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STATUS REPORT ON THE ADVANCED TEST
REACTOR MATERIALS SURVEILLANCE PROGRAM

G. E. Korth, J. M. Beeston, W. F. Zelezny

IDAHO NUCLEAR CORPORATION
NATIONAL REACTOR TESTING STATION
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Printed in the United States of America
Available from
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U. S. Department of Commerce
Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.65

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IN-1343
Issued: November 1969
Metals, Ceramics, and Materials
TID-4500

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IDAHO NUCLEAR CORPORATION
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U. S. Atomic Energy Commission Research and Development Report
Issued Under Contract AT(10-1)-1230
Idaho Operations Office

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ABSTRACT

The status of the ATR Materials Surveillance Program is presented. This program consists primarily of monitoring irradiation-induced property changes of beryllium and hafnium; to a more limited extent, 6061-T6 aluminum and Types 304, 348, and 17-4 PH stainless steel are included in the surveillance program. Data provided by this program will be used in predicting the behavior of ATR components, especially the beryllium reflector and the hafnium control rods. The frequency of replacement is dictated by irradiation damage (growth, embrittlement), material optimization in design, and reactivity changes.

Preirradiation data of the hafnium, aluminum, and stainless steels are presented and will be used as a basis for monitoring property changes that can be used as criteria for predicting service life of the ATR components. The schedule for the transfer of the capsules containing beryllium from the ETR to the ATR is presented. Fifteen new capsules will also be inserted in the ATR when it begins Cycle 1.

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STATUS REPORT ON ADVANCED TEST REACTOR MATERIALS SURVEILLANCE PROGRAM

I. INTRODUCTION

Materials within or adjacent to the Advanced Test Reactor (ATR) core will be subjected to high total exposures of fast neutrons and attendant flux gradients. In this environment, both embrittlement and dimensional instability (bowing and growth) are known to occur. To predict the service life and produce information important to analysis of operational hazards of some of the reactor components, this surveillance program was initiated to monitor the mechanical changes of ATR materials in the core at operating temperatures. These materials are principally beryllium and hafnium, with samples of 6061-T6 aluminum alloy and Types 17-4 PH, 304, and 348 stainless steels.

Monitoring a number of different property changes is necessary to evaluate the service life of a component since it is difficult to estimate which property change will be dominant in rendering a particular component useless or unsafe in a given application. In some applications, bowing or growth of a component would be much more detrimental than embrittlement; in other cases, the decrease in ductility would be the deciding factor in replacing a reactor component. Therefore, the purpose of the ATR Materials Surveillance Program is twofold: (a) to determine which irradiation-induced property change is most critical in rendering a component unsafe or nonfunctional, and (b) to predict a safe neutron exposure to which a given component can be subjected before replacing it. By monitoring property changes of encapsulated specimens fabricated of materials with a similar history to that of the various components, the service life can be calculated before it is actually reached. In all cases except with the hafnium and aluminum, the specimens will considerably lead the components in total neutron exposure. The end result of the surveillance program will be to keep ATR operating costs at a minimum by optimizing replacement frequency of vital components and assisting in this optimum replacement through a knowledge of the operational risks of these components.

II. MATERIALS

1. BERYLLIUM

The neutron reflector in the ATR is constructed of beryllium. The service life of the reflector depends upon its ability to resist corrosion and maintain dimensions and sufficient strength and ductility to withstand thermal cycling and vibration due to hydraulic flow without severe cracking and spalling. The parameters being monitored in beryllium as a function of fluence are growth, compressive strength and ductility, corrosion, and the helium buildup due to nuclear reactions. Helium is believed to be the primary source of undesirable property changes in beryllium.

The initiation of the beryllium phase of the ATR Materials Surveillance Program is found in another document^[1]. Sixty-four capsules containing five beryllium specimens each were placed in the ETR prior to Cycle 71 startup. As soon as the ATR startup tests are completed, the beryllium specimens will be transferred starting with ATR Cycle 1. Four grades of beryllium were selected for the surveillance program and are presently in the ETR: (a) ATR hot-pressed, which is the beryllium specified for the ATR, Specification M-182, conforming to a chemical composition of 98.0% Be and 2.0% BeO; (b) hot-pressed beryllium with a composition of 98.0% Be and 1.5% BeO; (c) hot-pressed, hot-extruded beryllium conforming to a composition of 98.5% Be and 1.2% BeO; and (d) vacuum cast material having a nominal composition of 1% BeO (max) and 99% Be (min). Zone-refined single-crystal beryllium pieces with known crystal orientations were also procured. They were not included in the capsules inserted in the ETR but will be inserted in the ATR at the time of transfer. These samples will be used to study compression strength of irradiated beryllium as a function of crystal orientation. The zone-refined samples also will be used to measure any lattice parameter expansion due to irradiation using the electron microprobe analyzer and the Kossel Line technique which requires single crystals. The lattice parameter will be measured after fast neutron exposures of approximately 0.5×10^{19} , 1×10^{19} , 1×10^{20} , 1×10^{21} , and 1×10^{22} n/cm². The three lower fluence samples will be irradiated in a lower flux facility (eg, the B holes in the ATR). The two highest fluence samples will be included with the other beryllium capsules in the

H- and A-holes in the ATR neck shim housing. Preirradiation data of the beryllium single crystals are shown in Table A-I of Appendix A. Kossel diagrams for two different crystal orientations are shown in Figures A-1 and -2.

The zone-refined beryllium specimens are 0.087 inch smaller in diameter than the other beryllium specimens. Also, since the tolerances on the spark-machined, zone-refined beryllium are of the order of ± 0.005 inch, an inner capsule with the single crystals sealed inside and filled with NaK was designed to be shrunk fit into the standard surveillance capsule. This inner capsule assembly is shown in Figure A-3. The void space above the NaK contains helium.

Three capsules, Nos. 44, 49, and 50^[a], were removed at the start of ETR Cycle 80, and two more, 51 and 52^[a], were removed at the start of ETR Cycle 86. Growth measurements, compression tests, impact tests, fractography, transmission electron microscopy, and annealing-swelling tests were conducted on the specimens contained in the five capsules. The results of tests on specimens from all capsules are to be reported in other documents.

Four capsules, Nos. 1, 8, 9, and 15, were removed at the start of ETR Cycle 100. The recovery of the specimens from these capsules, subsequent property measurements, and mechanical tests are currently being conducted except for the specimens from capsule 15 (which will be transferred to the ATR as corrosion specimens). Also, during Cycle 100 shutdown the entire experiment assembly was moved from the K-6 to the G-6 position in the ETR. At the time of the ETR to ATR transfer, 49 capsules will be transferred and the six remaining capsules, Nos. 21, 36, 43, 61, 62, and 64, will undergo post-irradiation testing. Of the 49 capsules transferred, two (Nos. 26 and 63) will be opened; these specimens (and also No. 15) will be placed in open corrosion capsules in the ATR core. In contact with the reactor cooling water, they will be removed periodically (about every six cycles), inspected, measured for corrosion, and returned to the reactor.

The postirradiation testing will consist of growth measurements, compression tests, impact tests, fractography, transmission electron microscopy, annealing-swelling tests, and gas analysis. In addition to the incremental heating and length

[a] See Reference 1 for capsule identification.

measurements (annealing-swelling tests), measurements made with a dilatometer will be performed to obtain isotherms of dimensional changes versus time. These types of measurements, coupled with transmission electron microscopy, will yield kinetic data on the gas release of the helium formed by nuclear transmutations.

In further support of the ATR beryllium surveillance program, residual stress measurements are to be performed on MTR reflector pieces which will be available September 1969, from the MTR beryllium which was replaced. Preliminary measurements obtained from a piece of the MTR beryllium reflector that spalled off after a fast fluence of approximately 4×10^{22} n/cm² (E > 1 MeV) did show the presence of residual stress. The results of this test were not conclusive but residual stress buildup was definitely evident and a minimum value of 2000 psi was detected. The residual stress, in reality, is probably higher than this measured value, but as the test was preliminary and exploratory, the apparatus used gave only indicative results. The residual stress buildup may well be the limiting factor of the service life of the ATR beryllium.

An ATR loading schedule listed by ATR location for the beryllium specimens, as well as the other materials, is given in Table E-I in Appendix E. A listing by type of material is given in Table E-II.

2. HAFNIUM

Hafnium in the ATR is used for flux control and shutdown; therefore, it is located in the core of the reactor where it will be subjected to high total exposures of fast and thermal neutrons. To serve its intended purpose, the hafnium must maintain certain mechanical strength, tolerances, and certain levels of reactivity. Irradiation damage, including physical dimensions, is affected by increasing the fluence of fast neutrons; the ability to absorb neutrons is changed with the attendant thermal flux. Therefore, the hafnium phase of the ATR surveillance program was initiated to monitor changes of the hafnium components in their operating environment.

Hafnium is used as a flux control material in three functions: (a) fixed neck shims, (b) safety rods, and (c) outer shim control cylinders. The fast fluence (E > 1 MeV) in the neck shim rods will lead that of the safety rods

by a factor of four and the outer shim cylinders by a factor of seven. Therefore, the fixed neck shims have been designated for hafnium surveillance.

The parameters that will be monitored by periodic removal will be changes in dimensions and reactivity. In addition, destruct tests will be made at successive intervals for strength and ductility changes. Also, the radiation damage will be analyzed by the use of transmission electron microscopy. The details of monitoring the property changes are described in succeeding paragraphs.

2.1 Material History

The grade of hafnium used for flux control in the ATR is outlined in Specification M-180, "ATR Specification for Hafnium Wrought Products". This document refers to MIL-H 23191 (SHIPS), military specification hafnium wrought products, which requires the chemical composition to be 95.3% hafnium (min), 200 to 500 ppm iron, and 100 to 400 ppm oxygen. The major impurity allowed is zirconium, which in the ATR hafnium was between 2.9 and 3.0 %. The hafnium used for the fixed neck shims was manufactured by the Wah Chang Corporation of Albany, Oregon. Its report of the measured properties, as specified by MIL-H 23191 (SHIPS) of the two heats used in neck shim manufacture, is summarized in Tables B-I and -II in Appendix B.

The history of the ATR hafnium fixed shim rods is as follows:

- (1) Hafnium sponge manufacture
- (2) Conversion to crystal bar
- (3) Ingot consolidation using consumable electrode process
- (4) Hot-rolled and forged into 0.600-inch diameter bar at temperatures between 1500 and 2000°F
- (5) Grit-blasted and pickled in nitric acid (25 to 35 vol%), hydrofluoric acid (3 to 5 vol%), and water solution
- (6) Annealed six hours at 1475°F in one micron or less vacuum
- (7) Machined into desired shape
- (8) Cleaned and pickled
- (9) Corrosion tested in steam at 750°F and 1500 psi for 80 to 84 hours.

The samples used for measurement of the properties shown in Tables B-I and -II were taken immediately after Step 6 in the history sequence (shown above). In addition to the samples taken for tests, retainer samples were cut from the bar stock and stored at the Wah Chang Corporation, as required

by Specification MIL-H 23191 (SHIPS). These hafnium retainer samples were obtained by Idaho Nuclear Corporation as control specimens for growth and other tests. Photomicrographs from the two heats (in preirradiated conditions) represented by the retainer samples are shown in Figure B-1 of Appendix B. Both optical and transmission electron microscopes were used. Nine cylindrical specimens (0.400 inch diameter x 1.230 inches long) were machined from these retainer samples and will be encapsulated for insertion in the ATR core for growth measurements, compressive yield strengths, and transmission electron microscopy.

2.2 Dimensional Changes

To monitor dimensional changes of the fixed shim rods, reference measurements were made on the spline pitch diameter (D_1) and spline root diameters (D_2) between the spacer nibs (see Figure B-2 in Appendix B). There are eight spacer nibs, hence, seven measurements. The diametrical difference ($D_1 - D_2$) will be used to monitor growth based on the assumption of negligible or equal corrosion rates in both areas. There are presently eight fixed shim rods for ATR use (numbered FS-1 through FS-8), four of which are in the reactor. The weight and reference dimensions are shown in Table B-III, Appendix B. These measurements were made using a Bausch and Lomb Optical Gage, Model DR-25B, having an accuracy of $\pm 20 \mu$ in. and an analytical balance with an accuracy of ± 0.1 mg.

A backup and correlating measurement was made between two machined fiducial marks on spacer nibs. A low expansion Invar block with fixed indexing pointers of 19.896 inches and photography were used to measure the distance between the marks. A six-inch scale was used for calibrating the magnification. The dimensions, as measured by the above method, are listed in Table B-IV. Since the marks do have a finite width, the distance listed is the inside-to-inside measurement. The measuring fixture is shown in Figure B-3. All measurements were made in the hot cell so that the same method and equipment could be used on the postirradiation measurements. This method of measurement is limited to an accuracy of ± 0.001 inch, which gives a percentage error of 0.07%. One fixed shim rod would be removed, inspected, and measured at intervals of about one year. As described later, a destruct test also is to be made.

Dimensional stability also will be monitored on the cylindrical specimens machined from the retainer samples mentioned previously. The geometry of

these specimens greatly facilitates precision dimensional measurements. Since these specimens are encapsulated in an inert environment (vacuum), the uncertainty due to corrosion products will be eliminated. The preirradiated measurements of these specimens are shown in Table B-V.

2.3 Strength and Ductility

Tensile strength and ductility will be measured by machining test specimens from irradiated fixed shim rods. One shim rod would be destructively tested (at intervals of about one year) after dimensional measurements have been performed. To make a tensile specimen from the hollow, splined, fixed shim rod, it will be machined into a tube with a reduced section. The ID will be reamed out to remove any surface flaws, and the OD will be turned down to remove the splines. The machined tensile specimen is shown in Figure B-4. The specimen will be pulled as a tube specimen as per ASTM E-8. The cylindrical specimens from the capsules will be used to measure compressive yield strength.

2.4 Corrosion

The corrosion rate will be measured by the diametrical and weight changes of the fixed shim rods. The preirradiated weight and diametrical measurements of the eight shim rods have been given in Table B-III.

2.5 Reactivity Changes

The burnup of hafnium or loss of reactivity will be monitored by ATRC measurements on the fixed neck shim rods before the destruct tests. Thus, four shim rods (at intervals of one year) would give measurements over a period of four years or more, if required.

2.6 Lattice Parameter Measurement

By monitoring changes in the lattice parameter of hafnium, the buildup in residual stress, if present to any significant degree, can be measured. The expansion of the lattice is often found to be a contributing factor in the growth of an irradiated metal. The lattice parameter of samples taken from both heats of the hafnium retainer samples was measured with the shielded X-ray diffractometer by the CPP analytical section of Idaho Nuclear Corporation. The shielded diffractometer was used so that the postirradiation measurement would be performed in the same apparatus under the same conditions. The a₀

was determined from the (200) line and the c_o from the (201) line using the calculated a_o . The values are: $a_o = 3.1964 \text{ \AA}$; $c_o = 5.0678 \text{ \AA}$.

2.7 Suppressor Plates

In a fuel plate experiment conducted in the ETR, small hafnium suppressor plates were included in the experiment assembly to suppress the neutron flux at the ends of the fuel plates and thus eliminate high fluxes due to end effects. A set of suppressor plates (18) was included in the hafnium surveillance program to investigate radiation damage mechanisms. The experiment containing the suppressor plates was in the G-12 position of the ETR during Cycles 99, 101, and 102. It is estimated that the various suppressor plates received a total fast fluence of $0.8 \text{ to } 2 \times 10^{21} \text{ n/cm}^2$ during the three cycles. Flux monitors were in the G-13 North position, which is directly adjacent to G-12; therefore, accurate fluences will be available for these cycles of the ETR.

The suppressor plates were rolled and sheared from hafnium stock left over from the hafnium plates used on the ATR outer shim control cylinders. Therefore, this material was subject to the same specification (Specification M-180, "ATR Specification for Hafnium Wrought Products") as the fixed neck shims. Since the suppressor plates had been cold-worked, they were given the following treatment prior to insertion in the reactor: (a) annealed in argon at 850°C for three hours; (b) degreased and pickled in nitric acid (30 vol%), 48% hydrofluoric acid (4 vol%) and water solution; and (c) surface-treated in steam at 1500 psig and 750°F for 24 hours. This gives the suppressor plates basically the same history as the fixed shim rods except the surface treatment on the fixed shims was specified as 80 to 84 hours steam exposure.

The postirradiation tests and measurements on the hafnium suppressor plates will include: (a) strength and ductility measurements, by making tensile specimens from the $1.25\text{-} \times 0.22\text{-} \times 0.05\text{-inch}$ plates, (b) observation of irradiation-produced defects using transmission electron microscopy as a function of fluence and annealing temperature, (c) metallography, and (d) growth measurements. All 18 plates are impression-stamped 1 through 6, which corresponds to the identification number on the fuel plate experiment assembly. There are six assemblies in the train with three plates per assembly. Six suppressor plates (one from each assembly) were ground to yield square edges, and then width measurements were taken directly across the impression-stamped

number with a one-inch micrometer reading to within ± 0.0001 inch using the vernier scale. Assuming negligible corrosion, these measurements will yield results within 0.04% error. All preirradiation data of the suppressor plates are shown in Table B-VI and Figure B-5.

3. ALUMINUM

Recent data from a number of sources indicates that aluminum irradiated to high fluences (10^{22} n/cm²) suffers significant damage and ATR components should be monitored in the surveillance program on a limited basis to determine growth, primarily, at ATR operating conditions. Aluminum is used in the ATR core in a number of applications. Some of the major aluminum components in the core are the neck shim rod housing, outer flux trap baffle, inner flux trap baffle, and the side plates for the fuel elements which are required to meet ASTM B221-61-6061-T6511, ASTM B210-61-6061-T6, ASTM B210-61-6061-T6511, and ASTM B209-61-6061-T6 (30 ppm B max) specifications, respectively. Therefore, ASTM B211-67-6061-T651 aluminum was chosen for the ATR surveillance test specimens.

Sixteen 0.400-inch-diameter x 1.230-inch-long cylindrical specimens will be encapsulated and inserted in the ATR core prior to Cycle 1 startup. These specimens will be removed according to the schedule shown in Table E-II. Tests to be performed on the aluminum samples are as follows: (a) growth measurements, (b) compressive yield strength, (c) gas analysis, (d) transmission electron microscopy, and (e) effects of annealing on microstructure. Preirradiation data for the aluminum are shown in Figure C-1 and Table C-1.

4. STAINLESS STEEL

Although considerable investigations have been conducted on the irradiation effects of stainless steels, there is still a need to measure growth of these materials at ATR operating conditions. Stainless steels are used in the ATR for various miscellaneous parts in and adjacent to the core. The major and more critical stainless steel components are made from types 304, 348, and 17-4 PH; therefore samples of these three types have been included in the

surveillance program. The stainless steels used for specimens are identified in Table B-I, Appendix D.

Fourteen type 304, 16 type 17-4 PH, and 16 type 348 stainless steel slugs (0.400 inch diameter x 1.23 inches long) will be encapsulated and inserted into the ATR core prior to Cycle 1 startup. The stainless steel specimens will be subjected to the same postirradiation tests as the aluminum, that is growth measurements, compressive yield strength, gas analysis, transmission electron microscopy, and effects of annealing on microstructure. Preirradiation measurements, including electron and optical micrographs, are shown in Table D-II and Figures D-1, -2 and -3. Location in the ATR core and the unloading schedule are shown in Table E-II.

III. ETR-ATR TRANSFER

The beryllium specimens presently in the ETR will be transferred to the ATR prior to ATR Cycle 1 startup. The estimated date for the transfer is the fall of 1969. Upon removal from the ETR, the capsule trains will be disassembled, reassembled, and inserted into the ATR core in the locations as indicated by the schedule given in Table E-II. The applicable installation drawing is INC 533-0670-40-400-035769. This drawing designates all necessary support hardware required for the installation.

In addition to the beryllium specimens transferred from the ETR, 15 new capsules will be inserted into the ATR core. These capsules will contain aluminum, three types of stainless steels, and hafnium specimens as described in Section II. The locations of the new capsules are given in Table E-II.

The new capsule tubes to be added at the time of transfer (capsule Nos. 65 through 79) will be essentially the same as the non-lead aluminum capsules described on page 26 of IN-1043 (Reference 1), except for the following: (a) the inert environment inside the new capsules will be a vacuum (10^{-6} Torr, max) instead of argon; (b) the 1/4-28NF socket-head set screw and associated threaded hole will be eliminated on the new capsules; and (c) the end pieces of the new capsules will be welded by an electron beam welder instead of the heliarc process.

IV. ATR IRRADIATION

1. LOADING

All materials surveillance capsules will be inserted into holes in the neck shim rod housing. The ATR core cross section is shown in Figure E-1 of Appendix E. The A- and H-holes will be utilized as given in Table E-III.

The removal schedule of the capsules is given in Table E-I of Appendix E. In the case of the H-4, H-7, H-8, H-16, and A-10 holes, the entire capsule train is not unloaded after a given cycle; one or more capsules are to remain for further irradiation exposure. When this situation arises the entire capsule train is to be removed including the top and bottom spacers. The bottom spacer and the appropriate capsule(s) are then removed and a new bottom spacer is installed, which is longer, to accomodate for the removed capsule(s). Bottom spacers have been fabricated so that all the hardware required for completing of the entire irradiation schedule shown in Table A-II is available. The bottom spacers required when a partial capsule train is removed are shown in Table E-IV.

2. PROJECTED NEUTRON EXPOSURE

At the time of this writing, the plans for operating the ATR, beginning with Cycle 1, were to run at full power (250 MW), a fuel cycle of 17 days, and approximately one cycle per month. Based on these criteria and the fast neutron flux ($E > 1$ MeV) data^[3] from low level runs normalized to 250 MW, the predicted fluence for the capsules was calculated and is shown in Tables E-V.

After final decisions are made concerning cycle length, then an adjustment may be necessary in the unloading schedule so that target neutron exposures will remain as intended.

V. SUMMARY

The status of the ATR Materials Surveillance Program has progressed to the point where:

- (1) The capsules containing the beryllium samples are being irradiated in the ETR and have reached fluences of 0.42 to $1.12 \times 10^{22} \text{ n/cm}^2$ ($E > 1 \text{ MeV}$) at the end of Cycle 101.
- (2) Five capsules containing beryllium have been removed from the ETR and examined. Three more are currently under examination.
- (3) The program plan for hafnium surveillance has been outlined, and small hafnium plates meeting ATR specifications are currently being irradiated in the ETR.
- (4) 6061-T651 aluminum, types 304, 348, and 17-4 PH stainless steels have been added to the ATR Materials Surveillance Program on a limited basis. Preirradiation tests have been performed on these materials. Fifteen capsules containing the aluminum, stainless steels, and hafnium specimens have been fabricated. These capsules will be inserted in the ATR core when it begins Cycle 1.
- (5) Loading and unloading schedules for the ATR have been established, including the ETR-ATR transfer of the beryllium capsules.

VI. REFERENCES

1. J. M. Beeston and R. A. Mocn, Status Report on Advanced Test Reactor Beryllium Surveillance Program, IN-1043 (December 1966).
2. J. E. Cunningham, Severe Radiation Damage to Aluminum Alloys, ORNL-TM-2138 (March 1968).
3. N. C. Kaufman, J. L. Durney, J. C. Tappendorf, J. B. Willis, Reactor Physics Results from Low-Power Measurements in the Advanced Test Reactor, IN-1260 (February 1969).

**APPENDIX A-- PREIRRADIATION DATA
OF ZONE-REFINED BERYLLIUM SINGLE CRYSTALS**

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TABLE A-I

PREIRRADIATION DATA OF BERYLLIUM ZONE-REFINED SINGLE CRYSTALS

Specimen Number	Crystal Orientation	Approximate Diameter (in.)	Length (in.) ± 0.00002	Weight (g)	Density (g/cc)
549	(10 $\bar{1}$ 0) cylinder axis	0.311	0.20088	0.4612	1.8862
550[a]	(0001) cylinder axis	0.301	0.20138	0.4436	1.9088
551[b]	(10 $\bar{1}$ 1) cylinder axis	0.313	0.20137	0.4548	1.9206
606[c]	(10 $\bar{1}$ 0) cylinder axis	0.312	0.20080	0.4574	1.8987
607[d]	(0001) cylinder axis	0.306	0.20122	0.4256	1.8811
608	(10 $\bar{1}$ 1) cylinder axis	0.313	0.20140	0.4546	1.9195
609	(10 $\bar{1}$ 0) $\perp$ cylinder axis	0.300	0.86227	1.8055	1.8614
610	(11 $\bar{2}$ 0) $\perp$ cylinder axis	0.308	0.55790	1.2452	1.8665
611	(0001) $\perp$ cylinder axis	0.311	0.81500	1.8450	1.8613

[a,b,c] These samples will be irradiated to approximately 0.5×10^{19} , 1×10^{19} , and 1×10^{20} n/cm² (E > 1 MeV), respectively.

[d] This sample will be used as a calibrating control sample for the Kossel line technique of lattice parameter measurement and will not be irradiated.

FIG. A-2 INDEXED KOSSEL DIAGRAM OF BERYLLIUM SINGLE CRYSTAL WITH DIFFERENT ORIENTATION THAN THAT OF FIGURE A-1.

Assembly	Specimen No.s	ATR Location
A	608, 609, 610, 611	A-10-3
B	549	H-4-1

INC-B-13786

FIG. A-3 INNER CAPSULE ASSEMBLY FOR ZONE-REFINED SINGLE CRYSTAL BERYLLIUM SPECIMENS.

**APPENDIX B -- PREIRRADIATION
DATA AND MICROGRAPHS OF HAFNIUM**

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TABLE B-I

COMPOSITION LIMITS (PPM) OF ATR HAFNIUM FIXED NECK SHIM ROD STOCK

<u>Product Analyses</u>	<u>Heat Number</u>	
	<u>68-41029-Hf</u>	<u>68-41113-Hf</u>
Hf	>95.3%	>95.3%
Zr	2.9%	3.0%
Al	<25	<25
Cu	<40	<20
Fe	333	340
Ti	49	120
W	<20	<30
Mo	14	6
Ta	<200	<100
Cb	<100	<50
N	11	19
H	3.2	16
O	297	230
U	<0.5	<0.5
C	45	<30
U ₂₃₅	<0.007	<0.007

TABLE B-II

PHYSICAL PROPERTIES OF ATR HAFNIUM FIXED NECK SHIM ROD STOCK[a]

	Heat Number	
	<u>68-41029-Hf</u>	<u>68-41113-Hf</u>
Hardness (Ra)	52	50
Yield Strength (0.2% offset) psi	25,800	27,700
Tensile Strength (psi)	68,600	68,500
Percent Elongation in one inch	26	23
Percent Reduction in Area	33.3	31.7
Corrosion Test -- 28 day Steam at 750°F and 1500 psi		
Weight Gain (mg/dm ²)	7.04	9.16

[a] Measurements taken from samples annealed in one micron or less vacuum for six hours at 1475°F.

TABLE B-III

HAFNIUM FIXED SHIMS REFERENCE DIMENSIONS

Identification	Position					
	Spline Pitch Diameter[a]			Spline Root Diameter		
	No. 1	No. 2	No. 3	a	b	c
FS-1						
<u>77°F</u>					<u>83°F</u>	
1	0.38721	0.38685	0.38696	0.31863	0.31890	0.31946
2	0.38500	0.38587	0.38478	0.31972	0.31982	0.32062
3	0.38562	0.38511	0.38526	0.32093	0.32110	0.32182
4	0.38630	0.38578	0.38598	0.32075	0.32100	0.32080
5	0.38692	0.38657	0.38629	0.32041	0.32110	0.32117
6	0.38728	0.38744	0.38717	0.32000	0.31998	0.32006
7	0.38817	0.38785	0.38775	0.31760	0.31815	0.31753
FS-8				<u>82°F</u>		
1	0.38525	0.38558	0.38489	0.32180	0.31943	0.32159
2	0.38499	0.38496	0.38550	0.31880	0.31752	0.31892
3	0.38605	0.38734	0.38732	0.32063	0.31870	0.31992
4	0.38647	0.38740	0.38637	0.32153	0.32064	0.32121
5	0.38686	0.38672	0.38617	0.32111	0.32030	0.32073
6	0.38618	0.38540	0.38527	0.32136	0.31886	0.31990
7	0.38522	0.38554	0.38532	0.31690	0.31631	0.31730

729.5 gm

733.0 gm

[a] Positions are numbered consecutively clockwise when shim rod identification is facing the viewer.

TABLE B-III (Contd.)

Identification	Position					
	Spline Pitch Diameter [a]			Spline Root Diameter		
	No. 1	No. 2	No. 3	a	b	c
FS-4		76°F			82°F	
1	0.38621	0.38606	0.38625	0.31560	0.31547	0.31518
2	0.38458	0.38459	0.38437	0.31782	0.31805	0.31775
3	0.38631	0.38579	0.38646	0.32025	0.32016	0.31892
4	0.38687	0.38671	0.38654	0.31793	0.32066	0.31973
5	0.38594	0.38687	0.38607	0.32096	0.32051	0.32139
6	0.38549	0.38582	0.38568	0.32023	0.31978	0.32052
7	0.38637	0.38604	0.38599	0.31783	0.31817	0.31845
FS-3		76°F			76°F	
1	0.38577	0.38607	0.38584	0.32082	0.32010	0.31853
2	0.38749	0.38777	0.38814	0.32170	0.32301	0.32078
3	0.38780	0.38777	0.38772	0.32125	0.32210	0.32060
4	0.38446	0.38474	0.38467	0.32013	0.32050	0.31994
5	0.38669	0.38684	0.38708	0.32177	0.32084	0.32112
6	0.38587	0.38657	0.38609	0.32035	0.31981	0.31974
7	0.38454	0.38475	0.38432	0.31911	0.31857	0.31842

734.25 gm

729.7 gm

[a] Positions are number consecutively clockwise when shim rod identification is facing the viewer.

TABLE B-III (Contd.)

Identification	Position					
	Spline Pitch Diameter[a]			Spline Root Diameter		
	No. 1	No. 2	No. 3	a	b	c
FS-2					76°F	
1	0.38608	0.38615	0.38595	0.31570	0.31640	0.31574
2	0.38570	0.38561	0.38520	0.31910	0.31958	0.31927
3	0.38743	0.38760	0.38725	0.32105	0.32155	0.32142
4	0.38600	0.38684	0.38664	0.32002	0.31972	0.31873
5	0.38651	0.38704	0.38697	0.31937	0.31901	0.31767
6	0.38718	0.38721	0.38715	0.31925	0.31846	0.31761
7	0.38678	0.38701	0.38677	0.31800	0.31720	0.31670
FS-6		82°F			78°F	
1	0.38508	0.38558	0.38630	0.31609	0.31659	0.31610
2	0.38804	0.38810	0.38837	0.31940	0.31915	0.31943
3	0.38747	0.38742	0.38714	0.31989	0.32023	0.31984
4	0.38591	0.38587	0.38634	0.32032	0.32075	0.31995
5	0.38516	0.38517	0.38487	0.32017	0.32008	0.32137
6	0.38580	0.38567	0.38619	0.31885	0.31890	0.31998
7	0.38712	0.38716	0.38677	0.31847	0.31786	0.31848

727.1 gm

731.22 gm

[a] Positions are numbered consecutively clockwise when shim rod identification is facing the viewer.

TABLE B-III (Contd.)

Identification	Position					
	Spline Pitch Diameter[a]			Spline Root Diameter		
	No. 1	No. 2	No. 3	a	b	c
FS-7					78°F	
1	0.38554	0.38501	0.38529	0.31655	0.31689	0.31682
2	0.38590	0.38533	0.38549	0.31800	0.31928	0.31890
3	0.38737	0.38754	0.38735	0.32102	0.32131	0.32079
4	0.38562	0.38545	0.38478	0.32173	0.32198	0.32053
5	0.38732	0.38646	0.38575	0.32011	0.32100	0.32150
6	0.38573	0.38593	0.38550	0.32041	0.32133	0.32142
7	0.38717	0.38647	0.38637	0.31810	0.31918	0.31892
FS-5		76°F			78°F	
1	0.38644	0.38640	0.38539	0.31862	0.31768	0.31865
2	0.38724	0.38682	0.38722	0.31902	0.31850	0.31993
3	0.38636	0.38630	0.38592	0.32025	0.32037	0.32121
4	0.38755	0.38773	0.38766	0.32130	0.32142	0.32122
5	0.38872	0.38807	0.38797	0.32125	0.32070	0.32122
6	0.38720	0.38697	0.38690	0.32072	0.32030	0.32111
7	0.38674	0.38708	0.38690	0.32007	0.32020	0.32022

736.0 gm

738.06 gm

[a] Positions are numbered consecutively clockwise when shim rod identification is facing the viewer.

100X

Hafnium, Ht. No. 68-41029
Optical Micrograph of
Poison Material Used in
ATR Fixed Shim Rods

HF-HNO₃ Etch

100X

Hafnium, Ht. No. 68-41113
Optical Micrograph of
Poison Material Used in
ATR Fixed Shim Rods

HF-HNO₃ Etch

54,000X

Hafnium Ht. No. 68-41029
Transmission Electron
Micrograph of Poison Material
Used in Fixed Shim Rods

FIG. B-1 OPTICAL AND TRANSMISSION ELECTRON PHOTOMICROGRAPHS OF UNIRRADIATED FIXED SHIM ROD HAFNIUM.

FIG. B-2 FIXED HAFNIUM SHIM ROD SHOWING IDENTIFICATION MARKS AND FIXTURE FOR DIAMETRAL MEASUREMENTS.

TABLE B-IV

PREIRRADIATED LENGTH BETWEEN FIDUCIAL
INDEX MARKS ON FIXED SHIM RODS

<u>Shim Rod Number</u>	<u>Index Length (in.)</u>	<u>"A" End (in.)</u>	<u>"B" End (in.)</u>	<u>Rod Indexed[a] Length (in.)</u>
FS-1	19.896	-0.011	+0.005	19.890
FS-2	19.896	+0.004	+0.004	19.904
FS-3	19.896	-0.012	+0.004	19.888
FS-4	19.896	-0.010	0	19.886
FS-5	19.896	-0.006	-0.004	19.886
FS-6	19.896	+0.006	-0.024	19.878
FS-7	19.896	+0.003	-0.010	19.889
FS-8	19.896	-0.018	-0.005	19.873

[a] Since the index marks do have a finite width, the indexed length recorded is the inside-inside dimension.

FIG. B-3 MEASURING FIXTURE FOR MONITORING GROWTH OF HAFNIUM FIXED SHIM RODS.

TABLE B-V

PREIRRADIATED DATA OF HAFNIUM
SPECIMENS MACHINED FROM RETAINER SAMPLES

<u>Specimen Number</u>	<u>Length (in.)</u>	<u>Average Diameter (in.)</u>	<u>Weight (g)</u>	<u>Density (g/cc)</u>
560	1.23072	0.40022	32.8410	12.9440
574	1.23059	0.40033	32.8561	12.9442
575	1.23006	0.40039	32.8217	12.9323
590	1.23088	0.40007	32.7823	12.9289
599	1.23005	0.40023	32.7828	12.9275
600	1.23073	0.40014	32.7874	12.9280
605	1.23073	0.40056	32.7888	12.9014
618	1.23067	0.40017	32.7506	12.9119
623	1.23023	0.40023	32.7666	12.9192
Hardness (R_p)			88	
Compressive yield strength (0.2% offset) psi			44,950

FIG. B-4 HAFNIUM TENSILE SPECIMEN MACHINED FROM FIXED SHIM ROD.

TABLE B-VI

PREIRRADIATION MEASUREMENTS OF THE HAFNIUM SUPPRESSOR PLATES

<u>Tensile Tests (Room Temperature)[a]</u>		
Yield (0.2% offset)	24,800	psi
Ultimate	49,500	psi
Elongation	35	%
Reduction in Area	39	%
<u>Hardness (R_b)[a]</u>		87

<u>Width Measurements[b]</u>	
<u>Sample Number</u>	<u>Dimension (in.)</u>
1	0.2258
2	0.2271
3	0.2235
4	0.2216
5	0.2253
6	0.2286

[a] Average of four samples.

[b] Measurements made only on samples with ground edges. Since samples are not exactly parallel, the dimension was taken directly across stamped identification number. All measurements were taken after steam surface treatment.

HF-NO₃ etch

100X

Optical Micrograph from Same Material
as Used in Hafnium Suppressor Plates

54,000X

Transmission Electron Micrograph of
Hafnium Suppressor Plate Material

FIG. B-5 UNIRRADIATED OPTICAL AND TRANSMISSION ELECTRON MICROGRAPHS OF HAFNIUM SUPPRESSOR PLATE MATERIAL.

**APPENDIX C -- PREIRRADIATION
DATA AND MICROGRAPHS OF ALUMINUM**

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TABLE C-I

PREIRRADIATION DATA FOR 6061-T651 ALUMINUM SPECIMENS

<u>Specimen Number</u>	<u>Length (in.)</u>	<u>Diameter (in.)</u>	<u>Weight (g)</u>	<u>Density (g/cc)</u>
561	1.22972	0.40021	6.8439	2.7000
562	1.23031	0.40034	6.8466	2.6978
571	1.23012	0.40017	6.8408	2.6982
572	1.23007	0.40018	6.8428	2.6990
573	1.23014	0.40013	6.8389	2.6980
579	1.23017	0.40012	6.8409	2.6988
580	1.23028	0.40025	6.8479	2.6996
581	1.22956	0.40018	6.8400	2.6990
582	1.22990	0.40006	6.8362	2.6984
596	1.23050	0.40022	6.8451	2.6984
597	1.23035	0.40026	6.8465	2.6988
598	1.22979	0.39999	6.8386	2.7005
612	1.23067	0.39965	6.8201	2.6899
613	1.23036	0.40009	6.8356	2.6963
614	1.22938	0.40004	6.8246	2.6952
615	1.23060	0.39983	6.8306	2.6977
Hardness (R_b)				60
Compressive yield strength (0.2% offset) psi				43,900

Optical Micrograph
of 6061-T651 Aluminum

Keller's etch

100X

Optical Micrograph
of 6061-T651 Aluminum

Keller's etch

500X

Transmission Electron
Micrograph of
6061-T651 Aluminum

54,000X

FIG. C-1. OPTICAL AND TRANSMISSION ELECTRON MICROGRAPHS OF UNIRRADIATED 6061-T651 ALUMINUM USED IN ATR SURVEILLANCE SPECIMENS.

**APPENDIX D -- PREIRRADIATION DATA AND
MICROGRAPHS OF TYPES 304, 348, AND 17-4 PH STAINLESS STEELS**

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TABLE D-I

CHEMICAL ANALYSIS AND PHYSICAL PROPERTIES OF THE STAINLESS STEELS
AS REPORTED BY THE STEEL MANUFACTURER

- (1) Description: Type 304 stainless steel, 5/8 inch round per specification AMS 5639A, QQS 763 C Cond A; Mill Source -- Jones & Laughlin; Heat No. 51023.

(a) Chemical Analysis (%)

C	Mn	P	S	Ag	Cr	Ni	Mo	Cu	Co
0.06	1.61	0.027	0.025	0.55	18.68	9.15	0.27	0.19	0.11

(b) Physical Properties

Yield Strength (lb/in. ²)	56,500
Tensile Strength (lb/in. ²)	87,200
Reduction of Area (%)	77
Hardness (BHN)	170
Heat Treatment	Solution heat treat

- (2) Description: Type CG 17-4 PH solution treat stainless steel, 1/2 inch round per specification AMS 5643 H DMS 1764; Mill Source -- Republic; Heat No. 3341720.

(a) Chemical Analysis (%)

C	Mn	P	S	Si	Cr	Ni	Cu	Ta
0.047	0.40	0.022	0.002	0.49	15.82	4.25	3.95	0.25

(b) Physical Properties

Heat Treat[a]	Yield Strength (16/in. ²)	Tensile Strength (16/in. ²)	Elongation % in./in.	Reduction of Area%	Hardness (Brinell)
H-900	182,700	208,800	49.2	47.8	415
H-950	170,700	183,700	14	51.8	375

Hardness as shipped -- Brinell-341

- (3) Description: Type 348 stainless steel, 5/8 inch round per specification found in BNWL-CC-236, Appendix C, Heat No. 55700.

(a) Chemical Analysis (%)

C	Mn	P	S	Si	Cr	Ni	Mo	Cu
0.04	1.67	0.014	0.009	0.51	17.52	9.67	0.06	0.06
Cb	Ta	Co	Sn	N ₂				
0.58	0.03	0.018	0.009	0.037				

(b) Physical Properties

Yield Strength (lb/in. ²)	45,000
Tensile Strength (lb/in. ²)	90,500
Elongation (%)	50
Reduction in Area (%)	56
Hardness (BNH)	170

- [a] Specimens used in this program were heat-treated to condition H-1100 to meet ATR specification for 17-4 PH stainless steels.

TABLE D-II

PREIRRADIATION DATA OF TYPES 304, 348,
AND 17-4 PH STAINLESS STEEL SPECIMENS

<u>304 Stainless Steel</u>				
<u>Specimen Number</u>	<u>Length (in.)</u>	<u>Average Diameter (in.)</u>	<u>Weight (g)</u>	<u>Density (g/cc)</u>
556	1.22989	0.39999	19.9833	7.8906
557	1.22940	0.40025	19.9916	7.8888
566	1.23079	0.39990	19.9757	7.8854
567	1.22987	0.40011	20.0070	7.8954
576	1.22973	0.40030	20.0082	7.8893
577	1.22955	0.40029	19.9946	7.8854
578	1.22922	0.40025	19.9940	7.8889
586	1.23107	0.39935	19.9269	7.8860
587	1.23073	0.39986	19.9740	7.8867
591	1.22965	0.39987	19.9591	7.8873
592	1.23019	0.40029	20.0214	7.8919
617	1.22951	0.40027	20.0001	7.8887
619	1.22930	0.40015	19.9844	7.8885
620	1.23035	0.40020	20.0050	7.8880

Hardness (R_b)

91

Compressive yield strength (0.2% offset) psi

59,200

<u>348 Stainless Steel</u>				
<u>Specimen Number</u>	<u>Length (in.)</u>	<u>Average Diameter (in.)</u>	<u>Weight (g)</u>	<u>Density (g/cc)</u>
544	1.23105	0.40032	20.0551	7.8985
545	1.22995	0.40033	20.0650	7.9091
546	1.23080	0.40057	20.0343	7.8820
558	1.22931	0.40006	20.0354	7.9122
559	1.23066	0.40070	20.1157	7.9098
563	1.23024	0.40044	20.0850	7.9107
564	1.23077	0.39976	20.0339	7.9141
565	1.23026	0.40037	20.0680	7.9067
583	1.23081	0.40017	20.0731	7.9130

TABLE D-II (Contd.)

Specimen Number	Length (in.)	Average Diameter (in.)	Weight (g)	Density (g/cc)
584	1.23033	0.40000	20.0491	7.9134
585	1.22980	0.40043	20.0858	7.9143
588	1.23060	0.40046	20.0934	7.9109
589	1.23004	0.40018	20.0526	7.9095
603	1.23018	0.39977	20.0226	7.9130
604	1.22981	0.40037	20.0695	7.9101
616	1.22966	0.40001	20.0192	7.9055

Hardness (R_b)

88

Compressive yield strength (0.2% offset) psi

44,700

17-4PH Conditioned H-1100 Stainless Steel

Specimen Number	Length (in.)	Average Diameter (in.)	Weight (g)	Density (g/cc)
547	1.22796	0.39968	19.6497	7.7832
548	1.22863	0.39951	19.6431	7.7829
552	1.22846	0.39962	19.6508	7.7816
553	1.22678	0.39970	19.6290	7.7817
554	1.22834	0.39978	19.6608	7.7813
555	1.22864	0.39965	19.6502	7.7802
568	1.22816	0.39969	19.6511	7.7821
569	1.22817	0.39949	19.6316	7.7821
570	1.22824	0.39951	19.6411	7.7846
593	1.22900	0.39970	19.6619	7.7806
594	1.22888	0.39974	19.6736	7.7844
595	1.22823	0.39959	19.6500	7.7851
601	1.22766	0.39982	19.6653	7.7858
602	1.22700	0.39973	19.6448	7.7854
621	1.22891	0.39990	19.6747	7.7785
622	1.22738	0.39950	19.6256	7.7843

Hardness (R_c)

33

Compressive yield strength (0.2% offset) psi

141,600

Optical Micrograph
of Type 304 SS

Oxalic etch

100X

Optical Micrograph
of Type 304 SS

Oxalic etch

500X

Transmission Electron
Micrograph of Type
304 SS

54,000X

FIG. D-1 OPTICAL AND TRANSMISSION ELECTRON MICROGRAPHS OF UNIRRADIATED TYPE 304 STAINLESS STEEL USED IN ATR SURVEILLANCE SPECIMENS.

Optical Micrograph
of Type 348 SS

Oxalic etch 100X

Optical Micrograph
of Type 348 SS

Oxalic etch 500X

Transmission Electron
Micrograph of Type
348 SS

54,000X

FIG. D-2 OPTICAL AND TRANSMISSION ELECTRON MICROGRAPHS OF UNIRRADIATED TYPE 348 STAINLESS STEEL USED IN ATR SURVEILLANCE SPECIMENS.

Optical Micrograph
of 17-4PH, H-1100 SS

Oxalic etch

100X

Optical Micrograph
of 17-4PH, H-1100 SS

Oxalic etch

500X

Transmission Electron
Micrograph of 17-4PH,
H-1100 SS

54,000X

FIG. D-3 OPTICAL AND TRANSMISSION ELECTRON MICROGRAPHS OF UNIRRADIATED 17-4 PH, H-1100 STAINLESS STEEL USED IN ATR SURVEILLANCE SPECIMENS.

**APPENDIX E -- LOADING SCHEDULES OF ALL
ATR SURVEILLANCE SPECIMENS AND PROJECTED NEUTRON EXPOSURE**

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TABLE E-I

ATR SURVEILLANCE SPECIMENS

ATR[a] Location	Capsule Number	Specimen Number and Type Material[b]	ATR Removal Cycle
H-4-1	65	549 Single Crystal Be 545 348 ss 546 348 ss 547 17/4 ss 548 17/4 ss	12
H-4-2	28	420 Ex Be 419 Ex Be 312 Ex Be 310 Ex Be 308 Ex Be	4
H-4-3	45	K Wafers 527 HP Be (1.5% BeO) 526 HP Be (1.5% BeO) 525 HP Be (1.5% BeO) 524 HP Be (1.5% BeO)	4
H-4-4	56	K Wafers 148 HP Be (2811) 134 HP Be (2811) 105 HP Be (2811) 61 HP Be (2870)	4
H-7-1	17	177 HP Be (2811) 176 HP Be (2811) 175 HP Be (2811) 172 HP Be (2811) 169 HP Be (2811)	18
H-7-2	48	K Wafers 508 HP Be (1.5% BeO) 507 HP Be (1.5% BeO) 499 HP Be (1.5% BeO) 497 HP Be (1.5% BeO)	4
H-7-3	39	372 VC Be 368 VC Be 339 VC Be 334 VC Be 319 VC Be	4

[a] First two digits designate ATR hole number; third number designates the capsule sequence in train numbering from top to bottom.

[b] HP 2811 and HP 2870 are two different lots of ATR hot-pressed beryllium (2.0% BeO). VC is vacuum cast beryllium. Ex is extruded beryllium. K wafers are disks approximately 0.25 inch thick.

TABLE E-I (Contd.)

<u>ATR[a] Location</u>	<u>Capsule Number</u>	<u>Specimen Number and Type Material[b]</u>	<u>ATR Removal Cycle</u>
H-7-4	66	544 348 ss 552 17/4 ss 553 17/4 ss 554 17/4 ss 555 17/4 ss	4
H-8-1	70	556 304 ss 557 304 ss 558 348 ss 559 348 ss 560 Hf	90
H-8-2	67	561 Al 562 Al 563 348 ss 564 348 ss 565 348 ss	34
H-8-3	68	566 304 ss 567 304 ss 568 17/4 ss 569 17/4 ss 570 17/4 ss	34
H-8-4	69	571 Al 572 Al 573 Al 574 Hf 575 Hf	26
H-12-1	20	106 HP Be (2811) 104 HP Be (2811) 93 HP Be (2870) 86 HP Be (2870) 81 HP Be (2870)	114
H-12-2	32	249 Ex Be 248 Ex Be 247 Ex Be 242 Ex Be 240 Ex Be	114

[a] First two digits designate ATR hole number; third number designates the capsule sequence in train numbering from top to bottom.

[b] HP 2811 and HP 2870 are two different lots of ATR hot-pressed beryllium (2.0% BeO). VC is vacuum cast beryllium. Ex is extruded beryllium. K wafers are disks approximately 0.25 inch thick.

TABLE E-I (Contd.)

<u>ATR[a] Location</u>	<u>Capsule Number</u>	<u>Specimen Number and Type Material[b]</u>	<u>ATR Removal Cycle</u>
H-12-3	40	400 VC Be 387 VC Be 382 VC Be 367 VC Be 321 VC Be	114
H-12-4	71	576 304 ss 577 304 ss 578 304 ss 579 Al 580 Al	114
H-15-1	[c]	322 VC Be 83 HP Be (2870) 299 Ex Be 326 VC Be 109 HP Be (2811)	[c]
H-15-2~	[c]	424 Ex Be 341 VC Be 100 HP Be (2811) 422 Ex Be 355 VC Be	[c]
H-15-3	[c]	94 HP Be (2870) 418 Ex Be 358 VC Be 92 HP Be (2870) 313 Ex Be	[c]
H-16-1	72	581 Al 582 Al 583 348 ss 584 348 ss 585 348 ss	74

[a] First two digits designate ATR hole number; third number designates the capsule sequence in train numbering from top to bottom.

[b] HP 2811 and HP 2870 are two different lots of ATR hot-pressed beryllium (2.0% BeO). VC is vacuum cast beryllium. Ex is extruded beryllium. K wafers are disks approximately 0.25 inch thick.

[c] Corrosion samples will be in a single capsule open to the coolant water and will be removed every six cycles for examination and then reinserted.

TABLE E-I (Contd.)

<u>ATR[a] Location</u>	<u>Capsule Number</u>	<u>Specimen Number and Type Material[b]</u>	<u>ATR Removal Cycle</u>
H-16-2	75	586 304 ss 587 304 ss 588 348 ss 589 348 ss 590 Hf	50
H-16-3	73	591 304 ss 592 304 ss 593 17/4 ss 594 17/4 ss 595 17/4 ss	26
H-16-4	74	596 Al 597 Al 598 Al 599 Hf 600 Hf	12
A-1-1	7	31 HP Be (2870) 32 HP Be (2870) 33 HP Be (2870) 34 HP Be (2870) 35 HP Be (2870)	18
A-1-2	11	208 Ex Be 267 Ex Be 210 Ex Be 211 Ex Be 212 Ex Be	18
A-1-3	5	21 HP Be (2870) 22 HP Be (2870) 23 HP Be (2870) 24 HP Be (2870) 25 HP Be (2870)	18
A-2-1	24	76 HP Be (2870) 68 HP Be (2870) 62 HP Be (2870) 59 HP Be (2870) 54 HP Be (2870)	26

[a] First two digits designate ATR hole number; third number designates the capsule sequence in train numbering from top to bottom.

[b] HP 2811 and HP 2870 are two different lots of ATR hot-pressed beryllium (2.0% BeO). VC is vacuum cast beryllium. Ex is extruded beryllium. K wafers are disks approximately 0.25 inch thick.

TABLE E-I (Contd.)

<u>ATR[a] Location</u>	<u>Capsule Number</u>	<u>Specimen Number and Type Material[b]</u>	<u>ATR Removal Cycle</u>
A-2-2	29	309 Ex Be 304 Ex Be 300 Ex Be 291 Ex Be 288 Ex Be	26
A-2-3	60	354 VC Be 344 VC Be 332 VC Be 328 VC Be 323 VC Be	26
A-2-4	53	268 Ex Be 266 Ex Be 264 Ex Be 261 Ex Be 259 Ex Be	26
A-3-1	23	99 HP Be (2811) 91 HP Be (2870) 90 HP Be (2870) 84 HP Be (2870) 77 HP Be (2870)	34
A-3-2	34	480 Ex Be 471 Ex Be 468 Ex Be 467 Ex Be 463 Ex Be	34
A-3-3	58	379 VC Be 370 VC Be 364 VC Be 357 VC Be 356 VC Be	34
A-3-4	47	K Wafers 535 HP Be (1.5% BeO) 534 HP Be (1.5% BeO) 533 HP Be (1.5% BeO) 532 HP Be (1.5% BeO)	34

[a] First two digits designate ATR hole number; third number designates the capsule sequence in train numbering from top to bottom.

[b] HP 2811 and HP 2870 are two different lots of ATR hot-pressed beryllium (2.0% BeO). VC is vacuum cast beryllium. Ex is extruded beryllium. K wafers are disks approximately 0.25 inch thick.

TABLE E-I (Contd.)

<u>ATR[a] Location</u>	<u>Capsule Number</u>	<u>Specimen Number and Type Material[b]</u>	<u>ATR Removal Cycle</u>
A-4-1	19	120 HP Be (2811) 119 HP Be (2811) 118 HP Be (2811) 117 HP Be (2811) 115 HP Be (2811)	42
A-4-2	33	239 Ex Be 238 Ex Be 237 Ex Be 236 Ex Be 234 Ex Be	42
A-4-3	37	414 VC Be 409 VC Be 406 VC Be 405 VC Be 320 VC Be	42
A-4-4	27	297 Ex Be 296 Ex Be 290 Ex Be 289 Ex Be 284 Ex Be	42
A-5-1	57	K Wafers 161 HP Be (2811) 139 HP Be (2811) 103 HP Be (2811) 95 HP Be (2870)	50
A-5-2	31	263 Ex Be 260 Ex Be 251 Ex Be 250 Ex Be 246 Ex Be	50
A-5-3	46	K Wafers 531 HP Be (1.5% BeO) 530 HP Be (1.5% BeO) 529 HP Be (1.5% BeO) 528 HP Be (1.5% BeO)	50

[a] First two digits designate ATR hole number; third number designates the capsule sequence in train numbering from top to bottom.

[b] HP 2811 and HP 2870 are two different lots of ATR hot-pressed beryllium (2.0% BeO). VC is vacuum cast beryllium. Ex is extruded beryllium. K wafers are disks approximately 0.25 inch thick.

TABLE E-I (Contd.)

<u>ATR[a] Location</u>	<u>Capsule Number</u>	<u>Specimen Number and Type Material[b]</u>	<u>ATR Removal Cycle</u>
A-5-4	18	112 HP Be (2811)	50
		110 HP Be (2811)	
		102 HP Be (2811)	
		87 HP Be (2870)	
		79 HP Be (2870)	
A-6-1	25	137 HP Be (2811)	58
		98 HP Be (2811)	
		67 HP Be (2870)	
		64 HP Be (2870)	
		56 HP Be (2870)	
A-6-2	35	458 Ex Be	58
		451 Ex Be	
		447 Ex Be	
		444 Ex Be	
		442 Ex Be	
A-6-3	38	407 VC Be	58
		403 VC Be	
		401 VC Be	
		394 VC Be	
		360 VC Be	
A-6-4	30	287 Ex Be	58
		285 Ex Be	
		272 Ex Be	
		270 Ex Be	
		265 Ex Be	
A-7-1	6	26 HP Be (2870)	66
		27 HP Be (2870)	
		28 HP Be (2870)	
		29 HP Be (2870)	
		30 HP Be (2870)	
A-7-2	12	213 Ex Be	66
		214 Ex Be	
		215 Ex Be	
		216 Ex Be	
		273 Ex Be	

[a] First two digits designate ATR hole number; third number designates the capsule sequence in train numbering from top to bottom.

[b] HP 2811 and HP 2870 are two different lots of ATR hot-pressed beryllium (2.0% BeO). VC is vacuum cast beryllium. Ex is extruded beryllium. K wafers are disks approximately 0.25 inch thick.

TABLE E-I (Contd.)

<u>ATR[a] Location</u>	<u>Capsule Number</u>	<u>Specimen Number and Type Material[b]</u>	<u>ATR Removal Cycle</u>
A-7-3	42	351 VC Be 347 VC Be 340 VC Be 335 VC Be 329 VC Be	66
A-7-4	76	601 17/4 ss 602 17/4 ss 603 348 ss 604 348 ss 605 Hf	66
A-8-1	22	73 HP Be (2870) 72 HP Be (2870) 66 HP Be (2870) 55 HP Be (2870) 52 HP Be (2870)	74
A-8-2	55	257 Ex Be 256 Ex Be 255 Ex Be 253 Ex Be 252 Ex Be	74
A-8-3	41	385 VC Be 384 VC Be 371 VC Be 363 VC Be 337 VC Be	74
A-8-4	54	173 HP Be (2811) 158 HP Be (2811) 144 HP Be (2811) 133 HP Be (2811) 128 HP Be (2811)	74
A-9-1	4	16 HP Be (2870) 17 HP Be (2870) 18 HP Be (2870) 19 HP Be (2870) 20 HP Be (2870)	80

[a] First two digits designate ATR hole number; third number designates the capsule sequence in train numbering from top to bottom.

[b] HP 2811 and HP 2870 are two different lots of ATR hot-pressed beryllium (2.0% BeO). VC is vacuum cast beryllium. Ex is extruded beryllium. K wafers are disks approximately 0.25 inch thick.

TABLE E-I (Contd.)

<u>ATR[a] Location</u>	<u>Capsule Number</u>	<u>Specimen Number and Type Material[b]</u>	<u>ATR Removal Cycle</u>
A-9-2	10	203 Ex Be 204 Ex Be 205 Ex Be 206 Ex Be 207 Ex Be	80
A-9-3	2	6 HP Be (2870) 7 HP Be (2870) 8 HP Be (2870) 9 HP Be (2870) 10 HP Be (2870)	80
A-10-1	16	365 VC Be 369 VC Be 375 VC Be 377 VC Be 393 VC Be	90
A-10-2	14	223 Ex Be 224 Ex Be 225 Ex Be 226 Ex Be 227 Ex Be	90
A-10-3	77	608 Single Crystal Be 609 Single Crystal Be 610 Single Crystal Be 611 Single Crystal Be 612 Al 613 Al	90
A-10-4	79	614 Al 615 Al 616 348 ss 617 304 ss 618 Hf	4
A-11-1	3	11 HP Be (2870) 12 HP Be (2870) 13 HP Be (2870) 14 HP Be (2870) 15 HP Be (2870)	102

[a] First two digits designate ATR hole number; third number designates the capsule sequence in train numbering from top to bottom.

[b] HP 2811 and HP 2870 are two different lots of ATR hot-pressed beryllium (2.0% BeO). VC is vacuum cast beryllium. Ex is extruded beryllium. K wafers are disks approximately 0.25 inch thick.

TABLE E-I (Contd.)

<u>ATR[a] Location</u>	<u>Capsule Number</u>	<u>Specimen Number and Type Material[b]</u>	<u>ATR Removal Cycle</u>
A-11-2	13	218 Ex Be 219 Ex Be 220 Ex Be 221 Ex Be 222 Ex Be	102
A-11-3	59	383 VC Be 374 VC Be 362 VC Be 342 VC Be 331 VC Be	102
A-11-4	78	619 304 ss 620 304 ss 621 17/4 ss 622 17/4 ss 623 Hf	102

[a] First two digits designate ATR hole number; third number designates the capsule sequence in train numbering from top to bottom.

[b] HP 2811 and HP 2870 are two different lots of ATR hot-pressed beryllium (2.0% BeO). VC is vacuum cast beryllium. Ex is extruded beryllium. K wafers are disks approximately 0.25 inch thick.

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FIG. E-1 ATR CORE CROSS SECTION

TABLE E-II

ATR SURVEILLANCE SPECIMENS
(Listed by Type of Material)

<u>Type Material</u>	<u>Quantity of Specimens</u>	<u>ATR[a] Location</u>	<u>ATR Removal Cycle</u>
Be HP (2811)	3	H-4-4	4
	5	H-7-1	18
	1	A-3-1	34
	5	A-4-1	42
	3	A-5-1	50
	3	A-5-4	50
	2	A-6-1	58
	5	A-8-4	74
	2	H-12-1	114
	2	H-15-1	[b]
Be HP (2870)	1	H-4-4	4
	5	A-1-1	18
	5	A-1-3	18
	5	A-2-1	26
	4	A-3-1	34
	1	A-5-1	50
	2	A-5-4	50
	3	A-6-1	58
	5	A-7-1	66
	5	A-8-1	74
	5	A-9-1	80
	5	A-9-3	80
	5	A-11-1	102
	3	A-12-1	114
	3	A-15-1	[b]
Be HP (1.5% BeO)	4	H-4-3	4
	4	A-3-4	34
	4	A-5-3	50
Be Ex	5	H-4-2	4
	5	H-7-2	4
	5	A-1-2	18
	5	A-2-2	26
	5	A-2-4	26
	5	A-3-2	34
	5	A-4-2	42
	5	A-4-4	42

[a] First two symbols designate ATR capsule hole; last number designates sequence of capsule in train from top to bottom.

[b] Corrosion samples -- to be removed about every six cycles for inspection and reinserted.

TABLE E-II (Contd.)

Type Material	Quantity of Specimens	ATR[a] Location	ATR Removal Cycle
	5	A-5-2	50
	5	A-6-2	58
	5	A-6-4	58
	5	A-7-2	66
	5	A-8-2	74
	5	A-9-2	80
	5	A-10-2	90
	5	A-11-2	102
	5	H-12-2	114
	5	H-15-2	[b]
Be VC	5	H-7-3	4
	5	A-2-3	26
	5	A-3-3	34
	5	A-4-3	42
	5	A-6-3	58
	5	A-7-3	66
	5	A-8-3	74
	5	A-10-1	90
	5	A-11-3	102
	5	H-12-3	114
	5	H-15-3	[b]
Be Single Crystals	1	H-4-1	12
	4	A-10-3	90
Al 6061-T651	2	A-10-4	4
	3	H-16-4	12
	3	H-8-4	26
	2	H-8-2	34
	2	H-16-1	74
	2	A-10-3	90
	2	H-12-4	114
304 ss	1	A-10-4	4
	2	H-16-3	26
	2	H-8-3	34
	2	H-16-2	50
	2	H-8-1	90
	2	A-11-4	102
	3	H-12-4	114
348 ss	1	A-10-4	4
	1	H-7-4	4

[a] First two symbols designate ATR capsule hole; last number designates sequence of capsule in train from top to bottom.

[b] Corrosion samples -- to be removed about every six cycles for inspection and reinserted.

TABLE E-II (Contd.)

Type Material	Quantity of Specimens	ATR[a] Location	ATR Removal Cycle
	2	H-4-1	12
	3	H-8-2	34
	2	H-16-2	50
	2	A-7-4	66
	3	H-16-1	74
	2	H-8-1	90
17/4 PH ss	4	H-7-4	4
	2	H-4-1	12
	3	H-16-3	26
	3	H-8-3	34
	2	A-7-4	66
	2	A-11-4	102
Hf	1	A-10-4	4
	2	H-16-4	12
	2	H-8-4	26
	1	H-16-2	50
	1	A-7-4	66
	1	H-8-1	90
	1	A-11-4	102
K.wafers	-	H-4-4	4
	-	H-4-3	4
	-	A-3-4	34
	-	A-5-1	50
	-	A-5-3	50

[a] First two symbols designate ATR capsule hole; last number designates sequence of capsule in train from top to bottom.

TABLE E-III

LOADING OF THE H- AND A-HOLES OF THE ATR AT CYCLE 1

Reactor Location	Loading or Capsule Number
H-1	Hafnium shim
-2	Flux monitor
-3	Nitrogen ¹⁶ detector
-4	Capsules 56, 28, 45, 65
-5	Hafnium shim
-6	Flux monitor
-7	Capsules 17, 48, 39, 66
-8	Capsules 70, 67, 68, 69
-9	Hafnium shim
-10	Flux monitor
-11	Nitrogen ¹⁶ detector
-12	Capsules 20, 32, 40, 71
-13	Hafnium shim
-14	Flux monitor
-15	Corrosion specimens in open capsule
-16	Capsules 72, 75, 73, 74
A-1	Capsules 7, 11, 5
-2	Capsules 24, 29, 60, 53
-3	Capsules 23, 34, 58, 47
-4	Capsules 19, 33, 37, 27
-5	Capsules 57, 31, 46, 18
-6	Capsules 25, 35, 38, 30
-7	Capsules 6, 12, 42, 76
-8	Capsules 22, 55, 41, 54
-9	Capsules 4, 10, 2
-10	Capsules 16, 14, 77, 79
-11	Capsules 3, 13, 59, 78
-12	Flux monitor

TABLE E-IV

SCHEDULE FOR CHANGING BOTTOM SPACERS WHEN A
PARTIAL CAPSULE TRAIN IS REMOVED

ATR Hole Number	Cycle of Change	Capsules After Change	New Bottom Spacer (Item No.[a])
H-4	4	65	23
-7	4	17	23
-8	26	70, 67, 68	21
-8	34	70	23
-16	12	72, 75, 73	21
-16	26	72, 75	22
-16	50	72	23
A-10	4	16, 14, 77	15

[a] INC DWG 533-0670-40-400-035766.

TABLE E-V

PROJECTED FAST NEUTRON ($E > 1$ MeV) EXPOSURE OF CAPSULES
IN THE ATR A- AND H-HOLES^[a]

Capsule Position	Flux (n/cm ² sec) x 10 ⁻¹⁴	Fluence per Cycle (n/cm ²) x 10 ⁻²⁰	Fluence per Year (n/cm ²) x 10 ⁻²¹
Outboard A-Holes			
Core Midplane	3.7	5.4	6.5
Top of Capsule Train	2.2	3.2	3.9
Inboard A- and H-Holes			
Core Midplane	2.8	4.1	4.9
Top of Capsule Train	1.7	2.5	3.0

[a] Based on 17 day fuel cycle and one cycle per month.