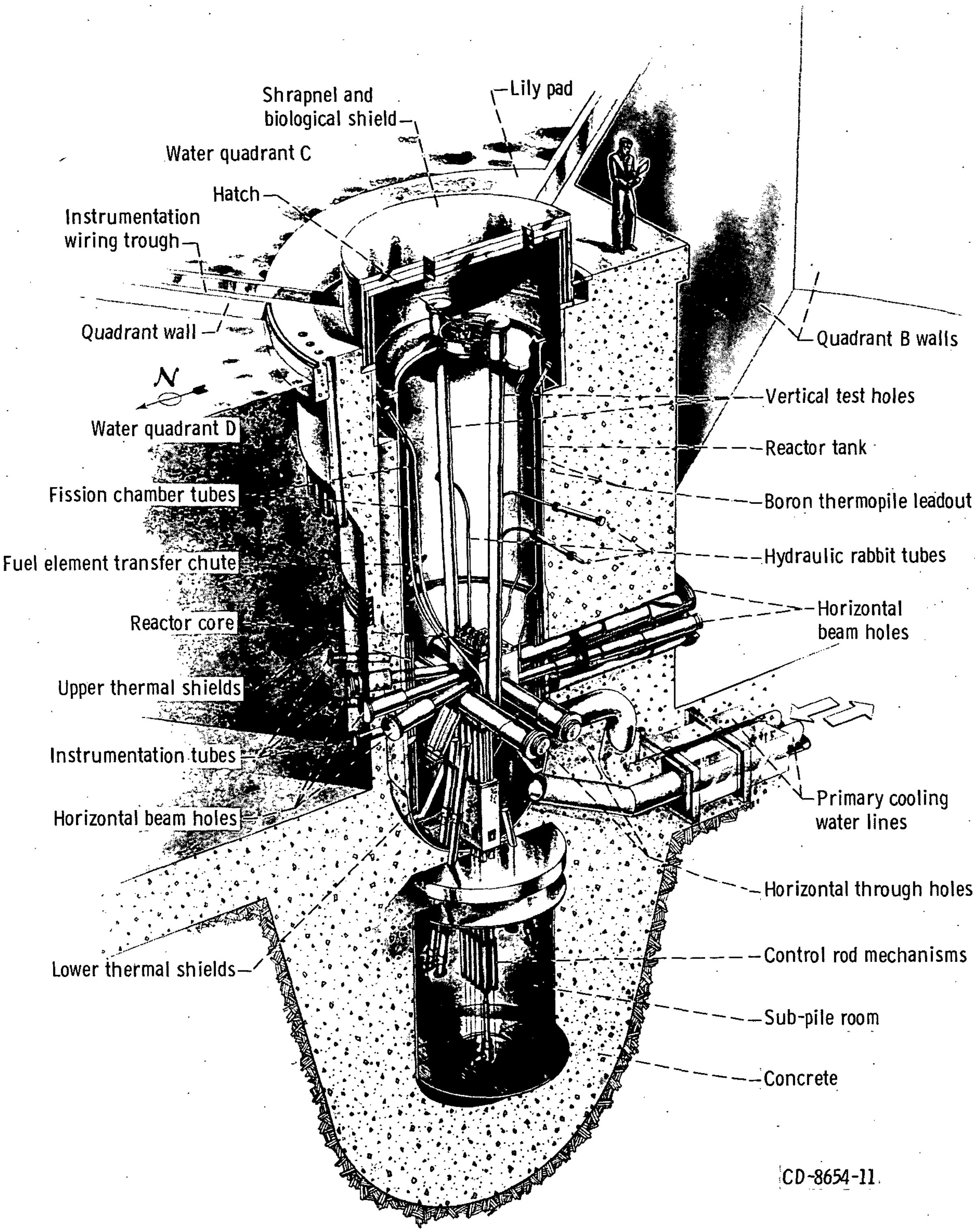
(2) The process was adaptable to remote underwater application.

(3) Electrodes could be used which would not contaminate the primary system. Nickel was selected as the electrode material over copper, tungsten, and graphite. Nickel was compatible from a corrosion standpoint with the aluminum clad fuel elements and did not form any troublesome activation products if plated out on the core components.

(4) The EDM could be used to remove the beryllium plate from the grooves if mechanical methods failed.

To replace the plates, the reactor tank dome was removed, all possible core components were removed, the water level lowered, and a work platform installed 6 feet above the reactor core. The reactor tank wall was covered with a heavy plastic sheet to reduce contamination and radiation. A circulating water pump was installed to provide cooling for the EDM electrode and collect the particles and chips from the EDM operation. A blower was used to remove the gases which were generated during the EDM operation. The blower discharge was through a high efficiency air filter to the stack. The blower also provided the fresh air for normal reactor tank working environment.

After the lower bolts were severed using EDM with nickel electrodes, the north plate and the top half of the broken south plate were lifted out. The lower half of the south plate could not be removed mechanically because it had swelled and was wedged into its retaining slots in the aluminum side plates and the lower grid. Various mechanical pulling devices were tried. Attempts to drill holes in the plate for attachment of pulling devices were unsuccessful. The mechanical properties of the plate varied. It crumbled in the



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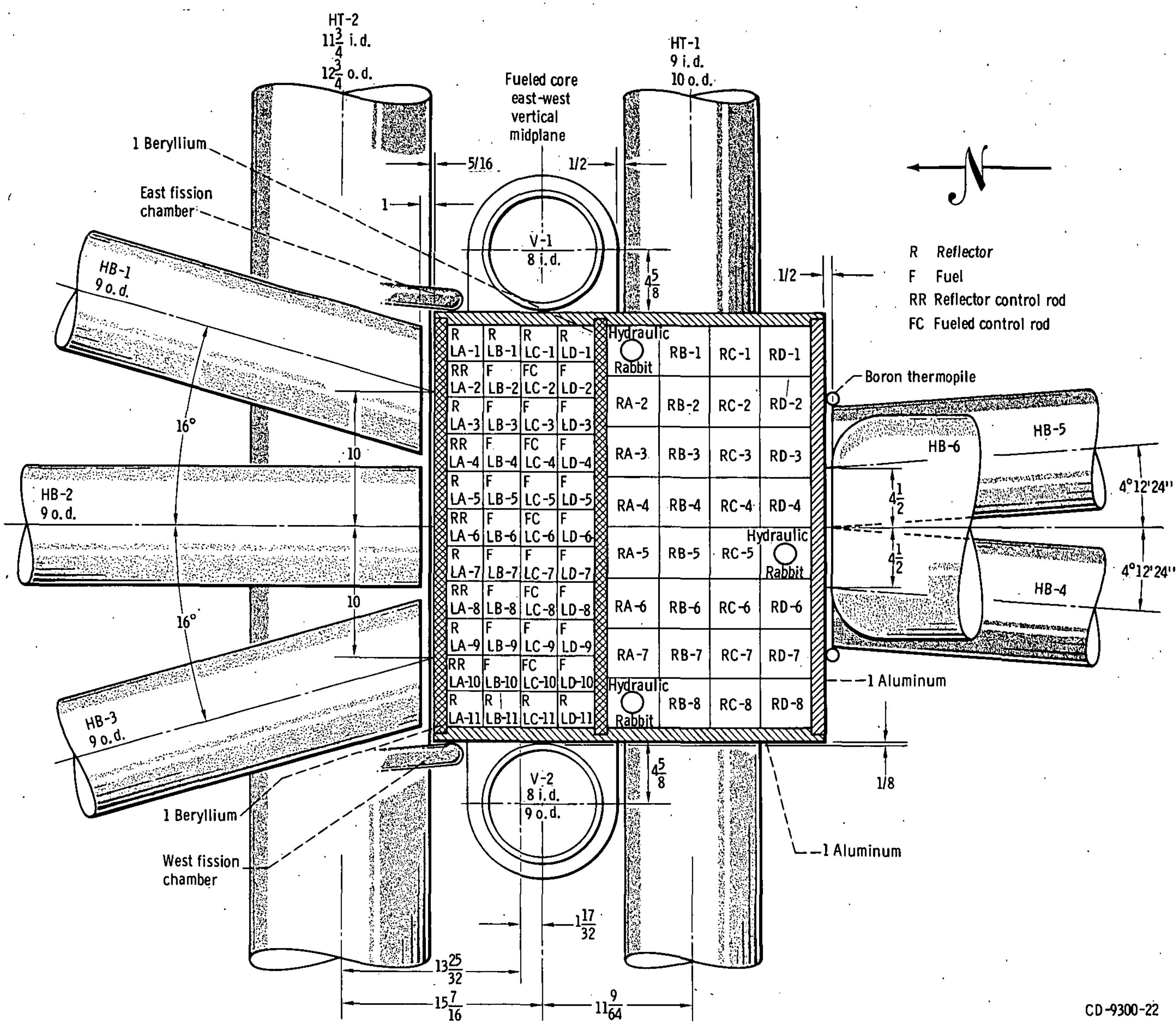

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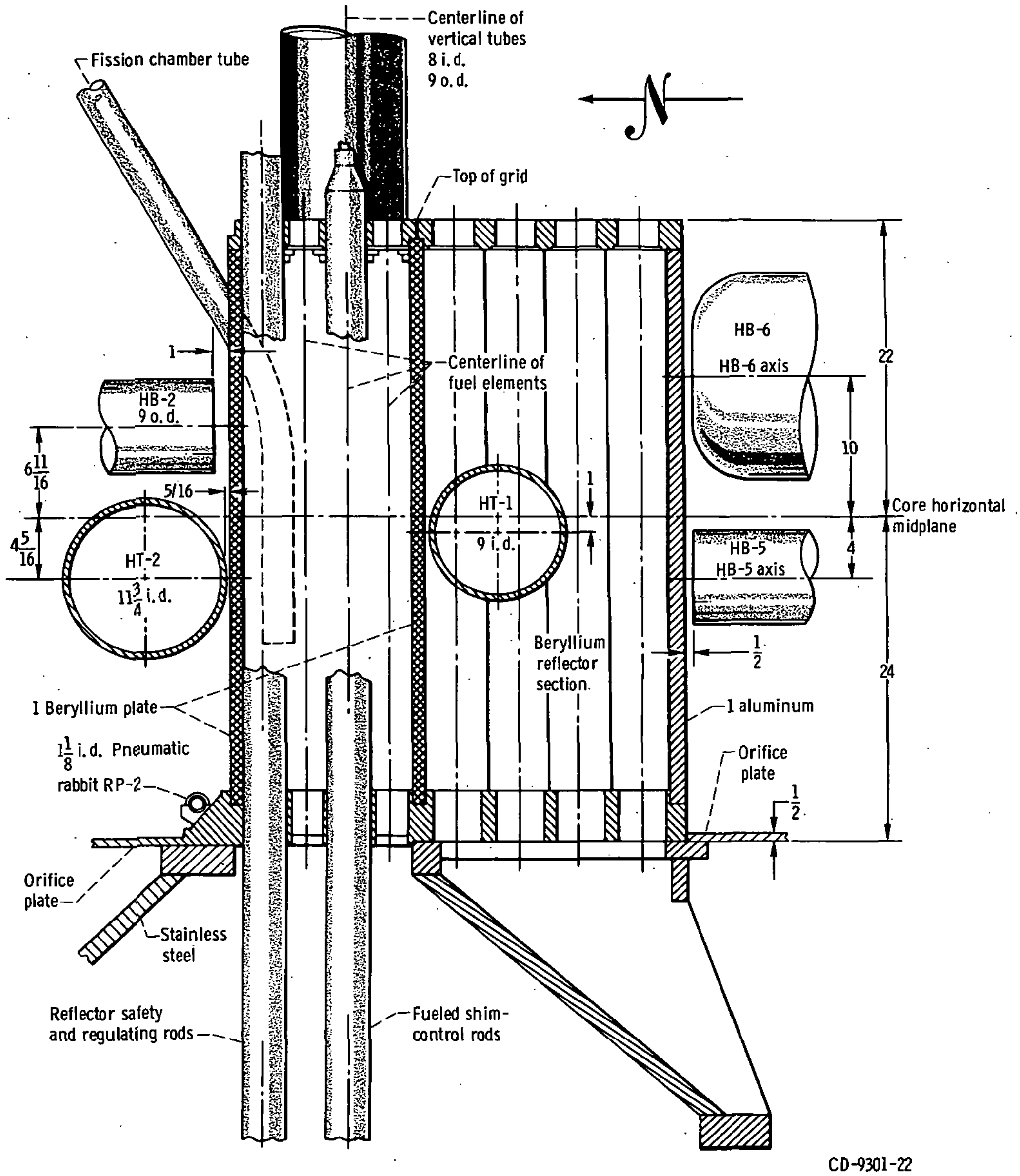

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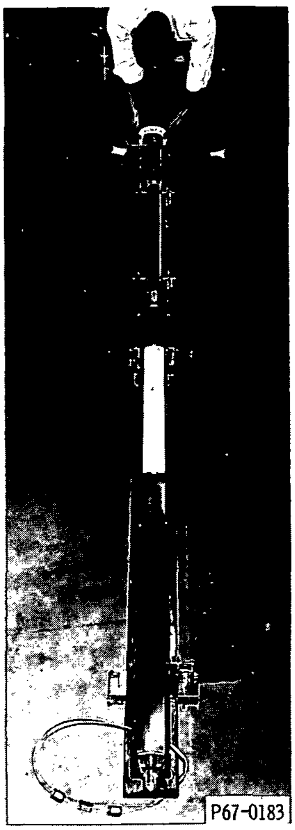

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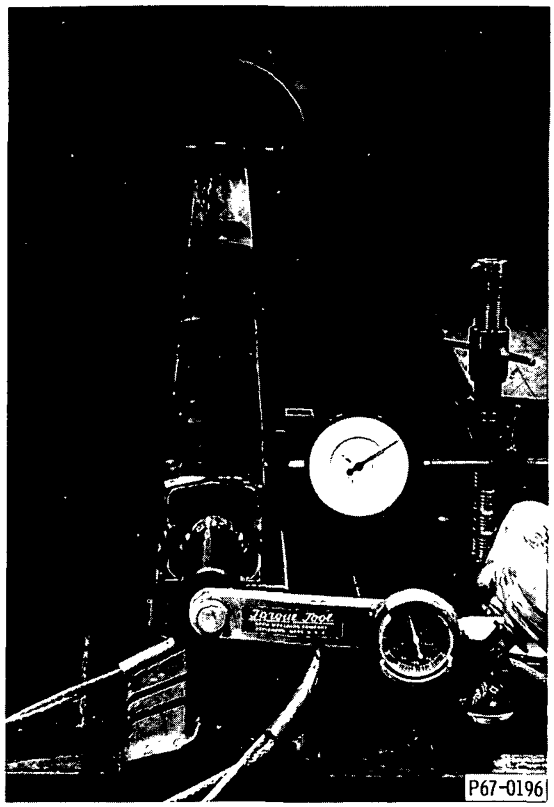

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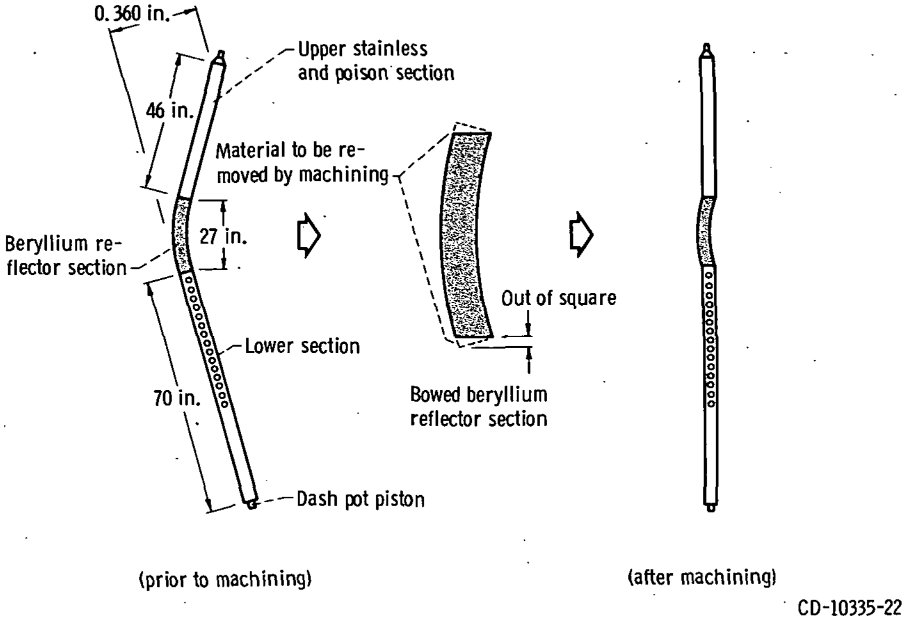

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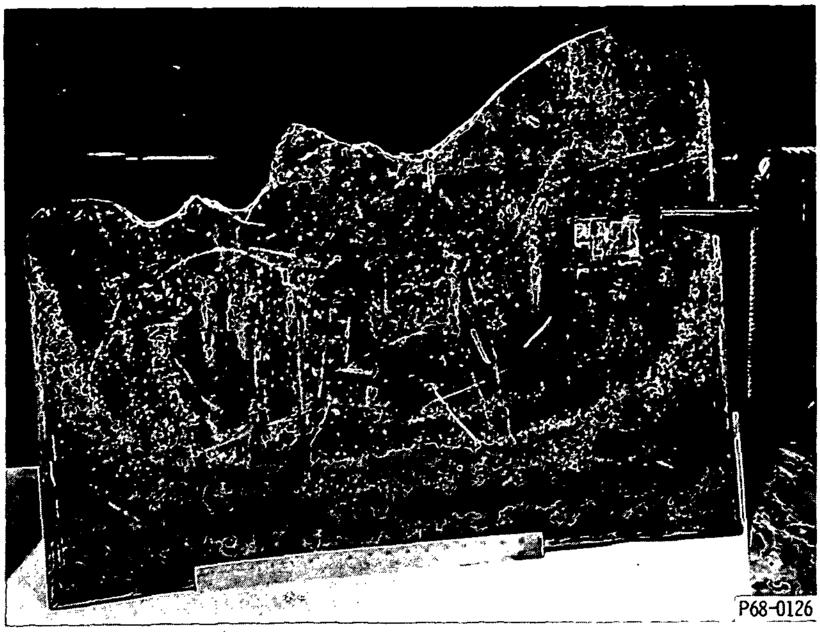

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From shutdown to critical the beryllium replacement required 94 days. Two persons working in the reactor tank reached one-half of the allowable (1.25 rem) quarterly health-safety radiation exposure.

The design of the north and south plate was changed to

(1) Make the plates interchangeable

(2) Make each plate so it could be rotated to bow in the opposite direction

(3) Reduce the thickness by 0.005 inch where the plate is held in the lower grid and end plate slots

(4) Cut back the sides and the bottom of the plate 0.025 inch to allow for length and width growth

Upon completion of the beryllium installation and the reactor tank work, the dummy fuel elements were installed in the core and the primary system operated for cleanup. It was discovered that after the many precautions taken to collect all the chips and avoid the loss of items in the reactor tank, significant amounts of debris were collected. The primary system strainer has openings of about 0.060 inch. Slivers with 0.060 inch diameter and longer length could pass through the strainer and scratch the aluminum cladding if caught between a fueled control rod and the adjacent stationary fuel element in C-row, or between fuel elements.

The tests to determine the effects of the new beryllium were the shutdown margin evaluation and control rod worth calibration. There were no measurable changes of the nuclear parameters.

BERYLLIUM MACHINING HEALTH HAZARDS

To determine the health hazards of using EDM on beryllium, an unirradiated piece was machined under controlled conditions and air samples obtained. The test was conducted in a portable fume hood with the beryllium test piece under 1 foot of water. Analysis of the air sample showed the concentration to be 50 micrograms per cubic meter. Therefore the following health safety controls were established for machining the irradiated reactor core beryllium in the reactor tank under 6 feet of water:

(1) Airline respirators were worn at all times in the reactor tank during EDM operation. Full face respirators were required in the reactor tank at all other times.

(2) A plastic enclosure was installed over the reactor tank with positive airflow to the radioactive waste air header.

(3) All personnel working in the reactor tank were required to wear anticontamination clothing and take showers at the completion of the day's work.

(4) In-tank air samples were taken during the operation.

All air samples collected indicated that the work was performed well below the permissible level (ref. 2) of 2 micrograms per cubic meter. The reactor tank airborne concentration during the EDM operation was 0.04 microgram per cubic meter. Smears taken on the reactor tank wall showed a buildup of beryllium contamination to levels of 500 micrograms per square meter. Special care was taken to avoid contact with the contaminated surfaces, and the surfaces were kept wetted.

Upon completion of the EDM work the reactor tank wall was decontaminated by wiping to less than 1.0 microgram per square meter. During initial cleanup of the primary system, a primary water sample indicated that the beryllium concentration was 6.6 micrograms per milliliter. This level has been considerably reduced with continued cleanup of the primary system during reactor operations.

DISCUSSION OF RESULTS

Neutron Fluences

Beryllium has the desirable nuclear properties for use in a reactor, but lacks ductility, which limits is use in structures. The beryllium test specimens surveillance inindicated a loss in the ductility with increasing neutron fluence. The failure of the south beryllium plate is typical of a brittle fracture. The maximum neutron fluence ($E > 0.1$ MeV) on the plate is 3×10^{22} neutrons per square centimeter, and the fluence at the side edges is 2.2×10^{21} neutrons per square centimeter. The fluences on the north plate are a factor of four lower.

Beryllium Material

The plates were made from a beryllium block of high purity hot pressed material. The trace impurities of high neutron cross section material were kept low. A gamma scan performed on the beryllium 73 days after the last irradiation revealed the major isotopes to be cobalt 50 = 1.1 millicuries per gram and scandium 46 = 1.5 millicuries per gram. The radiation level during removal of the plate was estimated to be 5000 roentgens per hour on contact.

During irradiation it is estimated that the temperature of the beryllium is from 50° to 75° C. Since the original installation the south plate grew about 0.050 inch in width (from actual measurements at the center of the plate), and it is estimated that the plate grew about 0.002 inch in thickness in the slot areas.

Bowing Rates

The bowing rate for each removable beryllium "L" Section piece was determined from actual measurements. The fast flux ratio ($E > 0.1$ MeV) is the average value for the position over the normal operating cycle of 14 days. The bowing rates are tabulated below.

Location	Fast flux ratio[a]	Position bowing rate, in./1000 MWD
LD-1	0.60	0.0007
LC-1	.68	.0008
LB-1	.60	.0007
LA-1	.28	.0003
LA-3	.86	.0010
LA-5	1.0	.0012
LA-7	1.0	.0012
LA-9	.86	.0010
LA-11	.28	.0003
LB-11	.60	.0007
LC-11	.68	.0008
LD-11	.60	.0007

[a] $1 = 1.8\times10^{14}$ neutrons/(cm^2)(sec).

For the control rod reflector section, the bowing rate and the out-of-squareness must be considered for the entire assembly.

The misalinement rate of the control rod reflector section is given below with an out-of-squareness factor of four applied to the position bowing rate:

Location	Fast flux ratio[a]	Position bowing rate, in./1000 MWD	Misalinement rate, in./1000 MWD
LA-2	0.67	0.0008	0.0032
LA-4	.97	.0011	.0044
LA-6	1.0	.0012	.0048
LA-8	.97	.0011	.0044
LA-10	.67	.0008	.0032

[a] $1 = 1.8\times10^{14}$ neutrons/(cm^2)(sec).

Positions LA-2 and LA-10 have regulating rods and one rod is operated partially inserted. A correction must be made to the misalinement rate based on the operating history.

The bowing rate for the south beryllium plate was measured to be 0.003 inch per 1000 MWD, and for the north plate 0.0008 inch per 1000 MWD.

CONCLUSIONS

In construction of reactor components in high fluence locations, the reactor designer must allow for changes in physical dimensions and mechanical properties of the material. All sensitive components should be readily replaceable and safety analysis made of the consequence of a failure of these components during reactor operation. Work with highly radioactive and toxic materials can be safely done with proper evaluations, tests, and planning. Surveillance programs must be related carefully to all the environmental parameters (fluence, temperature, physical, mechanical, etc.) and operating conditions of the materials.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 6, 1969,
122-29-05-01-22.

REFERENCES

1. Beeston, J. M.: Gas Formation and Compression Fractures in Irradiated Beryllium. Symposium on Flow and Fracture of Metals and Alloys in Nuclear Environments. Spec. Tech. Publ. No. 380, ASTM, 1964, pp. 395-416.
2. Anon.: Threshold Limit Values for 1967. American Conference of Governmental Industrial Hygienists, Cincinnati, 1967.

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