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**PATHFINDER ATOMIC POWER PLANT
BORON STAINLESS STEEL CONTROL
RODS FOR PATHFINDER REACTOR**

MASILE

**Final Summary Report
February 15, 1963**

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
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PATHFINDER ATOMIC POWER PLANT
BORON STAINLESS STEEL CONTROL
RODS FOR PATHFINDER REACTOR

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and

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by

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PATHFINDER ATOMIC POWER PLANT
BORON STAINLESS STEEL
CONTROL RODS FOR PATHFINDER REACTOR

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FOREWORD

This report "Boron Stainless Steel Control Rods for Pathfinder Reactor" is one of a series of reports on research and development in connection with the design of the Pathfinder Atomic Power Plant.

The Pathfinder plant will be located at a site near Sioux Falls, South Dakota, and is scheduled for operation in 1963. 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 Pathfinder Atomic Power Plant is a controlled recirculation boiling water reactor with an integral superheater. The boiler region operates at 600 psig and 489 F. The superheater produces 700-725 F steam at 535 psig. The boiler contains sixteen cruciform shaped rods which are individually driven in cruciform channels provided in the boiler fuel element quad boxes. There are forty-eight superheater control rods which are gang driven in four groups of twelve rods each. These rods run in special guide tubes within the superheater core. The boiler rods may be "run in" or "scrammed" during normal or emergency reactor operation. The superheater rods will always be "run in" by the superheater control rod drives. The neutron absorbing material for the control rods is two weight per cent natural boron stainless steel.

Allis-Chalmers has acquired considerable design, development and fabrication experience with boron stainless steel. Design experience gained involves control rods for the critical facility, Pathfinder reactor, and a literature survey on irradiation effects on 2.0 w/o boron stainless. The development and fabrication work included a welding development program, fabrication of the critical facility rods, and prototype testing of the rods under simulated reactor conditions.

2.0 OBJECTIVE

The objective of this report is to present a summary of the design experience and development work that Allis-Chalmers has performed on 2 weight per cent

boron stainless steel for use in control rods.

3.0 SUMMARY AND CONCLUSIONS

Two weight per cent natural boron stainless steel is the nuclear control material being used in the Pathfinder boiler and superheater control rods. An extensive development, fabrication and design analysis program has been completed and shows the control rods will operate satisfactorily in the reactor under all foreseeable conditions.

A literature survey was conducted to determine the effects of neutron irradiation on the 2.0 w/o boron stainless steel. From the analysis of the data, the maximum local burnup on the boiler rods is limited to 1.0 core a/o and the superheater rods to 0.5 core a/o to remain well below the onset of any deleterious effects. The boiler rods will be removed from the reactor due to a loss of negative reactivity control prior to becoming burnup limited. The superheater rods will be removed from the reactor when they have received 0.5 core a/o burnup.

A detailed design analysis and test program was carried out on the boiler control rods. All the stresses imposed on the material are below the yield strength. The deflections were calculated and are not sufficient to restrict any movement of the cruciform during reactor operations and scrams. A welding development program produced a sound fabrication method for producing the control rods. The critical facility rods were fabricated by this method and met all specifications. A prototype rod was extensively

tested in the hot control rod drive test, including a large number of scrams. The rod showed no deleterious effects. The Pathfinder boiler control rods are being fabricated using the developed welding procedure and a subsequent high temperature stress relief to relieve any residual stresses due to welding.

All aspects of the design, test, and fabrication of the superheater control rods were considered. The stresses due to axial and radial differential expansion were calculated and found to be greater than the yield. However, the resulting strains occurred slowly over the rod lifetime, and are much lower than the maximum allowable strain. The deflections were checked and are not sufficient to restrict the movements of the control rod. The rods are designed to accommodate any helium release and swelling that may occur. The rods are fabricated and met all specifications.

The maximum burnup boiler and superheater rod will be removed from the core at one-half design burnup and examined for detrimental effects. Any rod showing indications of serious deterioration will not be replaced in the core, but rather discarded and replaced with a new rod.

It is concluded that the boiler and superheater control rods will operate satisfactorily under the design conditions in Pathfinder.

4.0 BACKGROUND

4.1 TWO WEIGHT PER CENT BORON STAINLESS STEEL

Boron stainless steel has been found to be an effective control material which has been and is being used in several power reactors.

Studies have shown that boron stainless alloys have satisfactory corrosion resistance under reactor operating conditions, adequate fabricability, and suitable structural properties.

Two weight per cent natural boron stainless steel has been selected as the control material for the Pathfinder reactor. The alloy is basically a 304 stainless steel with the addition of natural boron. The solubility of boron in the steel alloy is less than 0.1 w/o, and the remaining boron is present as a complex boron phase dispersed throughout the steel matrix. The phase has been identified as a transitional metal boride of the probable form $(\text{Fe, Cr})_2\text{B}$ (Ref. 2) with some nickel also present.

4.2 DESCRIPTION OF IRRADIATION EFFECTS ON 2.0 WEIGHT PER CENT BORON STAINLESS STEEL

A survey of the literature on irradiation experience with boron stainless steel was conducted. This was done to determine the effect of neutron irradiation and boron-10 burnup on the 2.0 w/o natural boron stainless steel control rods being used in the Pathfinder reactor. This will soon be issued as Allis-Chalmers Topical Report ACNP-63006. The literature reviewed included data from capsule irradiation specimens and full sized control rods used in operating reactors. From this survey, it was concluded that the Pathfinder control rods will operate satisfactorily and retain their integrity throughout their prescribed reactor lifetime.

The effects of irradiation and boron-10 burnup on boron stainless steel may be divided into four major categories as follows:

1. burnup gradient
2. mechanical properties, and hardness
3. cracks
4. swelling and gas release

The data available in each category were examined in detail and correlated with the Pathfinder rods and operating conditions.

The majority of the irradiation experience with boron stainless has been at conditions similar to that which the boiler control rods will experience in Pathfinder. A very limited amount of irradiation experience is available on boron stainless at high temperatures (superheater conditions). Most of these data are on samples tested at elevated temperatures during post-irradiation examinations.

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 < 0.05 barns giving an average cross section of 762 ± 3 barns for natural boron. The neutron absorption cross section decreases with increasing neutron energy according to the $1/v$ law. The neutron boron-10 reaction is as follows: $B-10 (n, \alpha) Li-7$, that is, when the $B-10$ atom has absorbed a neutron,

the unstable atom immediately emits an alpha particle (helium nucleus) and transmutes to a Li-7 atom.

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 of the boron is about five times larger than its weight per cent. Thus, 2.0 w/o natural boron has an atom concentration of 9.5 a/o total boron and 1.95 a/o of B-10. By using the units of core atom per cent, irradiation data from different sources and materials having varying B-10 contents and burnups may be compared and evaluated on a common basis.

4.2.1 Burnup Gradient From Surface to Center

A surface density of 0.054 g/cm^2 of boron (natural) is required for an initial black control rod and additional boron must be added to obtain a suitable reactor lifetime.

When neutrons are absorbed in a rod having a boron concentration higher than that required for blackness, the neutron absorption reaction will take place near the surface of the material. As the boron is depleted at the surface, the reaction zone will move toward the center of the blade.

The maximum allowable point burnup in the boiler control rods is 1.0 core a/o. This will result in the surface having a local burnup of about 1.3 core a/o and the center 0.6 core a/o. Thus even at the point of maximum burnup,

the burnup at the center of the blade will be low enough, so that the boron stainless will retain most of its initial mechanical properties throughout the reactor lifetime.

4.2.2 Mechanical Properties and Hardness

Available irradiation data on the changes of mechanical properties of 2 w/o boron stainless are very limited.

Examination of these data (which covers burnups of 0.8 core a/o and greater) shows that the tensile and yield strength will increase and the yield will approach the tensile strength. The per cent elongation will decrease.

The extent of changes in mechanical properties is dependent on burnup, but the relationship is not known due to lack of experimental data. The maximum point burnup of the Pathfinder boiler rods at end of life is 0.91 core a/o, but the average burnup is only ONE-FIFTH of the maximum. Since the average burnup is so much smaller than the maximum, the change in mechanical properties for the major portion of the control rod is expected to be small. The minimum burnup in the cruciform occurs in the immediate area of the cruciform welds. The average burnup in this area is only ONE-THIRTIETH of the maximum point burnup. Thus, changes in properties in the weld area should be very small. Prior to insertion in the reactor, the cruciforms will be high

temperature stress relieved after welding to relieve all residual stresses and provide the most desirable mechanical properties.

Unirradiated 2.0 w/o boron stainless has a low impact strength when compared with normal stainless steel. However, laboratory tests have shown the cruciforms have the necessary toughness and impact resistance to withstand scram loads of nine times greater than normal. The impact strength of the material will be reduced somewhat during irradiation. But the ability of the cruciforms to withstand scram loads nine times greater than normal should more than compensate for the reduced impact strength caused by irradiation.

The superheater control rods will also experience a change in mechanical properties during irradiation. Since the rods are mechanically supported by the stainless steel cladding, radiation will have no effect on the integrity of the boron stainless rods.

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. Since the B-10 burns up in layers from surface to center of the blade width, the hardness is dependent on the burnup. However, a high hardness on the surface does not

indicate a high hardness at the center, since the burnup in the center is much lower. There is no experimental information available to provide a correlation between the change in surface hardness of the material and changes in mechanical properties due to irradiation. Thus, even though the hardness of irradiated material can be determined, no significant information can be derived from the data.

4.2.3 Cracks

Irradiation data on test samples and full sized control rods have shown that after substantial burnup, the matrix will develop micro and macro cracks. The results of an irradiation study of 2.0 w/o B-10 austenitic stainless steel samples (Ref. 8) indicates the start of submicrocracks at approximately 1.5 core a/o burnup. This is 50 per cent greater than the maximum allowable burnup for Pathfinder control rods.

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%) of the spot welds (Ref. 11). These rods had experienced approximately 8000 TMWD of irradiation in the EBWR reactor. The cracks were semicircular, averaging about 1/4 in. in length. Some of the cracks from the outermost row of welds extend to the edge of the blades.

Cracks were noticed in the Dresden 2 w/o natural boron stainless steel control rods when they were removed from the reactor to check the guide rollers (Ref. 11). The cracks were adjacent to the boron stainless steel welds joining the blades of the cruciform. High residual stresses remain in the weld area, and if not relieved by annealing, they would combine with the mechanical and thermal stresses present during reactor operation. The result would probably be sufficient to cause the observed cracks.

A welding procedure for the fabrication of the Pathfinder cruciform control rods has been developed to produce minimum stress in the final assembled cruciform. Following welding, the cruciform is high temperature stress relieved to relieve all stresses and restore maximum ductility in the material. It is very doubtful if any cracks will appear on the cruciform surface having an average burnup, or in the area of low burnup near the welds. It is possible that the small point area of the cruciform receiving maximum burnup could have some cracks appear on the surface at the end of life, although irradiation data indicates cracks will not start before 1.5 core a/o burnup. Due to the burnup gradient present from edge to center, the mechanical properties of the center of the blade should be relatively unaffected.

The cracks (if they are present) should be restricted to the surface of the material and the integrity of the cruciform will be preserved.

Due to the high temperatures present at shutdown in the superheater control rods and the possible accompanying swelling, cracks may form on the surface of the boron stainless rods. The burnup of the superheater control rods is limited to 0.5 core a/o and will minimize the possibility of cracks forming. However, the superheater rods are contained in a stainless steel clad which provides the necessary mechanical strength and structural integrity, and thus any crack formation would not be detrimental.

4.2.4 Swelling and Helium Gas Release

The quantity of helium generated in irradiated boron stainless is equal to the core a/o 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. Sufficient irradiation data has been collected to show a definite correlation between B-10 burnup and swelling of the metal for irradiation temperatures up to 600 F as shown by Figure 1. Due to the spread in the data caused by unlike samples, a band rather than a distinct curve is plotted. Figure 1 shows that a 1.0 core a/o burnup may

Figure 1 - Volume Per Cent Increase Vs. Core Atom Per Cent for Irradiated Boron Stainless Steel ($\leq 600^{\circ}\text{F}$) (43-025-299)

cause from 1 to 4 volume per cent increase (swelling) in the boron stainless steel alloy. However, no swelling of the cruciforms should occur except possibly at the point of maximum burnup, where the thickness of the blade may increase slightly.

The amount of swelling is also a function of temperature for a given burnup, above 750 F. Some post-irradiation anneals (Ref. 10) have been performed on irradiated specimens and are plotted on Figure 2. With substantial burnup the data shows the superheater rods swell above 1250 - 1300 F. The maximum hot spot temperature which the superheater rods experience is 1230 F at shutdown. Although the maximum control rod temperature is below the lower limit for appreciable swelling, the maximum allowable burnup of the superheater control rods is limited to 0.5 core a/o for initial reactor operation. When the allowable burnup has been reached, the rods will be carefully examined for any presence of swelling or other defects. If no indications of such are observed, consideration will be given for increasing the allowable burnup limit for extended use of these rods in the reactor.

Post-irradiation anneals of irradiated boron stainless samples have shown that a portion of the generated helium will be released (Ref. 8). Two austenitic samples having 3.7 a/o

▼▼●■ ≈ 1 CORE A/O BURNUP
 ○ ≈ 2 CORE A/O BURNUP

* ANNEALLING TIMES VARIED
 FROM 1 TO 24 HOURS

Figure 2 - Per Cent Volume Increase Vs. Irradiation Annealing Temperature for 1 and 2 Core a/o Burnup (43-025-300)

burnup annealed at 750 F for one hour had 41-43% of the generated He released. Two similar samples annealed at 750 F for one hour and at 930 F for an additional hour had 44-46% 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. A large gas space is incorporated in the structure of the superheater control rods to accommodate 100% release of the helium if necessary.

5.0 BOILER CONTROL RODS

5.1 DESCRIPTION

The cruciform control rods in the boiler core are used to control and shut down the reactor. The rods function in a steam and water atmosphere at a maximum metal temperature of 586 F. A program was instituted and completed to:

1. Develop the necessary fabrication techniques and experience.
2. Test prototype rods under near reactor conditions.

The results of the program were incorporated into the final design of the cruciform. A summary of the design analysis and supporting development program for the Pathfinder boiler control rods is presented in the following paragraphs. A detailed report (ACNP-63007) of the design analysis of the control rods will be issued in the near future.

The boiler control rods are cruciform in shape (Fig. 3). The neutron poison section is 72 in. long, and is 2.0 w/o natural boron 304 stainless steel alloy. The blades are 1/4 in. thick, and have an over-all width of 10-7/16 in. At the top of the poison section is a 3 in. wide cruciform extension of 304L stainless steel, and at the bottom is a 1/2 in. annealed 304L nose. The entire rod assembly weighs 164 pounds, and is 15 ft, 2-5/8 in. long.

The control rods are entirely of welded construction. The poison section is formed by butting two narrow plates to a wide plate and joining with a staggered 1/8 in. fillet weld. All the longitudinal welds are made in a special welding fixture to minimize twist and warp, so that the blades of the poison section fit within a 0.312 in. envelope. The welding technique is described later in greater detail. After welding, the cruciforms are high temperature stress relieved to relieve all residual stresses.

Location of the control rods in the annular boiler core is shown in Figure 4.

5.2 CONTROL ROD MATERIAL

Typical physical and mechanical properties of 2.0 w/o boron stainless steel plate used for the boiler cruciforms were determined, and are as follows:

Figure 3 - Boiler Cruciform Control Rod (43-025-345)

Figure 4 - Control Rod Core Locations (43-025-406)

Tensile Strength	82,300 psi
Yield Strength	42,700 psi
Per Cent Elongation	7.9
Per Cent Red. of Area	8.2
Rockwell B Hardness	96.8 $\pm$ 3
(avg. of 258 readings)	
Impact Strength	6.5 $\pm$.5 ft-lb

The impact strength is for unnotched samples 0.197" x 0.197" x 2.165". Samples of 304 stainless steel of the same size had an impact strength of 27.7 ft-lb.

A typical chemical analysis of the material is as follows:

C	-	0.036	Cr	-	18.82
Mn	-	1.93	Ni	-	10.65
Si	-	0.625	Co	-	0.045
S	-	0.006	B	-	2.09
P	-	0.011	Fe	-	Balance

All specified requirements on all heats were well within the Allis-Chalmers Specification for this material.

Samples of the material were examined microscopically to determine the size and distribution of the boride phase in the alloy.

Figure 5 shows typical photomicrographs of the material. It can be seen that the boride particles are quite small and uniformly dispersed throughout the alloy. The material is in the fully annealed state.

5.3. MECHANICAL DESIGN ANALYSIS

5.3.1 Clearances

The boiler cruciform guide channel is an integral part of the boiler core structure. A schematic of the control rod

NOTE:

Each 5 divisions represent 0.001"

Section Near Edge of Plate
(typical) ---- 280X

Section Near Center of Plate
(typical) --- 280X

Figure 5 - Microstructure of 2 w/o Boron Stainless Steel (Typical)

in the guide channel is shown in Figure 6. The minimum channel thickness is 0.419 in. and minimum total channel width is 10.773 in. The cruciform is manufactured to fit in a 0.312 in. envelope. The maximum calculated bow (as shown later) which could increase the envelope is 0.038 in. This results in a minimum channel thickness gap of 0.069 in. and an average gap of 0.164 in. The minimum channel blade width gap is 0.289 in. and the nominal is 0.350 in. Thus, even in the worst case of minimum gap between the cruciform and guide channel, sufficient clearance will always be available for the control rod to move up and down.

5.3.2 Bowing and Thermal Stresses

A thermal gradient is present in the cruciform when non-uniform cooling occurs on both surfaces of the blades. This situation develops when the cruciform is located in the corner of the guide channel (Fig. 6). One side of each blade is in contact with the wall of the guide channel and is considered an adiabatic interface for heat transfer calculation purposes. The opposite side of the blade is cooled through nucleate boiling by the cooling water. This situation causes a parabolic temperature gradient across the blade thickness. The temperature gradient causes the blade to bow normal to the plane described by the blade width and length. The effect of this bow is to reduce the channel thickness gap.

Figure 6 - Boiler Control Rod and Guide Channel (43-025-418)

A maximum parabolic ΔT of 70 F was calculated and assumed constant along the length of the blade. The maximum bow occurs along the outer edge of the blade and is 0.038 in. This reduces the minimum channel thickness clearance to 0.069 in. As soon as the blade starts to bow, it will move away from the channel wall and the parabolic ΔT will be reduced, since cooling will occur on the second side of the blade. Thus the maximum bow of 0.038 in. in reality should never be attained.

The inner edge of the blade is restricted from bowing because it is welded into the cruciform. The parabolic temperature gradient produces a thermal stress along this edge of 10,070 psi. This stress value is well below the yield point and presents no problem.

5.3.3 Mechanical Stresses

In the event of a scram, the boiler control rods will bottom on the control rod stub in the quad box with a maximum velocity of 22 in/sec. The impact stresses were calculated by the following independent methods:

1. Timoshenko, "Vibration Problems in Engineering", page 424.

$$\sigma_{\max} = 5,980 \text{ psi}$$

2. Lawson and Cox, "Mechanics of Materials", page 291.

$$\sigma_{\max} = 1,325 \text{ psi}$$

3. B. N. Cole, "Impact Stresses in Systems of Bars" The Engineer, March 3, 1950, page 264.

$$\sigma_{\max} = 3,200 \text{ psi}$$

Timoshenko's method takes into account both the wave and energy stresses. Lawson's and Cox's method considers only the energy stress, and Cole's method considers only the wave stresses. It can be seen that the sum of the stresses by Lawson and Cox, and Cole approximate the stress obtained by Timoshenko's method. In the analysis, the control rod is considered the striking body and the control rod stub the struck body. This stress is well below the yield and no damage will occur due to scrambling the rods.

The cruciform is subjected to a 300 lb axial load when latching or unlatching the drive mechanisms. The force required to cause buckling of the cruciform was computed as 525 lb. The maximum latching force cannot exceed 300 lb., therefore the cruciform will not fail by buckling.

5.4 FABRICATION

5.4.1 Welding Development Program

Boiler control rods for the Pathfinder reactor are fabricated of 1/4 in. thick 304 stainless steel containing 2 w/o natural

boron. Since this material presents some unusual fabrication problems, a program was instituted to investigate various methods of welding and fabrication. The program included studies on a four piece formed right angle rod, a two piece slotted rod and a three piece welded rod. The three piece welded construction offered the most straightforward assembly, and fabrication studies were based on this design.

Various welding processes and electrodes were studied to determine the best method of welding. The best results were obtained by using type E-308-16 coated electrodes with the hand metallic arc welding process. Typical cross sections of the weld joint were polished, etched and examined. The examination of these revealed that each fillet had penetrated beyond the junction of the plate edges and both legs of the fillet were approximately equal in length. The welds and the base metal showed no evidence of cracks. The welds were free from undercutting, overlap, trapped slag, and porosity.

5.4.2 Fabrication of Critical Facility Control Rods

Subsequent to the R&D welding program, Allis-Chalmers fabricated 16 cruciform boiler rods of 2.0 w/o boron stainless steel for the Pathfinder critical facility.

These rods are of similar design to the Pathfinder rods, and thus provided excellent fabrication experience. The rods were welded in the welding fixture using the alternating welding sequence. After welding, the boron stainless was examined for cracks and other fabrication defects, and no defects were found. The examination included a dye penetrant test. Upon completion of fabrication, the cruciforms were installed in the Pathfinder critical facility and have performed very satisfactorily.

5.4.3 Fabrication of Pathfinder Boiler Cruciforms

The boiler control rod is composed of one wide and two narrow plates welded into a cruciform. Each plate is composed of a 304L tip section, boron stainless plate and 304L connector section joined by welding. The joints are ground flat, dye checked and X-rayed. A welding jig is used to position the three plates into a cruciform. Welding is done with coated electrode E-308L-16. The welding procedure staggers the welds to balance the heat input and minimize any distortion. Following cooling, the rods are dye checked. No grinding is permitted on the finished welds.

After the cruciforms are fabricated, they are high temperature stress relieved. The purpose of the anneal is to relieve all residual stresses due to welding, and restore the best mechanical properties.

5.5 PROTOTYPE TESTING PROGRAM

5.5.1 Hot Control Rod Drive Test

A full size control rod drive test stand was built at the Greendale Laboratories. The primary purpose of the test stand was to experimentally test the control rod drive unit and dashpot designs. The test stand also included the use of a full sized prototype Pathfinder boiler control rod cruciform. The test stand was capable of operating either at room temperature or reactor conditions (600 psig and 489 F). The prototype cruciform was made of 2.0 w/o boron stainless steel fabricated by the same welding procedures that are used on the Pathfinder rods. The prototype does not have a 304L stainless tip on the bottom end. Therefore, when the rod is scrammed the boron stainless makes direct contact with the control rod stub in the guide channel. This is a more severe scram condition than will be encountered in the reactor.

The prototype control rod was cycled through a six foot stroke for a total of 22,388 cycles of which 990 were scram cycles. The majority of these cycles were at room temperature with the remaining at reactor operating conditions. The prototype was removed several times during the test for visual inspection. There was no evidence of wear or rubbing on the cruciform surface during any of the inspections. After

the test was completed, the prototype was removed and dye penetrant tested for cracks. No indications of cracks, signs of rubbing or wear spots were observed on the boron stainless surfaces.

As described above, the prototype control rod has undergone considerable testing and has experienced 990 scrams. Even though the test work does not exactly duplicate reactor conditions and the cruciform was unirradiated, the test still demonstrates the ability of the boron stainless control rod to withstand scram conditions without deleterious effects.

Near the end of the test series the cruciform was scrambled twice without the aid of the dashpot. The cruciform bottomed at a velocity of nine times the normal (200 in/sec) and an impact stress of approximately 50,000 psi. Even under these severe test conditions no deleterious effects were observed on the rod.

5.5.2 Critical Facility Operation Experience

The sixteen 2.0 w/o boron stainless steel control rods were used continuously throughout the Pathfinder critical facility test program. The cruciforms incurred approximately 200 scrams during this time. The rods received negligible irradiation during this time and operated at or near room

temperature. A recent examination of one of the cruciforms showed no cracks or surface defects present in the boron stainless. There is no 304L stainless tip on these cruciforms, so again the scram conditions on the boron stainless were more severe than will be experienced in actual reactor operation.

5.6 PREDICTED BURNUP RATES

The boiler rods serve a dual-purpose in the reactor. They are used to control the reactor during operation and to shut down the reactor during a shutdown procedure. During normal operation only a part of the rods are inserted into the core whereas during shutdown all rods are inserted into the core to stop the nuclear reaction. Physics analysis has determined that during operation an average of four control rods in the outer row will be approximately fully inserted to control the reactor. Other equivalent arrangements and combinations of rods may also be used. On this basis the nuclear lifetime of the fully inserted rods is approximately six months at full power and 0.8 load factor. During this same period of time, a small area of the rod incurs a maximum B-10 burnup of 0.91 core a/o while the average burnup is only ONE-FIFTH of the maximum. This is caused by a 1.5 axial and 3.0 radial flux factor. Figure 7 shows the burnup profile on a cruciform at the point where the axial flux is maximum (rod fully

NOTE: THIS PROFILE OCCURS AT THE MAXIMUM AXIAL FLUX POINT IN THE BOILER ON AN OUTER ROD FULLY INSERTED

Figure 7 - Atom Per Cent Burnup of Boiler Control Rod (43-025-405)

inserted in the core). It should be noted that the burnup of the rod decreases quite rapidly from 0.91 core a/o in both the radial and axial direction. The maximum and average burnups in the cruciform weld area are ONE-EIGHTH and ONE-THIRTIETH of the maximum rod burnup respectively.

It is important to note the very low burnup at the cruciform welds. With this low burnup, it is expected that the mechanical properties of the welds at the end of nuclear life will be similar to the unirradiated properties. Since dye penetrant examination has shown the cruciform welds of the unirradiated prototype rods to be sound (free of cracks) after 990 scrams, the welds of the irradiated rods should also be free of cracks.

Figure 7 shows that the boiler cruciform reaches the end of its nuclear lifetime prior to the irradiation damage limit (1.0 core a/o). Therefore the control rods always remain under the maximum metallurgical burnup limit as used in the Pathfinder reactor.

5.7 REACTOR HAZARDS EVALUATION

The possibility of a boiler control rod failing by some manner in the reactor is very remote. The only failure which can be postulated is the fracture of part or all of the cruciform during a scram.

In the case of an axial fracture along part or full length of a blade, the fracture would have to progress through the 304 stainless

on either end of the cruciform. It is known that 304 retains its ductility even after extended irradiation, and it is very improbable that the fracture would propagate through this material. Thus the blade would still be an integral part of the cruciform and cause no hazard to reactor operations.

In the case of a horizontal fracture across the entire cruciform during a scram the bottom part would remain in the bottom of the guide tube. When the rods would be withdrawn from the core to again start the reactor, a flux tilt would develop across the core resulting in increases in both the superheater and boiler hot channel factors. For the condition in which an entire inner boiler control rod remained in the core with the remaining seven inner boiler control rods full out, an increase of approximately 10% in the hot channel power density for both boiler and superheater would result. This represents the most severe condition. If a single outer boiler rod or a fraction of a rod would remain in the core, a smaller increase in the hot channel factor would result.

Upon returning to power after a scram in which a rod was fractured, the presence of the fractured rod in the core could be detected by either the test instrumentation in the superheater during the period it is there, or by comparing the controlling rod bank height with the height just prior to the scram. Reactor transients

would obscure detection of the fractured rod during startup, but once equilibrium power conditions are reached, a full inner boiler rod in the core would be obvious. Fractions of inner or outer rods would be less obvious but also correspondingly less of a perturbation to the reactor power distribution.

The core shutdown margin would not be affected, since the fractured part of the rod remains in the core.

5.8 SUMMARY

The various parameters which make up the design, test and fabrication procedures of the boiler control rod have been investigated. Detailed analysis indicates a fundamentally sound control rod meeting all design specifications.

The clearances between rod and guide tubes have been thoroughly analyzed. Deflections have been calculated for all conceivable conditions. Interference is improbable even under the worst conditions. The stress calculated for a temperature gradient across the blade thickness is well within the yield stress of the material. Impact stresses due to scrambling, and buckling stresses due to latching were considered and found to be well below the yield.

Since boron stainless steel presents some unusual fabrication problems, a program was instituted to investigate various methods

of welding and fabrication. This program was completed and a suitable welding procedure was developed for the fabrication of the cruciform. The welding procedure was used for the fabrication of the Pathfinder critical facility control rods. The fabrication of the cruciforms was very satisfactory and provided excellent experience. The rods were examined prior to service in the critical facility and found to be defect free. The control rods were used continuously throughout the critical facility test program. Examinations failed to disclose cracks or surface defects in the rods. A prototype rod has undergone extensive testing in the control rod test stand. The test demonstrated the ability of the control rod to withstand scram conditions without deleterious effects.

The predicted burnup of the control rods while in the reactor has been thoroughly reviewed. The average burnup of the cruciforms is 0.21 core a/o and the maximum is 0.91 core a/o during its nuclear lifetime. The maximum allowable burnup due to irradiation damage has been determined as 1.0 core a/o. Therefore, the cruciforms are not burnup limited due to irradiation damage to the boron stainless. The maximum burnup at the boron stainless welds is 0.12 core a/o.

The resulting reactor hazard associated with the remote possibility of a control rod failure has been evaluated. The only failure which

can be postulated is a fracture of part or all of the cruciform during a scram. The failure of a control rod would be determined during subsequent reactor power operation. Such failure will not impose any undue hazard upon the operation of the reactor since the fractured part of the rod will remain in the core.

6.0 SUPERHEATER CONTROL ROD

6.1 DESCRIPTION

The control rods in the superheater core are used to adjust steam temperature and shut down the reactor. The rods function in a steam atmosphere at a maximum temperature of 990 F during operation and 1230 F during shutdown. A program was instituted to test prototype rods under simulated reactor conditions. The results of this program were incorporated into the final design of the rods. Since the boron stainless in the control rod is encased in 304L stainless, the stress calculations performed apply to the 304L stainless steel clad. A summary of the design analysis and supporting program for the Pathfinder superheater control rods is presented in the following paragraphs. A detailed report (ACNP-63007) of the design analysis of the control rods will be issued in the near future.

Each superheater control rod (Fig. 8) consists of a 3/4 in. dia. poison section with a tubular extension of 304L stainless steel.

Figure 8 - Superheater Control Rod (43-025-342)

The poison material is 2.0 w/o natural boron 304 stainless steel alloy. The 3/4 in. dia. poison rod is clad with 0.020 in. 304L stainless steel which is mechanically bonded by sinking the clad onto the rod. The cladding tube is welded to the 0.060 in. 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 under neutron bombardment.

The superheater rods will normally be operated in a full out position and thus receive limited irradiation. The rods may be inserted for short term adjustment of exit steam conditions during power operation. Reactor operation does not require that the superheater rods be scrammed; instead, they will be "run in" under power by the drive units.

Figure 4 shows location of the control rods in the superheater core.

6.2 CONTROL ROD MATERIAL

Typical mechanical properties of the 2.0 w/o boron stainless steel rod used for the superheater control rods were determined, and are as follows:

Tensile Strength	94,200 psi
Yield Strength	64,100 psi
Per Cent Elongation	11.5
Per Cent Red. of Area	12.5

This is well above the specified minimum properties.

The chemical analysis of the finished rod material for the superheater control rods is given below. All the rods were made from the same heat.

C	-	.03	Ni	-	10.31
Mn	-	1.73	Mo	-	.06
Si	-	.90	Cu	-	.04
P	-	.008	Co	-	.03
S	-	.010	B	-	1.87
Cr	-	18.85	Fe	-	Balance

This is well within the specified chemical analysis.

6.3 MECHANICAL DESIGN ANALYSIS

6.3.1 Clearances

The superheater control rods ride in individual guide tubes. The maximum o.d. of the control rod is 0.795 in. The minimum i.d. of the guide tube is 0.898 in. Thus, the minimum diametral clearance between rod and guide tube is 0.103 in.

6.3.2 Thermal Stresses

A. Stresses due to axial temperature gradients.

Axial temperature gradients result in diametral differences along the length of the rod. Any change in slope of the temperature profile induces bending stresses into the clad. The maximum change in the slope of the axial temperature profile occurs at the points where the extension tube and end plug are joined to the poison

section. Hence, the bending stresses are greatest at these points. The axial and radial stresses at the top of the poison section were calculated to be 146 and 43.8 psi and 347 and 104 psi at bottom of the section.

Since the yield stress of 304L stainless at these operating conditions is 15,000 psi, the calculated stresses are negligible.

B. Differential Thermal Expansion - Axial

In this case both the average temperature and coefficient of thermal expansion for the boron stainless are larger than the values for 304L stainless, and an axial differential expansion between the poison section and clad occurs.

Thus, the poison section if free to expand, would be approximately 0.027 in. longer than the cladding. However, both are firmly fastened together and hence a compressive stress is induced in the rod and a tensile stress induced in the cladding. The stress in the cladding was found to be 8950 psi. This stress is below the yield stress of 304L stainless at these conditions.

C. Differential Thermal Expansion - Radial

The coefficients of thermal expansion differ for the boron

stainless poison rod and the 304L stainless clad.

Hence, when heated an interference between the poison section and clad occurs and induces a tangential stress in the cladding. This stress was found to be 12,000 psi. Since the yield stress of 304L stainless steel at 900 F is 15,000 psi, no yielding of the clad should occur.

The stress given above alternates as the rod is heated and cooled, hence, the cladding must be checked for fatigue failure. An allowable stress of 20,000 psi gives an infinite number of cycles for this material. The actual mean and alternating stresses are 6,000 psi, and were determined from the maximum tangential stress given above. The preceding values were plotted on a modified Goodman diagram and found to fall well within safe limits.

D. Stresses due to circumferential ΔT .

When the control rod is located eccentrically in the guide channel, the maximum temperature shifts away from the centerline of the rod and a circumferential ΔT exists.

The deflection calculated for this case was found to be greater than the clearance available between the rod and guide tube. The calculated force exerted by the rod on the tube wall was found to be 11.6 lb. Even with a maximum friction factor, the calculated force is not sufficient

to cause binding between the control rod and process tube. The calculated force against the tube wall is very conservative, since the circumferential temperature gradient will be reduced as soon as the rod starts to bow due to better cooling.

6.3.3 Mechanical Stresses

A. Stresses due to helium release.

It was assumed all the generated helium in the boron stainless is released. For the case of 1230 F and ΔP (internal) of 154 psi the clad stress is 6,990 psi and for the case of 100 F and ΔP (external) of 357 psi the clad stress is 16,200 psi. The yield stress for 304L stainless in the above cases is 12,000 psi and 34,000 psi respectively. Hence, the stresses are well below the yield stresses of the cladding.

B. Elastic Collapse

The critical pressure (pressure at which elastic collapse will occur) was calculated for reactor conditions and found to be 32,800 psi. This is much greater than any conceivable reactor pressure. Hence, the tube is safe from elastic collapse. The maximum stress within the tube wall due to external pressure loading was calculated and found to be 6,810 psi. The yield stress of 304L

stainless at 500 F is 19,000 psi. Again, the stress is much below the yield stress.

C. Stress due to swelling of boron stainless steel.

As boron stainless is irradiated, some swelling of the material does occur. From experimental data collected, an approximate maximum swelling can be calculated.

Additional swelling will accompany the temperature increase encountered during shutdown. Hence, swelling may result in a total volume increase of 5%, which is assumed to take place radially. The strain in the clad due to radial expansion of the poison section is 2.5%.

The apparent stress was calculated and found to be much above the yield stress. However, the radial expansion will occur at a very slow rate and the stress will continually relieve itself. The total strain of 2.5% is well below the allowable strain of the material. An additional stress caused by this swelling exists at the lower end of the rod where the cladding is pulled away from its welded joint with the end plug. A stress of 47,000 psi was calculated. As in the case of the circumferential stress caused by the swelling, this stress is above the proportional limit and will not exist. Again, the radial expansion will occur at a very slow rate and thus the stress will continually relieve

itself. The total strain is less than 1% and therefore is much below the allowable strain.

D. Axial stress due to scram.

An additional cladding stress would result from an accidental scram of the superheater rods. Tests with the control rod drive dashpot have shown that the rod may be subject to a maximum deceleration of 10 g's.

The force on the cladding at the point where it is welded to the extension tube would then be 10 times the weight of the lower part of the rod. The maximum stress calculated is 4230 psi which is well below the yield strength.

6.4 PROTOTYPE TESTING PROGRAM

In order to evaluate the operation of the superheater control rods, several prototype rods and a test stand simulating a portion of the superheater core were constructed. A test program was performed in which the design features of the rods were analyzed and their mechanical performance evaluated. In operation, twelve rods form an integral unit driven by one control rod drive unit. The twelve rods are hung (by the top end fitting) from a cruciform shaped yoke, while the bottom ends float free. This particular configuration shall be referred to as the control rod assembly. The entire assembly is positioned by a series of guide tubes. In the fully

withdrawn position, seven feet of the control rod is still in the guide tube and six feet is in the open.

The test included an analysis of the wear characteristics, torsional rigidity, handling characteristics, and scram effects of the prototype superheater control rods. In addition, bowing of the guide tubes and misalignment of the drive mechanism was evaluated. No appreciable wear between the control rod and guide tube was observed after 250 cycles. No binding or galling was noted due to the rods or tubes being misaligned or bowed.

A prototype superheater control rod assembly was tested under simulated scram conditions. The purpose of the test was to determine if an accidental scram would have any adverse effects on the control rod assembly. The assembly was scrambled twenty times with a dashpot from a height of six feet. The assembly had an impact velocity of 22 ft/sec. Examination of the assembly following the tests showed no adverse effects. There was no evidence of galling, wear or cracks on the control rods. No noticeable deformation was found in the yoke assembly or control rod structure. No excessive vibrations were observed in the assembly during the tests.

The results of all the tests show the superheater control rod assembly remains mechanically operative under adverse conditions.

6.5 PREDICTED BURNUP RATES

The primary purpose of the superheater rods is to depress the superheater flux during a reactor shutdown. They may also be used for short time power or temperature adjustment by partial insertion into the superheater core. Thus, the burnup rate of B-10 in these rods should be low. However, due to the conditions in which they operate and the additional irradiation damage effects at high temperature, the rods have been limited to a burnup of 0.5 core a/o for initial reactor operation. Due to the unscheduled manner in which these rods may be used in the core it is difficult to determine in advance when the rods will reach the burnup limitation. This will be determined after reactor startup by calculating the rate of B-10 burnup in the rods when inserted so that it will be known when the allowed burnup has been reached. At this time the rods will be examined for the presence of swelling or other defects. If the rods are judged satisfactory, consideration will be given for extending the allowable burnup of these rods.

6.6 REACTOR HAZARDS EVALUATION

The possibility of a superheater control rod failing in the reactor is very remote. The only failure which can be postulated is the fracture of the clad or extension tube during an unintentional scram. The stresses were checked for the above case and were below the yield and thus the fracture should not occur. However,

if the fracture did occur, the poison rod would remain in the core and not endanger the reactor.

6.7 SUMMARY

In summary, all aspects of the design, test, and fabrication of the superheater control rods were considered. In reviewing the design criteria, the test results, and the fabrication procedures, the ensuing control rods will meet all expectations as to design, workability and dependability.

The clearances were checked. The minimum diametral clearance between the control rod and guide tube is 0.103 in. Deflection calculations indicated an interference between rod and process tube. However, the resulting force of the rod against the tube is not sufficient to cause binding or galling within the guide tube or restrict the movements of the control rods.

The stresses due to axial and radial differential expansion were calculated and found to be greater than the yield. However, the resulting strains occur very slowly over the rod lifetime and are much lower than the maximum allowable strain. The stress resulting from diametral differences between the cladding of the nose plug and poison section was negligible. Stresses due to accidental scram and internal heating were much below the yield stress of the material. Elastic collapse of the tube will not occur. Irradiation of boron stainless steel results in some swelling and helium

release within the material. The superheater control rods were designed to accommodate any helium release and swelling that may occur.

The results of a test program conducted with prototype rods demonstrated the control rod assembly will remain mechanically operative under adverse conditions including an accidental scram.

7.0 INSPECTION OF RODS DURING REACTOR OPERATION

The maximum burnup boiler and superheater control rod will be removed from the core at one-half design burnup, 0.5 and 0.25 core a/o burnup respectively (three full power months at an 0.8 load factor), and examined for any detrimental effects.

The selected rods will be removed from the core and transferred to the storage pool in accordance with the established operating procedures. The surface of the control rods will be examined by an underwater periscope. Particular care will be taken in the area of maximum burnup and in weld areas. Any discontinuity will be examined at higher magnification and photographs taken. The superheater rod will be checked for excessive swelling.

Any rod showing indications of surface cracks or other defects which are judged to adversely affect reactor operation will not be replaced in the core. Further, all rods of the type showing the defect will be removed and examined in the prescribed manner.

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