Report No. ACNP-63006

PATHFINDER ATOMIC POWER PLANT

BURN UP LIMITS FOR PATHFINDER TWO WEIGHT PER CENT NATURAL BORON STAINLESS STEEL CONTROL RODS

Submitted to

U. S. ATOMIC ENERGY COMMISSION
NORTHERN STATES POWER COMPANY
and
CENTRAL UTILITIES ATOMIC POWER ASSOCIATES

by

ALLIS-CHALMERS MANUFACTURING COMPANY
ATOMIC ENERGY DIVISION
Milwaukee 1, Wisconsin

Ref: AEC Contract No. AT(11-1)-589

DISCLAIMER

LEGAL NOTICE

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By: D. A. Patterson and D. A. Nehrig

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ALLIS-CHALMERS MANUFACTURING COMPANY

Under
Agreement dated 2nd Day of May 1957, as Amended
between
Allis-Chalmers Mfg. Co. & Northern States Power Co.
under
AEC Contract No. AT(11-1)-589

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ACNP 63006

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FOREWORD

One of a series of reports on research and development in connection with the design of the Pathfinder Atomic Power Plant, this particular report deals with the burnup limits for two weight per cent natural boron stainless steel control rods.

The Pathfinder plant will be located at a site near Sioux Falls, South Dakota, and is scheduled for operation in 1964. Owners and operators of the plant will be the Northern States Power Company of Minneapolis, Minnesota. Allis-Chalmers is performing the research, development, and design as well as being responsible for plant construction.

The U. S. Atomic Energy Commission, through Contract No. AT(11-1)-589 with Northern States Power Company, and Central Utilities Atomic Power Associates (CUAPA) are sponsors of the research and development program. The plant's reactor will be of the Controlled Recirculation Boiling Reactor type with Nuclear Superheater.

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1.0 INTRODUCTION

The purpose of this report is to review and evaluate the effects of neutron irradiation on 2 w/o boron stainless steel under Pathfinder reactor conditions and determine the maximum Boron-10 depletion while still insuring the integrity of the control rods.

The Pathfinder Atomic Power Plant is a 66 MWe (gross) controlled recirculation boiling water reactor with an integral central superheater. The boiler core operates at 600 psig and 489 F and the superheater core will produce exit steam at 825 F (725 F initially) and 540 psig. The boiler core contains sixteen cruciform-shaped rods which are individually driven in channels provided between the boiler elements. There are forty-eight superheater control rods which are gang driven in four groups of twelve rods each. These rods run inside removable channel tubes within the superheater core. The boiler rods may be scrammed to shut down the reactor during an emergency shutdown, but the superheater rods are "run in" under power by the superheater control rod drives. Locations of the control rods in the core are shown in Figure 1.

2.0 SUMMARY AND CONCLUSIONS

A survey of the literature on irradiation experience with boron stainless steel was conducted to determine the effect of neutron irradiation and boron-10 burnup on the two weight per cent natural boron stainless steel control rods being used in the Pathfinder reactor. The literature reviewed included irradiation test samples and full-size control rods

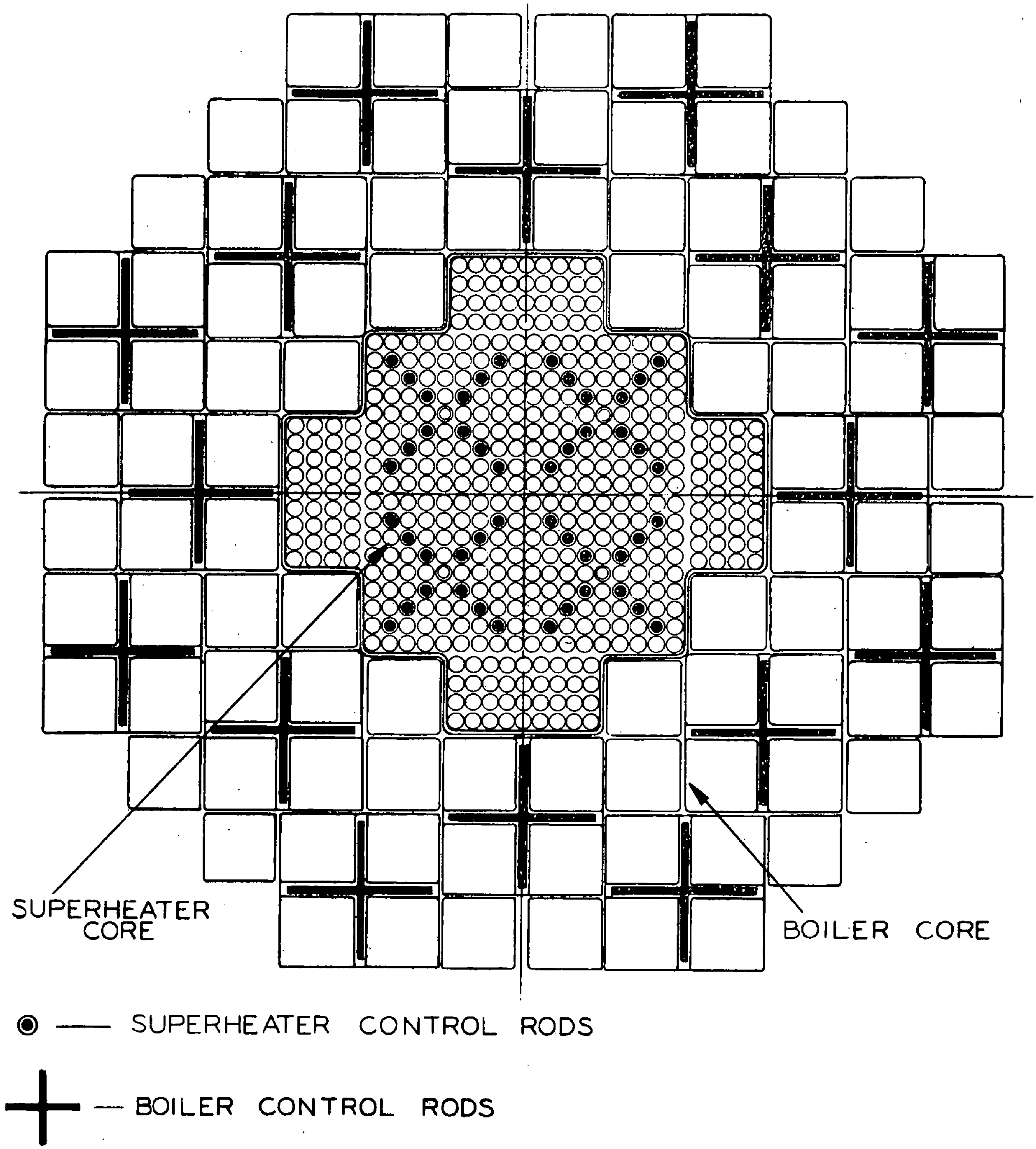

Figure I ... Control Rod Core Locations (43-025-406) in operating reactors. From the analysis of the survey, it was concluded that the Pathfinder control rods will operate satisfactorily and retain their integrity within the burnup limits prescribed.

The effects of irradiation and B-10 burnup on boron stainless were divided into three categories as follows:

1) mechanical properties,
2) cracks,
3) swelling and gas release.

These categories were examined in detail with the data available and correlated with the Pathfinder rods and operating conditions. The allowable local burnup of the boiler rods is limited to one core a/o (50% B-10 depletion) and the superheater rods are limited to one-half core a/o (25% B-10 depletion).

3.0 BACKGROUND

3.1 Control Rod Descriptions

The sixteen boiler control rods are cruciform in shape. The neutron poison section is 72 inches long and is two weight per cent natural boron stainless steel. The blades are 1/4 inch thick and have an overall width of 10-7/16 inches. At the top of the poison section is a 3 inch wide cruciform extension of 304L stainless steel and at the bottom is a 1/2 inch long 304L nose. The entire rod assembly is 178-23/32 inches long. A schematic drawing of the boiler cruciform is shown in Figure 2. The control rods are entirely of welded construction. The poison section

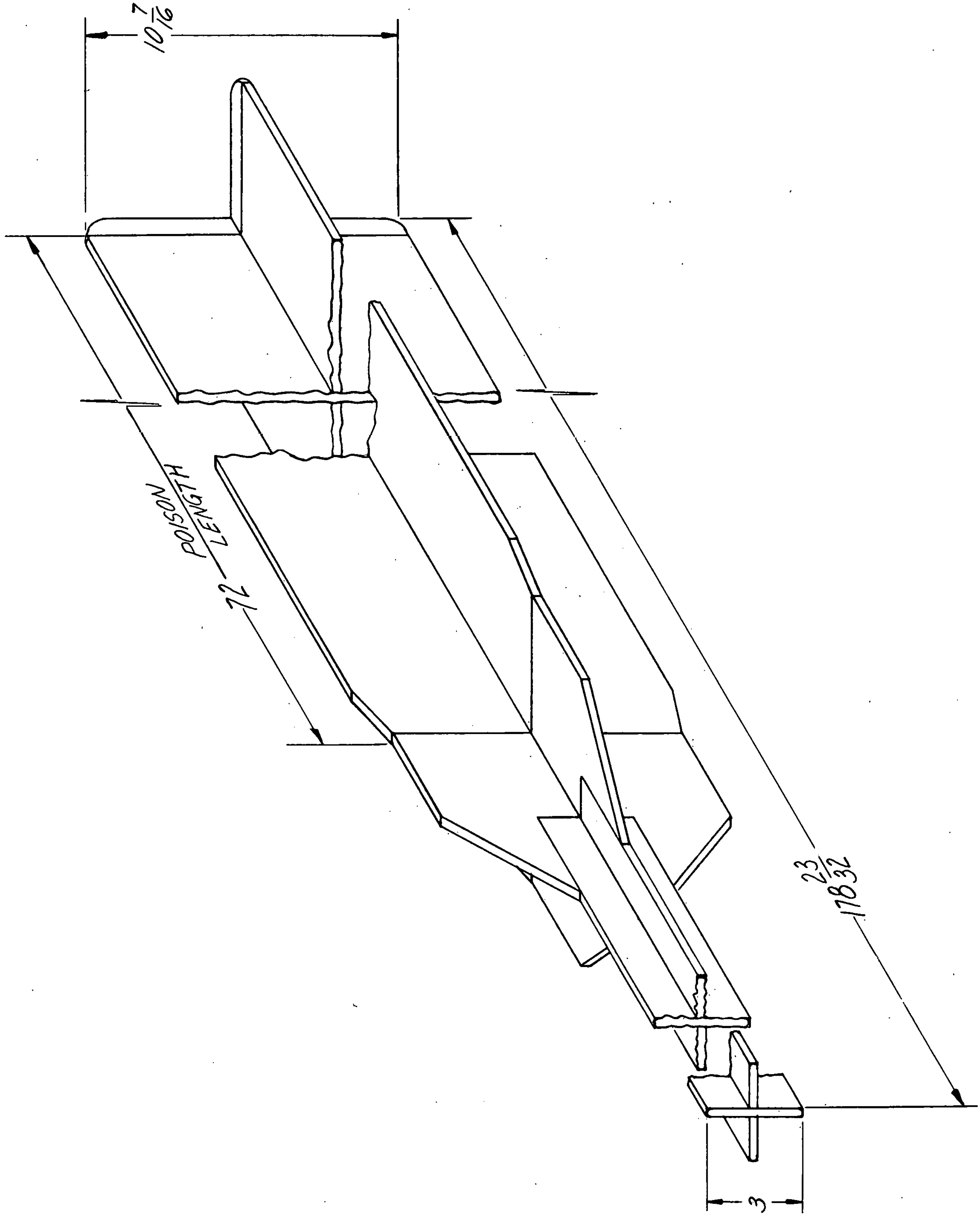

Figure 2 ... Boiler Cruciform Control Rod (43-025-345)

is formed by butting two narrow plates to a wide plate and joining with a staggered 1/8 inch fillet weld. All the longitudinal welds are made in a special welding fixture to minimize twist and warp. This is to enable the entire cruciform to fit within a 0.312 inch envelope. After welding, the cruciforms are high-temperature stress relieved to relieve residual stresses formed during fabrication.

The forty-eight superheater control rods are ganged into four groups of twelve rods each and connected to four drive units. Each control rod consists of a 3/4 inch diameter poison section with a tubular extension of 304L stainless steel. The poison material is two weight per cent natural boron stainless steel. The 3/4 inch diameter poison rod is clad with a 0.020 inch wall 304L stainless tube which is mechanically bonded by sinking the clad down onto the rod. The cladding tube is welded to the 0.060 inch wall extension tube on the upper end and a 304L tapered nose on the lower end. The sealed extension tube provides a large gas space for collecting helium that may be released from the boron stainless steel. A schematic drawing of the superheater control rod is shown in Figure 3.

3.2 Operating Conditions

The cruciform control rods in the boiler core are used to control and shut down the reactor. All sixteen rods will be used during startup and shutdown operations, while only the outer eight rods will normally be used during reactor operation at full power. The rods will function in a steam and water atmosphere at a maximum metal temperature of 586 F.

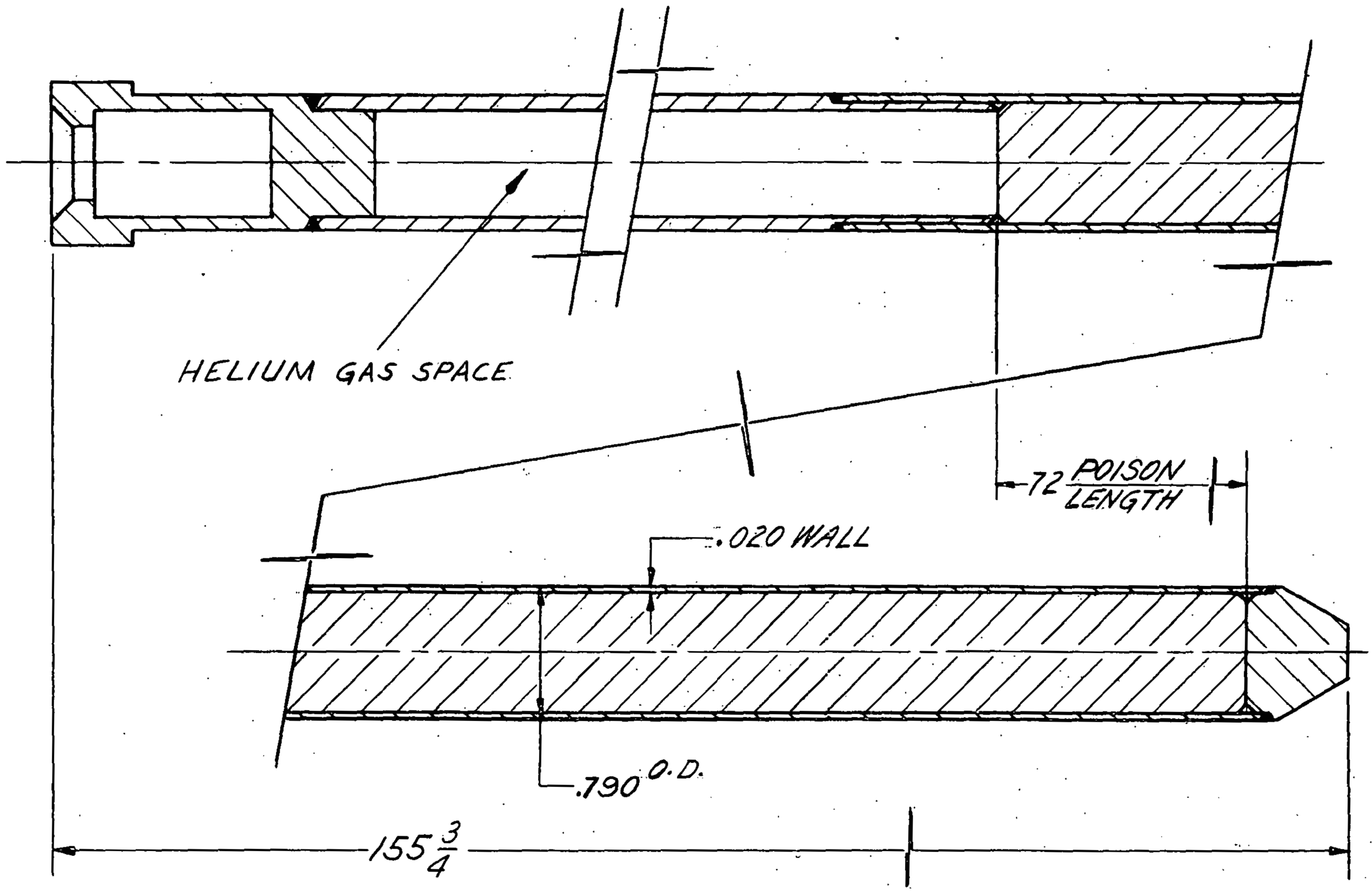

Figure 3 ... Superheater Control Rod (43-025-342)

The control rods in the superheater core are used to adjust steam temperature and shut down the reactor. During normal reactor operations, the superheater control rods will be fully withdrawn. If necessary, one or more groups of control rods will be partially inserted into the core to adjust the exit steam temperature. The rods function in a steam atmosphere at a maximum possible temperature of 990 F during operation and 1230 F (for less than 2 minutes) during shutdown.

3.3 Poison Material Description

3.3.1 Mechanical and Metallurgical Properties

Boron stainless steel is similar to normal 304 stainless steel with the addition of boron to give it a high thermal neutron absorption cross section. As the boron content increases, the tensile and yield strength increase but the ductility and impact strength decrease. Typical mechanical properties of two weight per cent boron stainless are as follows: Tensile Strength - 80,000 psi... Yield Strength - 40,000 psi...Per Cent Elongation - 8%...and Rockwell B Hardness - 97. The impact strength of unnotched samples (0.197" x 0.197" x 2.165") was 6.5 ft-lb. Samples of 304 stainless steel of the same size had an impact strength of 28 ft-lb.

The solubility of boron in stainless steel is less than 0.1 w/o and any excess boron is present as a brittle complex boride phase dispersed throughout the steel matrix. The phase has been identified as a transitional metal boride of the probable form $(Fe, Cr)_2B$.

Some nickel is also found within this phase. This indicates that the addition of boron primarily withdraws iron and chromium from the stainless matrix, leaving it enriched in nickel. The size of the boride particles range generally between 2 and 4 μ.[1]

The concentration of boron in stainless steel is normally specified in units of weight per cent, but due to its low atomic weight the atom concentration is about five times greater than its weight concentration. Thus 2 w/o boron is equal to 9.5 a/o (atom per cent) boron in the stainless steel.

At this time it is convenient to introduce a new term, core atom per cent, and its definition. Core atoms are all the atoms in the boron stainless steel alloy. The concentration of one particular element or isotope (such as B or B-10) can now be stated in terms of per cent of the total atoms. By using units of core atom per cent, irradiation data from different sources and materials having varying B-10 content and burnups may be compared and evaluated on a common basis. Figure 4 shows the relationship between atom per cent and weight per cent for boron stainless steel.

3.3.2 Nuclear Properties

The element boron consists of two isotopes, B-10 and B-11, with isotopic concentrations of 19.8 a/o and 80.2 a/o respectively. The thermal neutron absorption cross section of B-10 is 3840 ± 10 barns and B-11 is less than 0.05 barns giving an average cross section of

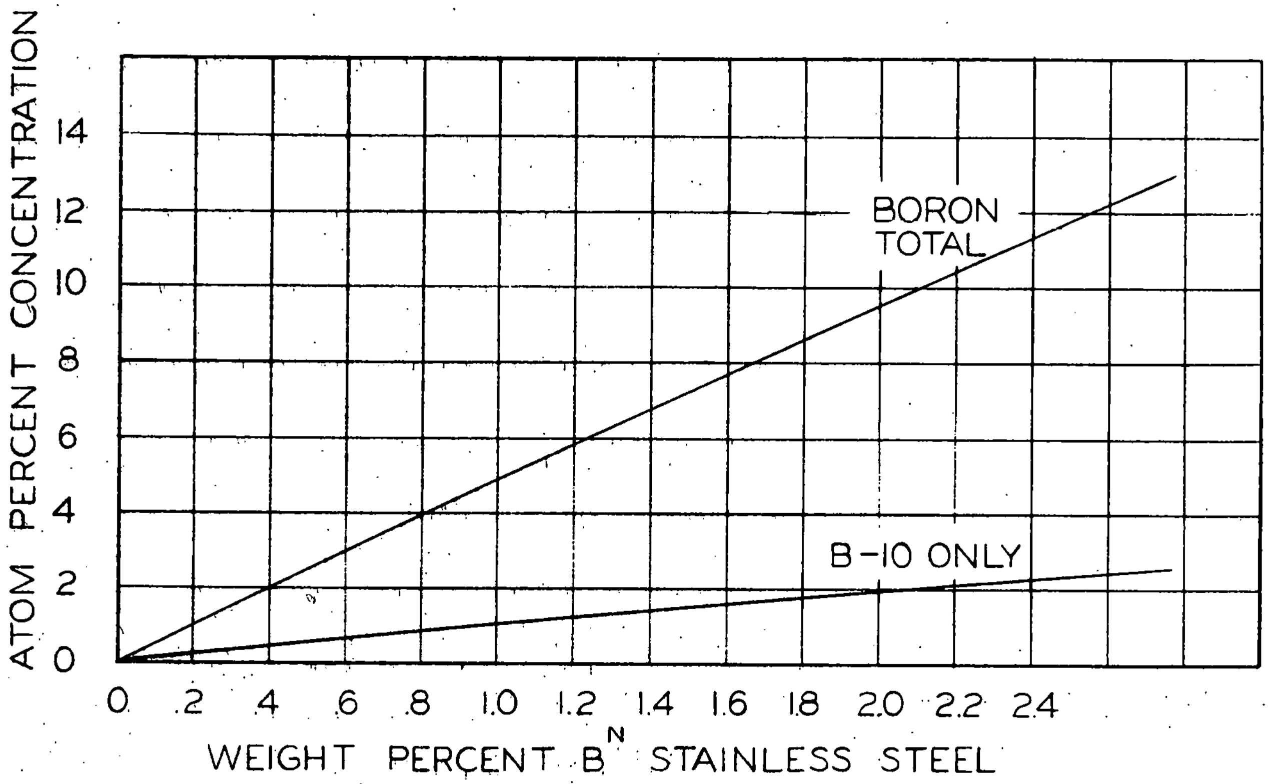

Figure 4 ... Atom Percent Vs Weight Percent for Boron (Natural) Stainless Steel (43-025-298)

762 ± 3 barns for elemental (natural) boron.[2] The neutron absorption cross section decreases with increasing neutron energy according to the 1/v law. Boron may be enriched in the B-10 isotope to provide a higher thermal neutron capturing efficiency and a larger B-10 atom concentration per unit volume.

The neutron B-10 reaction is as follows: B-10 (n, α) Li-7. When the B-10 absorbs a thermal neutron, the unstable boron atom immediately emits an alpha particle (helium nucleus) and transmutes to a Li-7 atom. The alpha particle picks up free electrons and becomes a stable helium atom. The immediate area previously occupied by the boron atom is now occupied by a helium and lithium atom. The helium atom is gaseous and the lithium atom is molten since it melts at 367 F.

4.0 IRRADIATION EFFECTS ON BORON STAINLESS STEEL

The neutron absorption reaction between a thermal neutron and a B-10 atom destroys the boron and produces a helium atom and a lithium atom. The introduction of a sufficient quantity of these foreign atoms into the original boron stainless steel alloy can have an adverse effect on the properties of the material. The onset and extent of damage to the boron stainless is dependent on the core atom per cent burnup of the B-10 atoms in the material and its operating temperature. A discussion of the information obtained from a literature survey on the effects of neutron irradiation and burnup limits of 2 w/o natural boron stainless steel are related in the following subsections.

4.1 Mechanical Properties

Experimental data on the changes of mechanical properties of boron stainless due to neutron irradiation and B-10 burnup are very limited. The available experimental data show that the tensile and yield strength will increase, with the yield strength approaching the tensile strength, and that the elongation and reduction of area will decrease. Table I shows the experimental data on the changes in mechanical properties vs. core a/o burnup of B-10 for various test samples.

Boron stainless has a low impact strength and is notch sensitive. Neutron irradiation reduces the impact strength of the material around 50 percent of its initial low value. Table 2 contains the results of impact tests of unirradiated and irradiated test samples. The material is sufficiently notch sensitive so that irradiated tensile specimens, which have the gage length indicated by punch marks, have broken at the punch marks during tensile tests. It is necessary for all boron stainless material to have a very smooth surface, to minimize the notch sensitivity of the material.

When thermal neutrons are abosrbed by the B-10 in a nuclear black control rod, the absorptions do not occur uniformly across the rod thickness but rather at a decreasing rate from the surface to center of the material. Thus, the core a/o burnup of B-10 on the surface is always higher than the average burnup and centerline burnup. As an example, two w/o natural boron stainless 1/4 inch thick, with an average burnup of 1.0 core a/o, will have a surface burnup of 1.3 core a/o and a center burnup of 0.6 core a/o. Therefore, even with a high average burnup, the centerline burnup will be relatively low and the material in this area will have retained most of its initial mechanical properties.

TABLE I

MECHANICAL PROPERTIES OF UNIRRADIATED AND IRRADIATED BORON STAINLESS STEEL

w/o Boron	Test Temp. °C	Core a/o Burnup	Yield Strength PSI	Tensile Strength PSI	Per Cent Elong.	Ref.
0	23	0	37,500	90,000	50	7
0	23	$2.7\cdot10^{20}$ nvt	82,000	104,000	40	7
1.0^{10}	23	0	93,400	121,900	15.6	6
1.0^{10}	23	0.7	149,500	153,500	3.4	6
1.0^{10}	23	1.1	------	137,100	1.6	6
1.8^{N}	23	0	41,300	84,200	8	7
1.8^{N}	23	0.5	136,000	151,000	0.5	7
1.8^{N}	315	0.5	85,500	119,000	----	7
2.0^{10}	23	0	------	88,400	8.1	5
2.0^{10}	23	0.3	------	93,300	0.5	5
2.0^{10}	23	0.8	------	78,800	0.4	5
2.04^{N}	23	0	47,000	89,000	5.4	7
2.04^{N}	23	0.6	97,800	120,000	----	7
2.04^{N}	315	0.6	71,300	106,000	----	7

TABLE 2

IMPACT STRENGTH OF UNIRADDIATED AND IRRADIATED SPECIMENS OF BORON STAINLESS STEEL

w/o Boron	Test Temp. °C	Core a/o Burnup or nvt Dose	Unirradiated ft-lb	Irradiated ft-lb	Ref.
0	23	$3.0\cdot10^{20}$	15.9	15.7	7
1.8^{N}	23	0.3	1.0	.44	7
1.8^{N}	315	0.3	1.0	.35	7
2.0^{10}	23	0.8	4.4	.16	5
2.0^{10}	315	0.8	2.3	.24	5
2.04^{N}	23	0.6	.64	.22	7
2.04^{N}	315	0.6	.64	.05	7

The hardness of the stainless matrix increases significantly during irradiation. The increase is greater than the hardening effect due to fast neutron flux bombardment and must be tied in with the burnup of the B-10 atoms. One set of irradiated samples increased from a hardness of 225 to 400 DPH.[5] Similar samples of plain stainless steel increased by only 50 DPH. Also, the hardening appears to take place very rapidly since samples having a neutron dose ranging from 8×10^{19} to 1×10^{21} nvt all had approximately the same final hardness. Another source [6] reports an increase in hardness from 28 to 50 Rockwell C after a neutron dose of 8×10^{20} nvt. Since the B-10 burns up in layers from surface to center of the material, a high hardness on the surface does not indicate a high hardness at the center. There is no experimental information available to provide a correlation between the change in surface hardness and changes in mechanical properties due to irradiation.

4.2 Cracks

Irradiation data on test samples and full-sized control rods have shown that after sufficient burnup, the matrix will develop micro and macro cracks.

Results of an irradiation study of 2 w/o B-10 austenitic stainless steel samples at WAPD[8] indicate three consecutive stages in the irradiation damage of these samples. A) In the first stage, the alloy exhibits negligible volume swelling and an increase in hardness and tensile strength with burnup; B) The second stage is noted by an increased volume swelling rate of the alloy with burnup, a decrease in tensile strength, a saturation of hardness and the initiation of submicrocrack formation; C) The third stage is characterized by the formation of microcracks in the alloy, gross swelling, and a complete loss of mechanical strength. The initiation of the second stage and the submicrocracks in austenitic stainless steel started at approximately 1.5 core a/o burnup.

Twelve tensile specimens of 18-8 stainless steel containing 1 w/o boron, enriched to 93 per cent in B-10, were irradiated to 0.7, 1.1, 1.8, and 4.0 core a/o burnup.[6] Post irradiation examination of the specimens prior to tensile testing showed a crack present in one of the specimens irradiated to 1.8 core a/o burnup. No cracks were observed in the remaining eleven samples, including the one irradiated to 4.0 core a/o burnup. No explanation was available for the cause of the crack.

Examination of the 2 w/o boron (natural) stainless steel control rods removed from EBWR has shown that cracking occurred at a large number (estimated at 60 per cent) of the spot welds.[11] The cracks are semi-circular, averaging about 1/4 inch in length. Some of the cracks from the outer-most row of welds extend to the edge of the blades. The rods have experienced approximately 8,000 TMWD of irradiation in the EBWR reactor which is equal to about 0.4 maximum core a/o burnup. The technique of spot welding inherently produces high residual mechanical stresses in the immediate vicinity of the weld which is exactly where all of the cracks occurred. The unstressed material showed no signs of crack formation.

Cracks were observed in the Dresden 2 w/o natural boron stainless control rods when they were removed from the reactor to check the guide rollers.[11] The cracks were adjacent to the boron stainless welds joining the blades of the cruciform and on the blades themselves. The cracks were not observed prior to irradiation, but appeared after a short irradiation time. The high residual stresses in the weld area (if not relieved by a thermal treatment), combined with the mechanical and thermal stresses present during reactor operation, would probably be sufficient to cause the observed cracks. Cold rolled plate was used in these rods which would be more likely to crack than annealed plate.

4.3 Swelling and Helium Gas Release

The quantity of helium generated in an irradiated boron stainless alloy is equal to the core atom per cent burnup or B-10 atoms that have been destroyed. The helium is generated principally in the complex boride phase which is dispersed throughout the stainless steel matrix. The gas collects in small pockets and voids produced by the destruction of the B-10, and exerts an internal pressure on the matrix. The magnitude of gas pressure is dependent upon the temperature and the quantity of gas atoms present. When the strength of the matrix is exceeded, swelling of the material occurs.

Low Temperature

Sufficient irradiation data has been collected to show a definite correlation between B-10 burnup and swelling of the metal. As shown by Figure 5, the data can be correlated by plotting per cent volume increase of the metal versus core atom per cent burnup. Due to the spread in the data caused by unlike samples, a distinct curve cannot be plotted but rather a band. The figure shows that 1 core a/o burnup can cause from 1 to 4 volume per cent increase (swelling) in boron stainless. This is for data irradiated at ≤600 F.

The following general observations have been made on swelling of boron stainless irradiated at ≤ 600 F. Yeniscovich, et al, estimate the rate of volume increase for austenitic boron stainless is 2-4 per cent per core a/o burnup for burnups greater than 1.5 core a/o.[8] W. E. Ray estimates that swelling and associated cracking becomes detrimental to

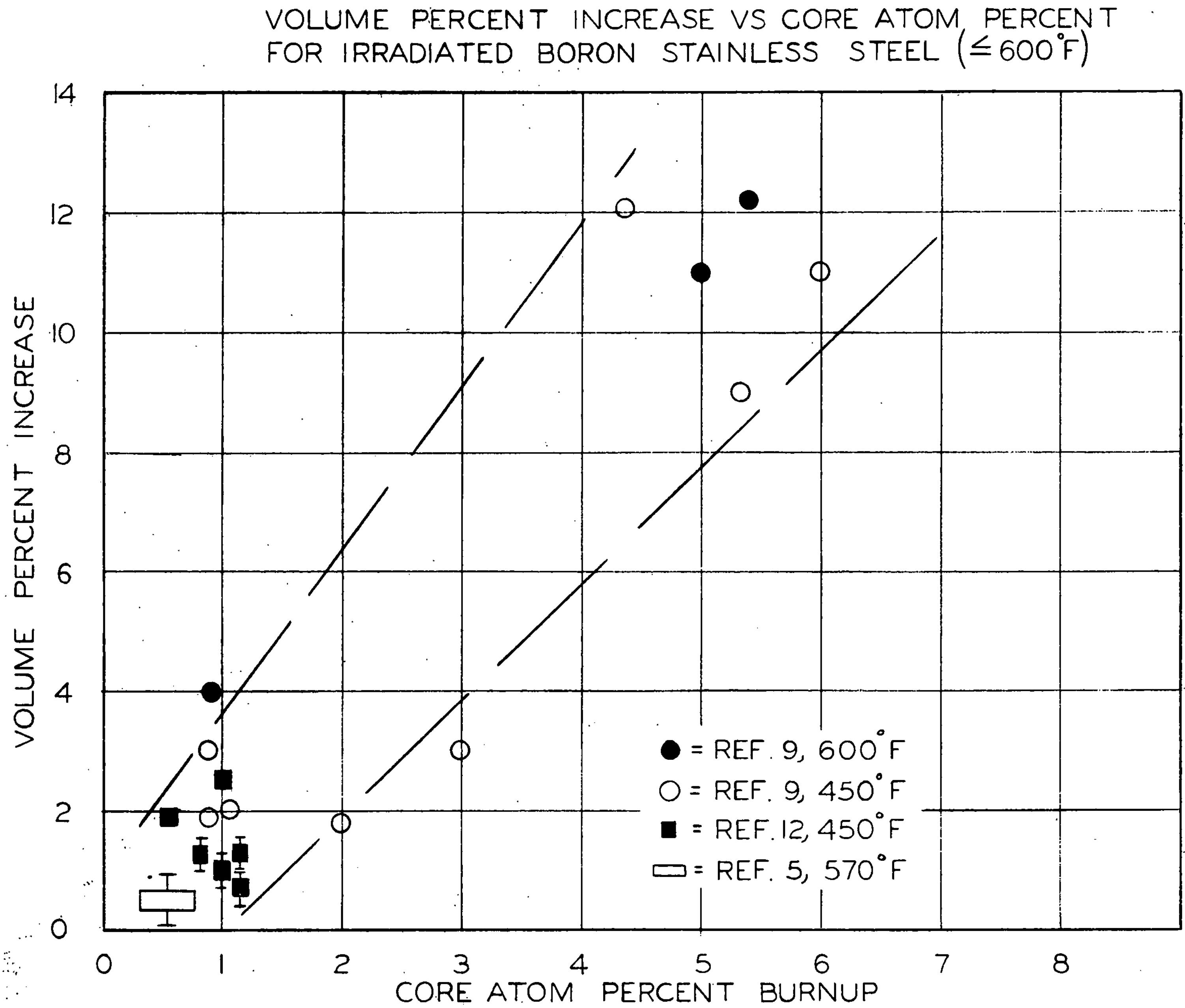

Figure 5 ... Volume Percent Increase Vs Core Atom Percent for Irradiated Boron Stainless Steel (≤ 600 F)

the integrity of the matrix above 1.5 core a/o burnup.[9] Reference 7 states that no growth appears to occur until 0.7 core a/o burnup. Beyond this point, growth is rapid and proceeds at an increasing rate. Reference 2 states a swelling rate of 2.6 volume per cent per core a/o burnup for a burnup range of 1.7 core a/o. It appears that a burnup beyond 1.0 core a/o would be detrimental.

High Temperature

The amount of material swelling is also a function of the irradiation temperature for a given burnup above 800 F. Some post-irradiation anneals have been performed on irradiated specimens. These data are plotted on Figure 6.[10] These anneals were from one to twenty-four hours at the selected temperatures. It is seen that above 1100 F the rate of swelling for 1 core a/o burnup shows a sharp increase and the 2 core a/o swelling becomes significant above 850 F. The swelling which occurred during the anneals was in addition to the swelling which took place during irradiation. If the samples had been irradiated at the annealing temperatures, the swelling most certainly would have been greater, and by as much as a factor of two. Thus, the presence of swelling at high temperatures poses a definite limitation on the allowable core a/o burnup for such applications.

Yeniscavich,[8] et al, while performing post-irradiation anneals on some of the boron stainless samples measured the amount of He gas released. Two austenitic samples having 3.7 a/o burnup annealed at 750 F for one hour had 41-43 per cent of the generated He released. Two similar samples

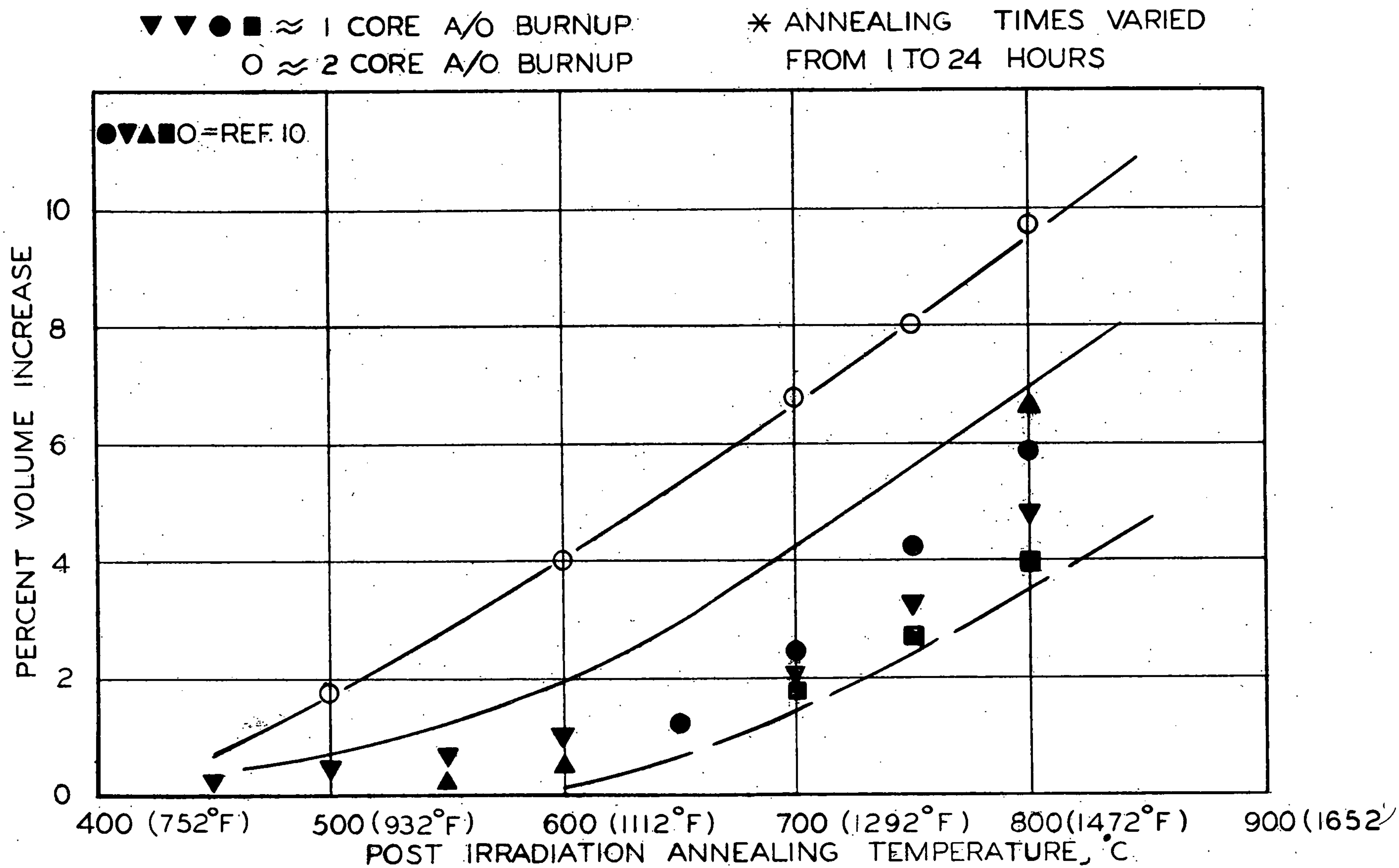

Figure 6 ... Percent Volume Increase Vs Post Irradiation Annealing Temperature for 1 and 2 Core A/O Burnup. (43-025-300)

annealed at 750 F for one hour and at 930 F for an additional hour had 44-46 per cent of the He released. This was the only reference found which gave specific amounts of gas release. However, all references which performed post-irradiation anneals to determine swelling also reported a gas release, but the quantity was not determined.

5.0 ALLOWABLE BURNUP LIMITS ON PATHFINDER CONTROL RODS

5.1 Boiler Control Rods

The available irradiation data on boron stainless alloys has established definite trends for the change of the material properties with B-10 burnup. Very little 2 w/o natural boron stainless has been irradiated and it is necessary to interpret data on other boron alloys, containing different boron concentrations and B-10 enrichments, to fill out the overall picture. The data indicate one core a/o burnup is the threshold for observable deleterious effects for 2 w/o natural boron stainless performing in Pathfinder boiler core conditions. Therefore, a one core a/o was set as the maximum point burnup limit for the Pathfinder boiler control rods.

Examination of test samples from two separate irradiation programs show that cracking of boron stainless will not occur before 1.5 core a/o burnup. Irradiated full size control rods from EBWR and Dresden have displayed cracks after moderate and short burnup, respectively. It is felt that the fabrication process used to make these control rods left high residual stresses in the material and that these stresses, plus the operating mechanical and thermal stresses, were sufficient to cause the cracks. A stress relief following fabrication would have greatly reduced the residual stresses and the cracking might not have occurred.

The Pathfinder control rods will be stress relieved to reduce all residual fabrication stresses and minimize the possibility of cracking of material during irradiation.

Irradiation data indicates approximately two to three volume per cent increase of the material will occur per core a/o burnup. Within the burnup limit, swelling will occur slowly and should not be detrimental to the material, or to the operation of the rod.

Mechanical properties of the 2 w/o boron stainless will change with irradiation. At one core a/o burnup, the tensile and yield strength will increase with the yield strength approaching the tensile strength. Elongation of the material will be reduced to about one percent and the impact strength will be greatly reduced. The large reduction in ductility of the material is the major burnup restriction as far as mechanical properties are concerned. Thus the burnup should not exceed one core a/o. Also, the rods must be relatively notch free and have a smooth surface finish to minimize notch sensitivity of the materials.

5.2 Superheater Control Rods

Swelling and gas release are the only irradiation effects which pose a limit on the superheater control rods. The mechanical strength and structure support of the control rod is supplied by the 304L stainless steel cladding. Any change in mechanical properties of the 2 w/o boron stainless will have no adverse effect on integrity of the control rod. Above the boron stainless rod, a gas chamber is provided within the control rod which is sufficiently large to contain any amount of helium that may be released during irradiation.

Some swelling of the boron stainless may occur if the rods accumulate sufficient burnup and are exposed to high temperatures (above 1000 F) for an extended length of time (refer to Fig. 6). Due to the manner in which these rods will be used in the reactor it is very doubtful if such a condition will occur. A maximum burnup of 0.5 core a/o has been set for these rods to insure that the swelling and gas release will not be detrimental to the integrity of the control rod. The control rods have been designed to adequately accomodate any swelling that the burnup may cause. Details on this subject are presented in Reference 13.

BIBLIOGRAPHY

1. "Neutron Abosrber Materials for Reactor Control," W. Kermit Anderson and J. S. Theilacker, Naval Reactors Division of Reactor Development, USAEC, 1962.

2. BNL-607-T178, Neutron Cross Section Evaluation Group, Newsletter No. 1, 1960.

3. "Boron Stainless Steel Alloys," L. B. Prus, E. S. Byron, and J. F. Thompson, Nuclear Science and Engineering, Vol. 4, No. 3, Sept. 1958.

4. "Boron Containing Control Materials," D.N. Dunning, W. K. Anderson and P. R. Mertens, Nuclear Science and Engineering, Vol.4, No. 3, Sept. 1958.

5. WAPD-160, "The Effects of Irradiation on the Properties of Boron Stainless Steel Powder Dispersion Samples," J. D. Eichenberg, Jan. 1957.

6. IDO-16502, "Radiation Damage Studies of Boron Stainless Steel, Final Report," W. O. Schnaffit, Jan. 1959.

7. GEAP-3183, "Survey of the Physics, Metallurgy, and Engineering Aspects of Reactor Control Materials," June 1959.

8. WAPD-BT-24, "Reactor Technology-Irradiation Behavior of Boron-10 Iron-Base Alloys," W. Yeniscavich, R. G. Gray, and H. B. Meieran, December 1961.

9. "The Effects of Neutron Capture on Reactor Control Materials," W. E. Ray, Dresser Products, Inc., Great Barrington, Mass.

10. KAPL-2000-5, Pg. 35-42, "The Effect of Temperature on the Volume and Structural Stability of Irradiated Boron Containing Materials," W. V. Johnson and J. E. Noonan, March 1959.

11. Power Reactor Technology, Pg. 43-46, Vol. 4, No. 4, Sept. 1961.

12. "Discrete Fixed Poison Rods Containing Boron," W. E. Roy, W. A. Neisz, and H. W. Cooper, Nuclear Science and Engineering, Vol. 4, No. 3, Sept. 1958.

13. ACNP-63001, "Boron Stainless Steel Control Rods for Pathfinder Reactor, Final Summary Report", D. A. Patterson, D. A. Nehrig, R. H. Klumb and T. E. Peterson, Feb. 15, 1963.