BAW-10151A
(Formerly BAW-1623)

December 1981

CONTROL ROD GUIDE TUBE WEAR MEASUREMENT PROGRAM

Babcock & Wilcox
a McDermott company

BAW-10151A
(Formerly BAW-1623)

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CONTROL ROD GUIDE TUBE WEAR

ASUREMENT PROGRAM

Prepared for

The B&W Mark B User's Group

by

BABCOCK & WILCOX
Nuclear Power Group
Nuclear Power Generation Division
P. O. Box 1260
Lynchburg, Virginia 24505

Babcock & Wilcox

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

NOV 10 1981

J. H. Taylor
NOV 17 1981

Mr. James H. Taylor
Manager, Licensing
Babcock & Wilcox Company
P. O. Box 1260
Lynchburg, Virginia 24505

Dear Mr. Taylor:

Subject: Acceptance for Referencing of Topical Report BAW-1623

The Nuclear Regulatory Commission has completed its review of the Babcock and Wilcox (B&W) report number BAW-1623 entitled "Control Rod Guide-Tube Wear Measurement Program" dated June 1980. Although this report was not submitted as a licensing topical report, the subject matter must be addressed in license application for Babcock and Wilcox power plants. Therefore, we have reviewed it in that light and request that Babcock and Wilcox treat it in a like manner. The report provides a description of pertinent details of B&W core designs, an eddy current technique for measuring guide tube wear, wear data obtained from irradiated fuel assemblies, and fuel assembly stress analyses that ascertain residual design margins. The NRC Safety Evaluation is enclosed.

Based on our review of the areas identified above, we conclude that the report demonstrates the adequacy of the B&W nuclear steam supply system design relative to fuel assembly guide tube wear.

As a result of the review, we conclude that the Babcock & Wilcox report BAW-1623 entitled "Control Rod Guide Tube Wear Measurement Program" dated June 1980 is consonant to the NRC Licensing Topical Report Program and is acceptable for referencing in license applications to the extent specified and under the limitations in the report and the enclosed Safety Evaluation.

We do not intend to repeat our review of this topical report when it appears as a reference in a particular license application except to assure that the material presented is applicable to the specific plant involved. Our acceptance applies only to the features described in the topical report.

In accordance with established procedures, it is requested that Babcock and Wilcox publish an approved version within three months of receipt of this letter. The approved version is to include this letter and the enclosed evaluation following the title page.

Should Nuclear Regulatory Commission criteria or regulations change such that our conclusions as to the acceptability of the report are invalidated, Babcock and Wilcox and/or the applicants referencing the topical report will be expected to revise and resubmit their respective documentation or submit justification for the continued effective applicability of the topical report without revision of their respective documentation.

Sincerely,

James R. Miller, Chief
Standardization & Special
Projects Branch
Division of Licensing

Enclosure:
Topical Report Safety Evaluation

JUL 2 8 1981

ENCLOSURE

SAFETY EVALUATION FOR BAW-1623, "CONTROL ROD GUIDE TUBE WEAR MEASUREMENT PROGRAM"

Introduction

Unexpected wear of rodded guide tubes has been observed in discharged pressurized water reactor fuel assemblies (for example see Refs. 1-3). It has been concluded that coolant flow is responsible for inducing vibratory motion in the normally fully withdrawn safety and regulating control rods. The cause of the vibration primarily stems from two sources: (1) axial flow along the control rods and (2) upper plenum horizontal flow across the control rods. When these vibrating rods are in contact with the inner surface of the guide tubes, a fretting wear of the guide tube wall takes place. Significant wear is limited to the relatively soft Zircaloy-4 guide tubes because the Inconel-625 and 304-stainless steel control rod claddings are relatively wear-resistant materials. The extent of the wear is both time- and plant-dependent and has in some non-B&W designs extended completely through the guide tube wall.

Guide tubes function principally as the main structural members of the fuel assembly and as channels to guide control rod motion. Significant loss of mechanical integrity due to wear or hole formation could (a) result in the inability of the guide tubes to withstand loadings during operational transients and fuel handling accidents and (b) hinder the ability to scram the control rods. Therefore, the NRC has been reviewing this issue on a generic basis with vendors and owners' groups and on a case-by-case basis with individual applicants and licensees.

Babcock & Wilcox previously assessed (Ref. 4) the potential for guide tube wear in their plants. The B&W assessment, however, did not provide a means for predicting the rate of wear nor actual wear measurements on fuel assemblies; therefore, a near-term operating license applicant (Ref. 5) and all B&W licensees (Refs. 6-11) were required to provide confirmatory measurements on irradiated fuel assemblies that verify that the B&W plants will not experience through-the-wall wear in guide tubes.

Consequently, a Mark B User's Group was formed and in cooperation with B&W submitted (Ref. 12) the details of a surveillance program conducted in Oconee 1 and 3 and Rancho Seco.

Summary of Report

All operating B&W plants use the 177-fuel-assembly NSSS in which fuel rods are arrayed in 15 x 15 matrices. The skeletonal frame of a fuel assembly consists of 16 Zircaloy-4 guide tubes, 1 Zircaloy-4 instrument tube, 8 Inconel-718 spacer grids, and 2 cast stainless-steel end fittings. The guide tubes are typically 0.016 inch thick with an inner diameter of 0.498 inch. Guide tubes are secured to the upper and lower end fittings by lock-welded nuts.

Each B&W control rod assembly has 16 304-stainless-steel-clad control rods having outer diameters of 0.440 inch. Each control rod assembly can be used in either a safety or regulating mode. When the control rods are in the fully withdrawn (parked) position, the tip of the control rods rest at approximately 9 inches inside the fuel assembly guide tube.

The B&W upper reactor internals design has 2 features that minimize crossflow excitation and turbulence on the control rods. First, the upper plenum directs most (approximately 82%) of the flow in the axial direction. Therefore, since less flow (18%) is discharged directly to the outlet nozzles, any control rod vibration dependence on outlet nozzle location is minimized. Second, the upper plenum tubes provide full-length shielding and continuous lateral support, thus further insulating control rods against crossflow and turbulence effects.

Operating B&W NSSS designs are alike; however, there do exist plant variations in fuel assembly guide tube flow rates. In order to encompass the variations, fuel assemblies to be examined for wear were selected from 3 plants: Oconee 1 represents a low-flow plant, Oconee 3 represents an intermediate-flow plant, and Rancho Seco represents a high-flow plant. The 4 assemblies selected from Oconee 1 had experienced 3 cycles, the 6 assemblies from Oconee 3 averaged 2 cycles, and the 9 assemblies from Rancho Seco had 1 1/2 cycles of rodded operation. These assemblies were selected in order to survey the effects of core position, operating time, and fluence.

To determine the degree of wall fretting, a standard type of high-frequency eddy current technique was employed. Instrument calibration was obtained with machined standards that simulated wear. To obtain comparative base voltages, the technique used a unique feature consisting of a duplicate ECT probe that transversed a reference guide tube. The technique was found to be capable of resolving localized wear (i.e., one-sided wear) down to 5% local wall loss.

Machined standards that represented uniform circumferential defects yielded voltage outputs that were about twice those from standards that represented localized defects of equivalent depths. Consequently, all wear measurements were conservatively interpreted as indications of localized defects. Testing with standards constructed from zirconium hydride demonstrated that the presence of hydrides would be conservatively indicated as a loss of wall material.

The interpretation of the wear measurements focused on resolving 2 concerns: (1) could excessive wear in any single guide tube cause localized through-wall wear and (2) could some lesser degree of wear in all 16 guide tubes result in unacceptable fuel assembly stresses.

With regard to the first concern, the largest measured through-wall wear in (a) Oconee 1 was 10% (25 guide tubes examined), (b) Oconee 3 was 27% (31 guide tubes examined), and (c) Rancho Seco was 57% (139 guide tubes examined). Because the data from Rancho Seco (the plant with the highest flow rate) constituted the largest data sample and contained the greatest wear indications, a statistical analysis was performed on the Rancho Seco data to determine the probability of hole formation. The probability of a hole occurring in 150 weeks of rodded operation was found to be only 0.000011.

With regard to the second concern, the average through-wall wear in (a) Oconee 1 was 0.5%, (b) Oconee 3 was 2.8%, and (c) Rancho Seco was 5.7%. From stress analyses, the maximum allowable wear for the B&W NSSS is associated with buckling failure during seismic-plus-LOCA loading. That allowable wear is 55% uniform circumferential wear to all 16 guide tubes in an assembly. Again, using the Rancho Seco data, the probability of experiencing 55% uniform circumferential wear in an assembly's 16 guide tubes was found to be 0.000001 after 150 weeks of rodded operation.

Summary of Staff Evaluation

Guide tube wear measurements taken with a proven ultrasonic technique on a representative number of fuel assemblies irradiated in Oconee 1 and 3 and Rancho Seco revealed acceptable wear that in no case extended through the cladding wall. Wear and stress analyses conservatively demonstrated a low probability for (a) hole formation or (b) lack of positive design margin for about three cycles of operation. The low susceptibility for guide tube wear in the B&W NSSS is attributable to key design features such as the use of thin, flexible control rods that have ample upper plenum support and shielding.

Consequently, we conclude that the Mark B Owner's Group has (a) justified the adequacy of the B&W 177-fuel-assembly NSSS relative to guide tube wear and (b) resolved staff concerns.

Regulatory Position

The as-submitted report BAW-1623 is an acceptable report that may be referenced as a supporting document to plant safety analysis reports associated with the B&W 177-fuel-assembly NSSS.

References

1. Letter from A. E. Scherer (Combustion Engineering) to V. Stello (NRC), Docket No. 50-336, dated December 23, 1977.

2. Letter from W. Johnson (Maine Yankee Atomic Power) to V. Stello (NRC), Docket No. 50-309, dated February 14, 1978.

3. Letter from A. E. Lundvall, Jr., (Batimore Gas and Electric) to V. Stello (NRC), Docket No. 50-317, dated February 17, 1978.

4. Letter from J. H. Taylor (B&W) to B. K. Grimes (NRC), dated January 12, 1979.

5. Letter from L. S. Rubenstein (NRC) to S. H. Howell (Consumers Power), Docket No. 50-329/330, dated November 15, 1979.

6. Letter from R. W. Reid (NRC) to W. Cavanaugh, III, (Arkansas Power and Light), Docket No. 50-313, dated November 23, 1979.

7. Letter from R. W. Reid (NRC) to W. P. Stewart (Florida Power), Docket No. 50-302, dated November 23, 1979.

8. Letter from R. W. Reid (NRC) to L. E. Roe (Toledo Edison), Docket No. 50-346, dated November 23, 1979.

9. Letter from R. W. Reid (NRC) to W. O. Parker, Jr., (Duke Power), Docket No. 50-269/270/287, dated November 23, 1979.

10. Letter from R. W. Reid (NRC) to J. J. Mattimoe (Sacramento Municipal Utility District), Docket No. 50-312, dated November 23, 1979.

11. Letter from R. W. Reid (NRC) to R. C. Arnold (Metropolitan Edison), Docket No. 50-289, dated November 23, 1979.

12. Letter from J. H. Taylor (B&W) to D. G. Eisenhut (NRC), dated July 18, 1980.

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1. SUMMARY

During November 1979 the utilities operating B&W-designed plants received letters from the NRC expressing a need to examine control rod guide tubes. This request was based on observations of guide tube wear at other vendors' plants. As a result, the Mark B User's Group formulated a program, with B&W assistance, to measure guide tube wear and to verify the integrity of the guide tubes. The results of this program show that guide tube wear is well within allowable limits.

All 177-fuel assembly B&W plants employ the same design for both fuel assemblies and reactor internals; however, there are variations in primary coolant flow rates from plant to plant. This variation in flow rate causes a corresponding variation in velocity in the vicinity of the control rods and guide tubes.

To encompass this velocity variation in the measurement program, three plants were selected to be representative of the range in velocity. Oconee 1 (Duke Power Co.) represents the "low" flow plant, Oconee 3 represents an "intermediate" flow plant, and Rancho Seco (SMUD) represents the "high" flow plant. Conclusions drawn from measurements at these plants are judged to be valid for all of the B&W 177-fuel assembly (177-FA) plants.

Guide tube wear measurements were taken on Oconee Units 1 and 3 in December 1979 and on Rancho Seco in February 1980. In all 56 guide tubes in 10 fuel assemblies were inspected at Oconee, and 139 guide tubes in 9 fuel assemblies were inspected at Rancho Seco.

In general, all wear greater than 5% was located approximately 9 inches down from the top of the control rod guide tube, which corresponds to the safety rod park position and in some cases the regulating rod park position. All measurements at both Oconee and Rancho Seco are referenced to one-sided wear and would be lower if uniform wear around the tube were assumed.

Through-wall wear averages 1.9% and 5.7% were measured at Oconee (average of 56 tubes) and Rancho Seco (average of 139 tubes), respectively. The results from the Rancho Seco examination show that the largest measured individual wear indication was 57% through-wall wear. The results from the Oconee examination show less wear, with the largest measured indication being 27%. Several conclusions can be drawn from the results of this program:

1. The magnitude of the measured wear is low and well within the design criteria.
2. A statistical analysis shows that the probability of through-wall wear is unlikely (probability less than 10^{-5}) for 150 weeks of power operation.
3. The average wear for a fuel assembly (average of 16 tubes) is low, and the structural integrity of a fuel assembly is maintained.
4. The amount of wear appears to increase with primary coolant flow velocity. The Rancho Seco plant experienced the largest wear indication and is representative of a unit with a large flow rate.
5. Fuel assembly guide tubes containing axial power shaping rods (APSRs), orifice rods (ORAs), and burnable poison rods (BPRAs) were also examined. Only guide tubes showing withdrawn control rods indicated wear greater than 5%, and no significant wear was seen in guide tubes containing APSRs, ORAs, and BPRAs control components.
6. No "core-position" dependence was found for observed wear.

2. SYSTEM DESCRIPTION

2.1. Guide Tube Design

B&W's 15 × 15 array fuel assembly design includes 16 Zircaloy guide tubes. In addition to providing structural continuity for the fuel assembly, the guide tubes provide continuous guidance to the control rods while they are inserted in the fuel assembly. Welded to each end of a guide tube are flanged and threaded sleeves, which secure the guide tubes to each end fitting by lock-welded nuts (Figure 2-1). Typical guide tube and control rod dimensions are shown below.

	Guide tube	Control rod
Cladding material	Zircaloy-4	Type 304 SS
Tube OD, in.	0.530	0.440
Cladding ID, in.	0.498	0.398
Length, ft-in.	13-1.5625	--

2.2. Control Rod Assembly (CRA) Design

Each CRA has 16 control rods, a stainless steel spider, and a female coupling (Figure 2-2). The 16 control rods are attached to the spider by a nut threaded to the upper shank of each rod. After assembly, all nuts are lock-welded. The control rod drive is coupled to the CRA by a bayonet connection. Full-length guidance for each CRA is provided by guide tubes in the upper plenum assembly and in the fuel assembly. The CRAs and guide tubes are designed with flexibility and clearances to permit freedom of motion within the fuel assembly guide tubes throughout the stroke.

Each control rod contains a neutron absorber material. The material is an alloy of silver-indium-cadmium (Ag-In-Cd) and is clad in cold-worked type 304 stainless steel tubing. Stainless steel end pieces are welded to the tubing to form a water- and pressure-tight container. The stainless steel tubing provides the structural strength of the control rods and prevents corrosion of the absorber material.

2.3. Guide Tube/Control Rod Interface

As shown in Figure 2-1, the control rod tip always remains inside a fuel assembly guide tube during normal reactor operation. The axial locations of the control rod tip inside the guide tube vary and depend on the control rod's intended function. When a control rod is used as a safety rod, it is positioned in the "full-out" mode. In this case, the tip of the control rod is approximately 9 inches inside the guide tube.

2.4. Guide Tube and Upper Plenum Flows

The B&W upper reactor internals design in addition to the full-length guidance for the CRAs, has two features that minimize crossflow excitation and turbulence on the CRAs. The first is an upper plenum, which directs approximately 82% of the flow in an axial direction while allowing only 18% of the flow to be taken out directly into the outlet nozzles. This strong tendency towards axial flow will minimize any dependence of CRA vibration on outlet nozzle location. The second feature is the use of the full-length upper plenum tubes enclosing each CRA in the upper reactor internals. These full-length tubes provide additional protection for the CRAs against crossflow and turbulence.

Figure 2-1. Guide Tube, Schematic Diagram

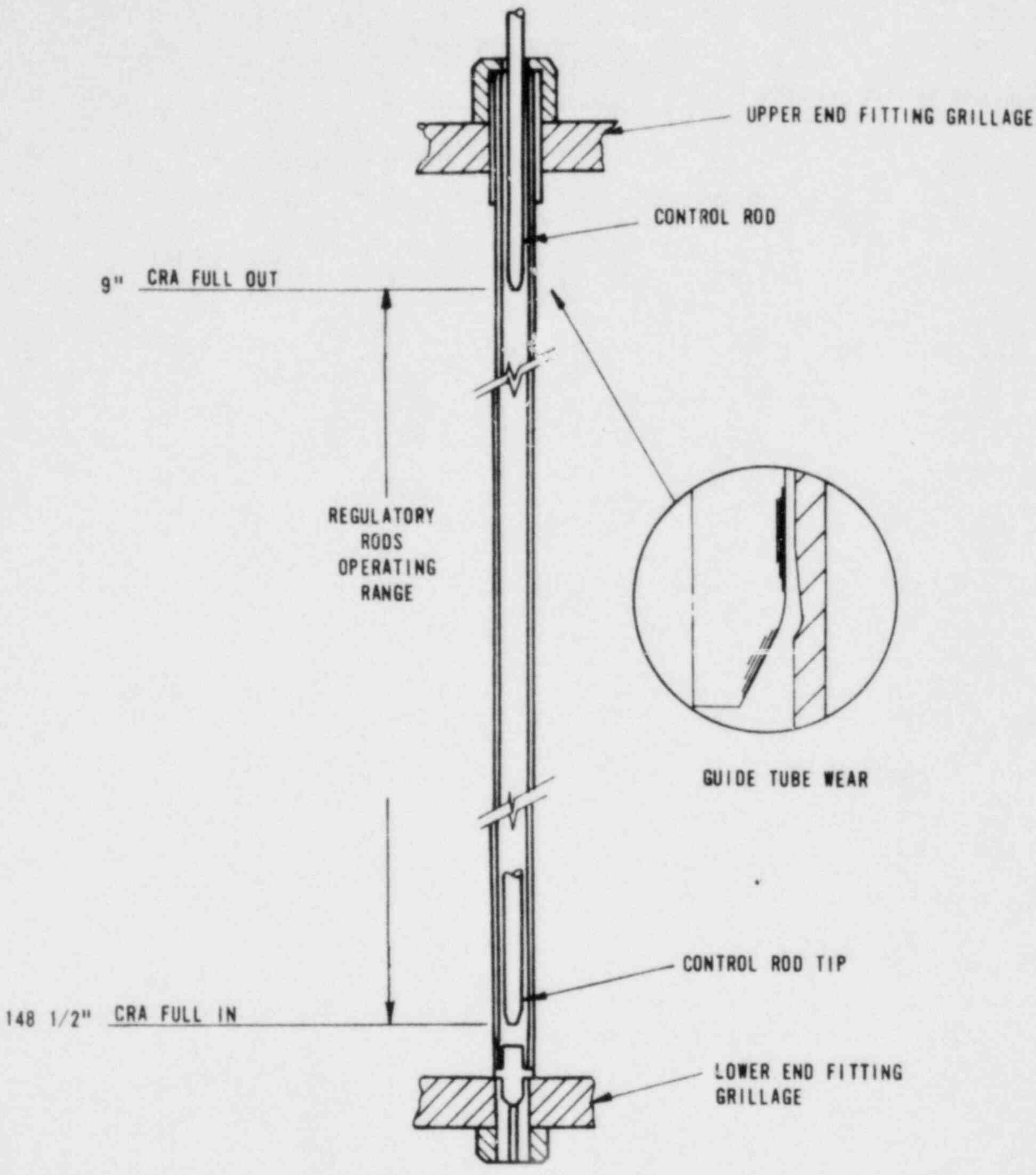
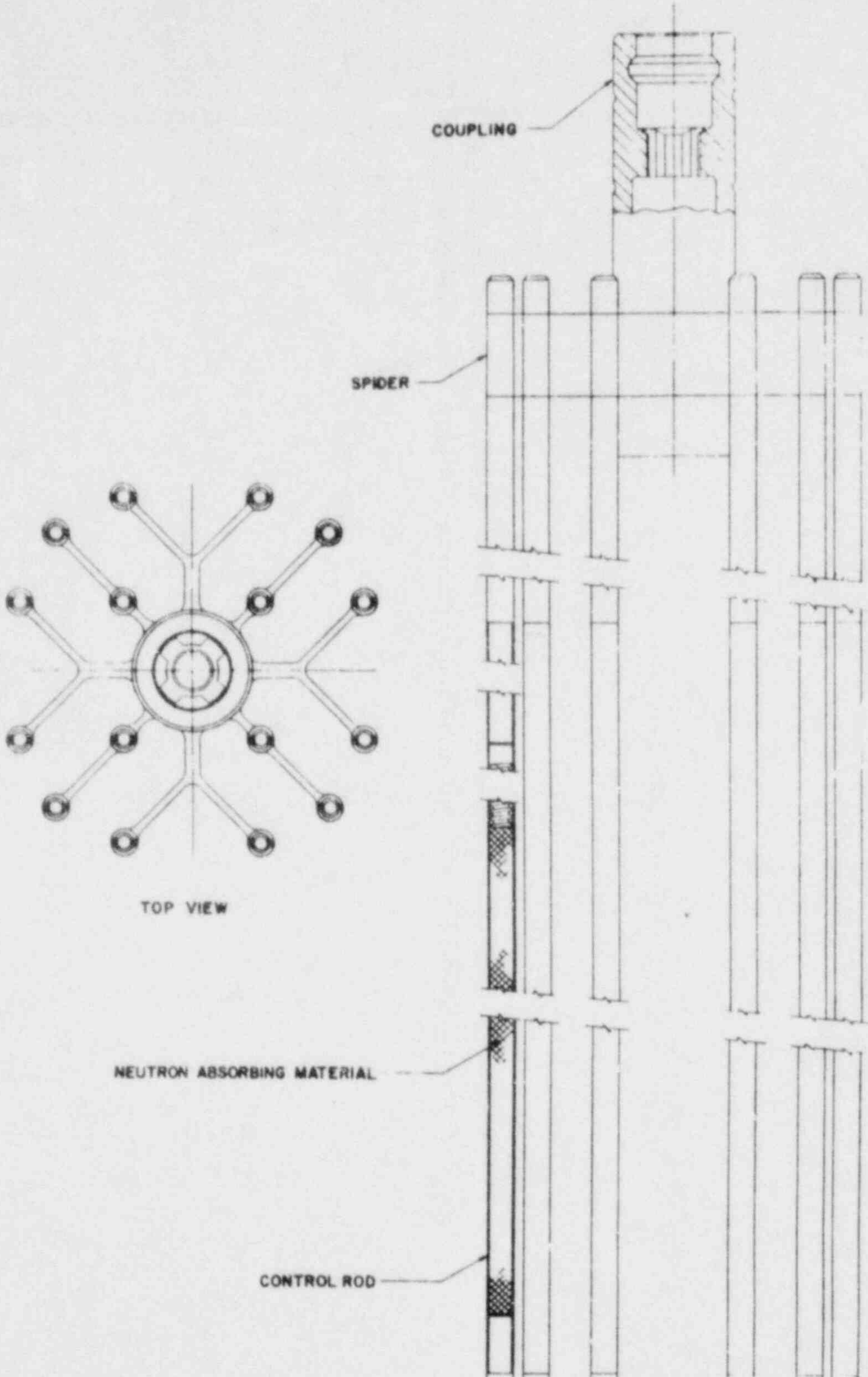


Figure 2-2. Control Rod Assembly



3. MEASUREMENTS

3.1. Selection of Assemblies

3.1.1. Fuel Assembly Core Location and Exposure Time

Fuel assemblies were selected from across the core and for various effective full-power days (EFPD) of control rod operation in the safety position to determine the effect of core-position, time, fluence exposure, etc. To obtain the effect of flow rates on guide tube wear, fuel assemblies were examined at Oconee 1, Oconee 3, and Rancho Seco, the nominal flows of which run from approximately 109 to 114% of design flow.

Table 3-1 lists the fuel assemblies selected from the three reactors. Figures 3-1 and 3-2 show the core locations of the fuel assemblies inspected. Table 3-1 also gives the operating histories of the fuel assemblies examined.

3.1.2. Types of Wear Mechanisms

Several flow-related mechanisms may cause CRA vibration and guide tube wear; two of these appear to be the most probable. The first is turbulent flow along the rod or crossflow across the control rods in the upper internals, resulting in wear at the lower tip of the rod when in the park position. The second hypothesized mechanism is axial flow inside the guide tube and a turbulent vibration response. In both cases, an increase in primary coolant flow could result in higher rod vibration and possible higher wear; however it is felt that turbulent flow with some possible crossflow in the internals area is the most probable cause of rod vibration.

The objective of this analysis is not to determine the cause of the wear at this time but to determine the extent of wear experienced and evaluate its effects on the safe operation of the fuel assembly.

3.1.3. Operation Histories

Seven of the nine fuel assemblies examined at Rancho Seco had operated for one cycle (460 EFPD) with the control components as either regulating rods or safety rods. Both configurations are located at the same elevation and for this analysis are considered the same. One assembly, No. 1B11, experienced an additional 272 EFPD during the second cycle, but since the assembly showed no wear, the results can be incorporated with those for the first seven assemblies.

One fuel assembly, No. 1B41, with BPRAs in the first cycle and an ORA in the second cycle, was examined and showed no wear at any location along the full length of the guide tube.

The guide tubes measured at Oconee 1 all had undergone three cycles of operation with a combination of safety rod and regulating rod locations. Guide tubes measured at Oconee 3 averaged two cycles of operation, also with a combination of safety rod and regulating rod locations.

3.2. Description of Measurement System

3.2.1. Eddy Current Technique

An eddy-current probe was used to determine the tube wall thickness relative to a reference tube. This technique uses a high-frequency (900 kHz) eddy-current signal to develop a field that passes through the tube wall. The probe measures changes in the conductivity of the field, which is proportional to tube thickness.

In order to calibrate the eddy-current signals, standards were machined with known defects and calibration charts were made. Four standards — 20, 40, 60, and 76% through-wall thinning — were made and used throughout both the Oconee and Rancho Seco tests. These standards depict a localized defect in approximately one fourth of the tube ID circumference.

These standards were used as the basis for all the measurements and reported results. For comparison, some samples with uniform circumferential defects were measured; the results show that a localized defect produces approximately half the eddy-current signal of a uniform circumferential defect of the same depth. All measurements in this report are referenced to one-sided wear and would be lower if uniform wear around the circumference were assumed.

3.2.2. Equipment

The eddy-current probes used in these measurements used a circumferentially wound differential coil. This is simply two coils in the same probe spaced about 0.25 inch apart and measuring relative changes in tube wall thickness. Since the exact geometry of the defects was not known, it was decided to use two probes instead of one. The second probe was inserted in a reference tube. The instrument measured the diameter of the tube being investigated by comparing it to a reference tube.

Eddy-current signals for both calibration and measurement were recorded on tape as well as on a strip chart. Thus, the operator could monitor the recordings and repeat the measurement on tubes that indicated large or unusual defects.

3.2.3. Procedure

Fuel assemblies to be measured were identified before the program started and were examined in the spent fuel pool. A guide tube for the eddy-current probe was lowered to each fuel assembly and registered on the guide tube nut with the aid of a television camera. The probe was then driven to the bottom of the guide tube and the measurement taken while withdrawing the probe.

As the probe passed through the guide tube, it also detected the three holes drilled in the bottom of the guide tube as well as the eight spacer grids. The eddy-current signal can measure both increases and decreases in guide tube mass and clearly shows the three drilled holes as decreases and the spacer grids as increases in material.

Calibration signals are recorded at the beginning and end of each tape and at intervals to ensure that the eddy-current signals did not degrade. These calibrations were plotted for Oconee and Rancho Seco data, and average calibration curves were used in the data reduction and analysis. Throughout both tests, the calibrations did not vary significantly, and little drift was observed.

3.2.4. Accuracy

The accuracy of the measurements is dependent on the type of defect being measured. Since a localized defect was assumed, these measurements will tend to be conservative. Potential errors due to the recording system are minimized since both calibration and data signals are read from a strip chart.

Data below 5% are not considered accurate as indications of defects. The calibration curves appear linear through 40% and are plotted through 76%. Due to the nonlinearity of the system, data in the high range (above 60%) are not considered accurate.

Each guide tube was examined for the full length of the tube, including the three flow holes located in the bottom. These holes serve as a check on the calibration and verified the upper limit calibrations.

The eddy-current probes also detect the presence of the eight spacer grids and allow for accurately locating any defect in the tubes. Good eddy-current signals were produced throughout each of the seven spans. Once the eddy-current probe enters the vicinity of the upper end fitting, the signals are no longer valid. Finally, standards were made with varying amounts of zirconium hydride and were eddy-current tested to determine the effects of hydride formation on the calibration. The results of these tests show that the hydride material has lower resistance and gives the same indication as the absence of material. Therefore, the presence of hydride material would indicate more wear than actually exists and would give conservative results. The effects of hydride formation on the results of this program are believed to be insignificant.

Table 3-1. Data on FAs Inspected

Plant	FA No.	Cycle	Core location	Rod bank[a]	EFPD	Total EFPD w/rod bank in safety location
Oconee 1	1 D05	2	H-8	7	53	
				4	239	793
		3	H-8	4	308	
		4	H-8	5	246	
	1 D54	2	B-10	6	237	
				5	55	609
		3	E-9	1	308	
		4	O-5	1	246	
	1 D43	2	F-14	6	237	
				5	55	609
		3	G-11	1	308	
		4	M-3	1	246	
	1 D20	2	L-2	6	237	
				5	55	609
		3	K-5	1	308	
		4	E-13	1	246	
Oconee 3	3 A09	1	O-11	5	478	638
		3	H-8	5	160	
	3 A39	1	F-6	2	478	478
		4	D-4	6	264	
	3 A55	1	O-5	5	478	478
		3	F-8	6	160	
	3 A53	1	G-7	5	478	478
		4	E-5	4	264	
	3 A28	1	D-6	8	478	264
		4	C-5	1	264	
	0 OKS	2	B-6	4	292	
		3	O-9	5	160	452
		4	O-10	--	--	
Rancho Seco	1 B11	1	H-8	7	165	
				4	295	732
		2	H-8	1	272	
	1 A24	1	C-7	2	460	460
	1 A23	1	O-9	2	460	460
	1 A22	1	E-13	4	165	460
				6	295	
	1 A28	1	E-5	7	165	460
				4	295	

Table 3-1. (Cont'd)

Plant	FA No.	Cycle	Core location	Rod bank[a]	EFPD	Total EFPD w/rod bank in safety location
	1 A32	1	K-3	2	460	460
	1 A29	1	M-11	7	165	460
				4	295	
	1 B41	1	M-8	LBP	460	--
		2	O-8	ORA	272	
	1 C01	1	B-6	6	165	
		1	B-6	5	295	732
		2	C-7	7	272	

(a) Rod banks 1-5 are safety rods; rod banks 6 and 7 are regulatory rods.

Figure 3-1. Core Location of Fuel Assemblies Examined at Oconee 1 and Oconee 3

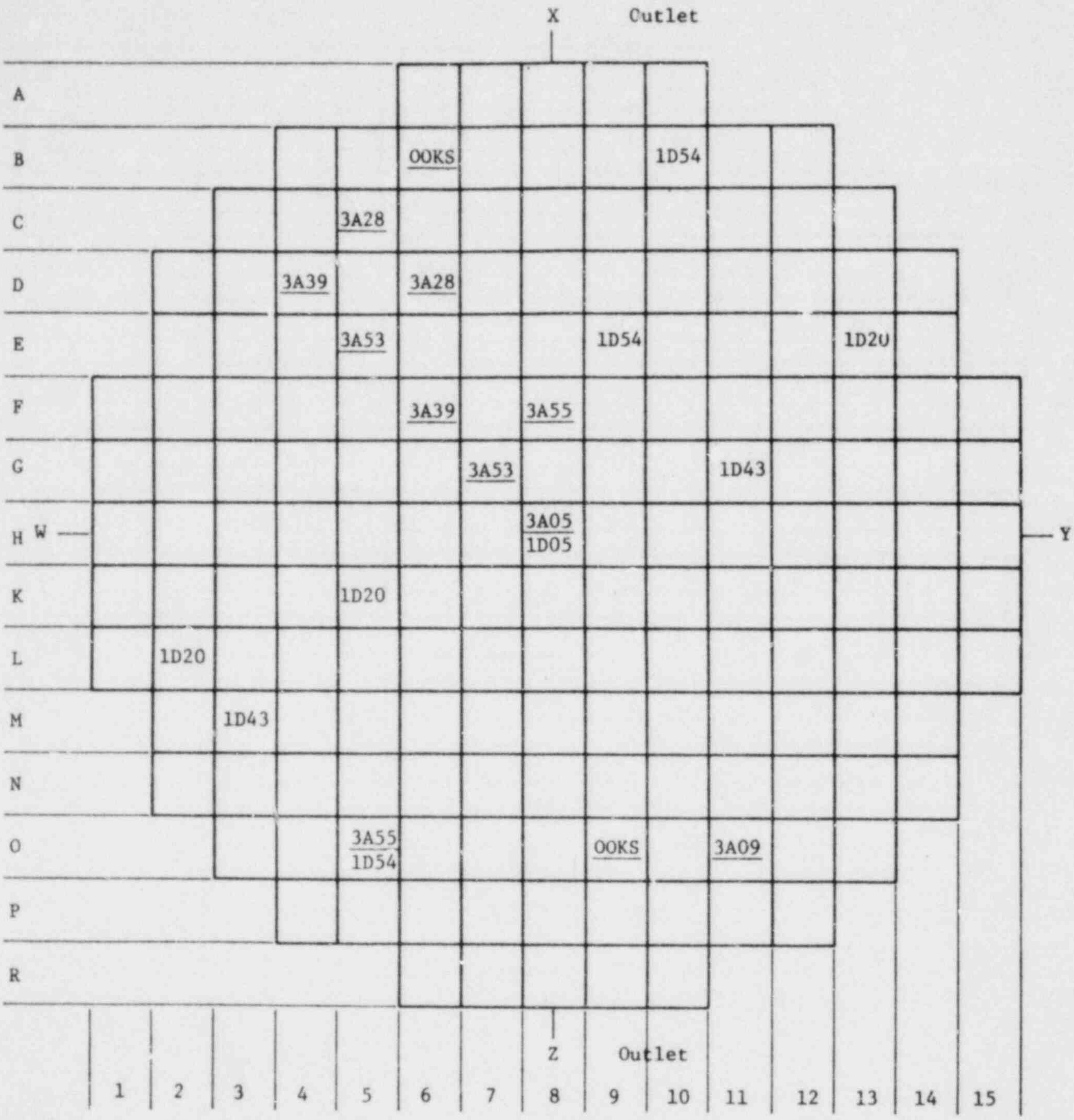
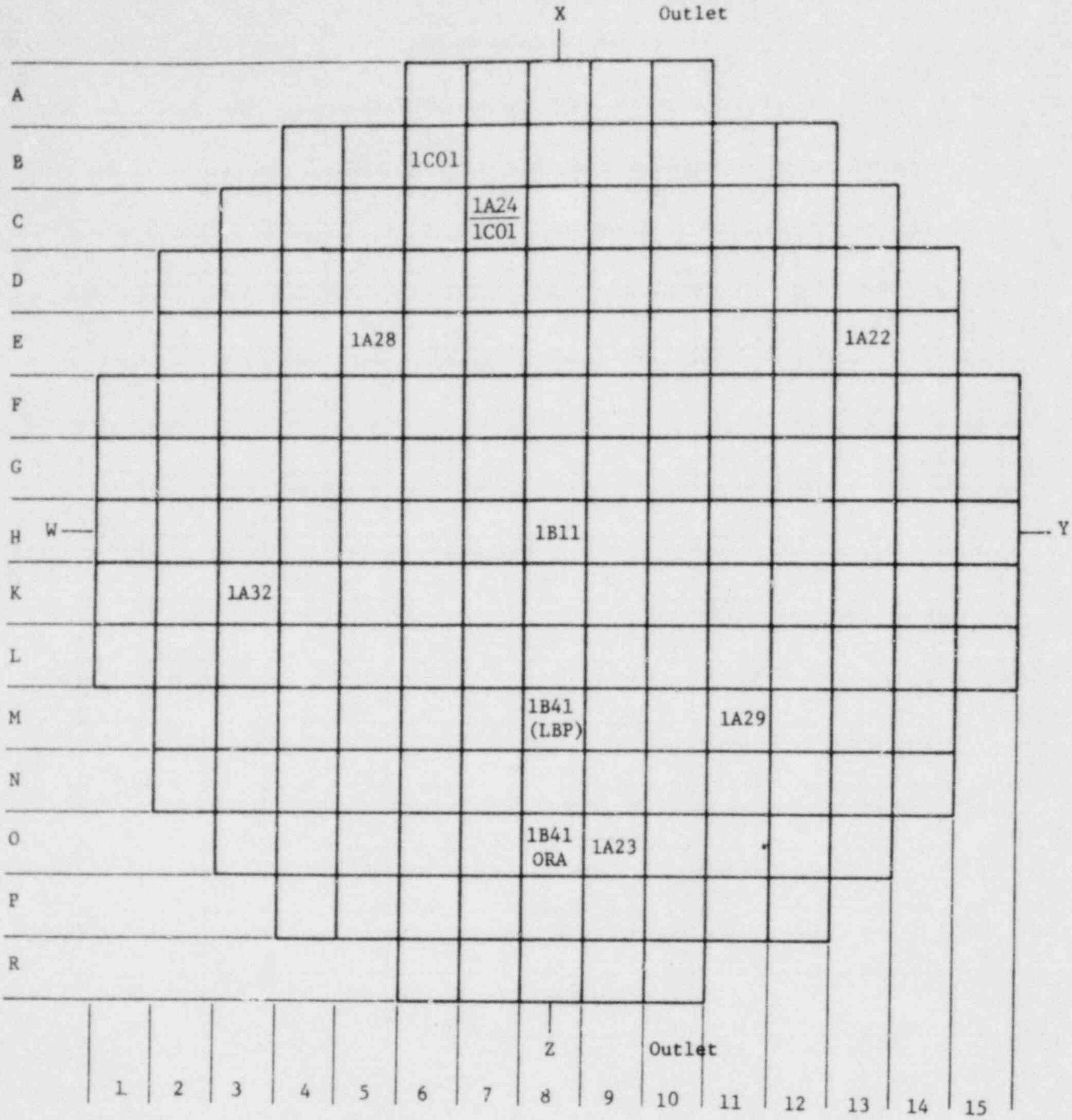


Figure 3-2. Core Location of FAs Examined at SMUD



4. RESULTS

Two potential areas of concern were investigated. The first concern is that any one guide tube could wear through at the control rod park position (approximately 9 inches from the top of the control rod guide tube). The second concern is that smaller amounts of wear in all 16 guide tubes in a fuel assembly could cause high stresses in that fuel assembly.

4.1. Through-Wall Wear

The results from the Rancho Seco examination (high flow rate) indicates that the largest measured wear was 57% (through-wall wear). In general, the wear was located approximately 9 inches down from the top of the guide tube, which corresponds to the location of the lower tip of the control rods of the safety banks in their park position. This location also corresponds to the control rod park position for control banks in some reactors. Four Rancho Seco fuel assemblies indicated wear ranging from 6.9 to 14.9% for one and one half cycles of operation. The other five assemblies examined indicated no wear. Table 4-1 shows the wear indication for each tube measured.

The results from the Oconee examination (low flow rates) indicate less wear than Rancho Seco, with a maximum measured indication of 27% (in Oconee 3). The average wear for each Oconee fuel assembly was low, with a maximum of 6.7%. Table 4-2 shows the wear indication for each tube measured.

4.2. Fuel Assembly Average Wear

The second concern was that each guide tube would have some wear and that unacceptable stresses could occur. A stress analysis was performed that showed that through-wall wear for a single tube was acceptable. This analysis also considered the case with some wear in each guide tube. Two types of wear were considered – localized wear on only one side of the tube and uniform wear around its circumference. The results of this analysis show an allowable of 100% wear for localized (one-sided) defects and 55% wear for uniform circumference wear. Therefore, if the average wear in any fuel assembly (average of 16 tubes) does not exceed 55% uniform wear, than the fuel assembly will maintain a positive design margin.

The results of both the Oconee and SMUD measurements show small average wear with the maximum average of 14.9% for one SMUD assembly with 1½ cycles of operation. The 14.9% was one-sided wear which is compared to an allowable wear of 100%. The distribution of wear indications is plotted in Figures 4-1 and 4-2.

4.3. Statistical Analysis

A statistical analysis was performed on both the Rancho Seco and Oconee data to determine the probability of any one tube experiencing through-wall wear. An analysis was also performed to determine the probability of the average of 16 tubes in one assembly reaching 55% wear. The data used in the Rancho Seco analysis assume 460 EFPD of operation, which is approximately 47% of three cycles of operation. The data measured at both Oconee 1 and 3 were for varying lenghs of time and were extrapolated to three cycles of operation for this analysis.

Data from both Oconee and Rancho Seco were analyzed. The results from the latter plant examination were used in this analysis since it constituted the largest data sample and contained the highest wear indications. The Rancho Seco data are also consistent in that all of the assemblies with wear indications were from the first cycle of operation, while the Oconee data ranged from two to three cycles over the first four cycles of operation.

The amount of wear indicated is assumed to be random for each tube and for each assembly. The cause of the wear is also assumed to be random and a function of neither the FA location in the core nor the combination of FA and control components.

In an effort to show that the incore location is not related to higher wear, two fuel assemblies that used the same control components and operated in core location C7 for cycles 1 and 2 were examined. Fuel assembly 1A24 experienced the largest wear indication, while assembly 1C01 experienced no wear, indicating that the wear is randomly distributed and independent of core location. This indicates that the amount of wear in any core location may change for each cycle due to variations in control components (different alignment of control rods) and possible changes in coolant flow patterns in the core.

Wear indications from the Rancho Seco examination were ranked according to percent wear indication and plotted on probability paper. These results indicate that for wear indications above 5% the wear appears random and agrees with the first assumption.

The results from the Rancho Seco statistical analysis indicate the probability of one guide tube wearing a hole is very low and is not expected. The probability that a hole will occur in 150 weeks of operation is 0.000011. The results from this analysis also indicate that the probability of the average of 16 tubes in one assembly reaching 55% wear is also very low and is not expected. The probability of the average of 16 tubes reaching 55% wear is 0.000001 for 150 weeks of operation. This case assumes uniform circumferential wear, which is not expected. The more likely case is wear occuring on only one side of the guide tube. This case has a higher allowable wear (100% versus 55%) and hence a significantly smaller probability of reaching this wear.

Table 4-1. Oconee Control Rod Guide Tube Wear Test, Percent Wear Indication

Guide tube No.	Oconee 1 FA No.				Oconee 3 FA No.					
	1D05	1D20	1D54	1D43	3A09	3A55	00K5	3A39	3A53	3A28
1	3	0	0	0	5	--	14/2[b]	--	--	0
2	0	1	0	0	2	--	0	0	0	0
3	--	--	--	--	--	1	--	0	1	--
4	0	--	0	--	--	--	3	--	--	--
5	0	--	--	0	0	0	--	0	--	0
6	--	--	--	--	--	--	--	--	5	--
7	--	--	--	--	--	--	--	10	--	--
8	0	0	0	0	0	--	0	--	--	--
9	--	--	--	--	--	--	--	--	--	--
10	0	--	--	--	27	--	--	--	--	0
11	--	0	0	0	--	--	4[a]	8	--	--
12	10	--	--	--	--	--	--	--	--	--
13	--	--	--	--	--	--	--	--	--	--
14	--	--	--	--	6	--	--	--	--	--
15	0	0	--	3[a]	--	3	0	2	4	0
16	--	--	4[b]	--	--	2	--	--	--	--
Average[c]	1.6	0.2	0	0	6.7	1.5	2.8	3.3	2.5	0

(a) Second span.
(b) Third span.
(c) First span.

Table 4-2. Rancho Seco Control Rod Guide Tube Wear Test, Percent Wear Indication

Guide tube No.	FA No. 1A22	1A23	1A24	1A28	1A29	1A32	1B11	1B41	1C01
1	24	7	0	0	0	6	0	0	0
2	0	5	0	0	0	4	0	0	0
3	9	21	16	0	0	18	0	0	0
4	0	11	0	0	0	24	0	0	0
5	0	5	8	0	0	24	0	0	0
6	28	4	57	0	0	15	0	0	0
7	8	5	23	0	0	0	N/A	0	0
8	25	4	15	0	0	0	0	0	0
9	18	0	14	0	0	3	N/A	0	0
10	35	5	6	0	0	0	N/A	N/A	0
11	41	3	6	0	0	0	0	0	0
12	4	4	0	0	0	4	0	N/A	0
13	0	18	23	0	0	24	0	0	0
14	28	3	10	0	0	34	0	0	0
15	8	11	21	0	0	0	0	0	0
16	11	4	20	0	0	0	0	0	0
Average	14.9%	6.9%	13.7%	0%	0%	9.8%	0%	0%	0%

Figure 4-1. Oconee Wear Amplitude

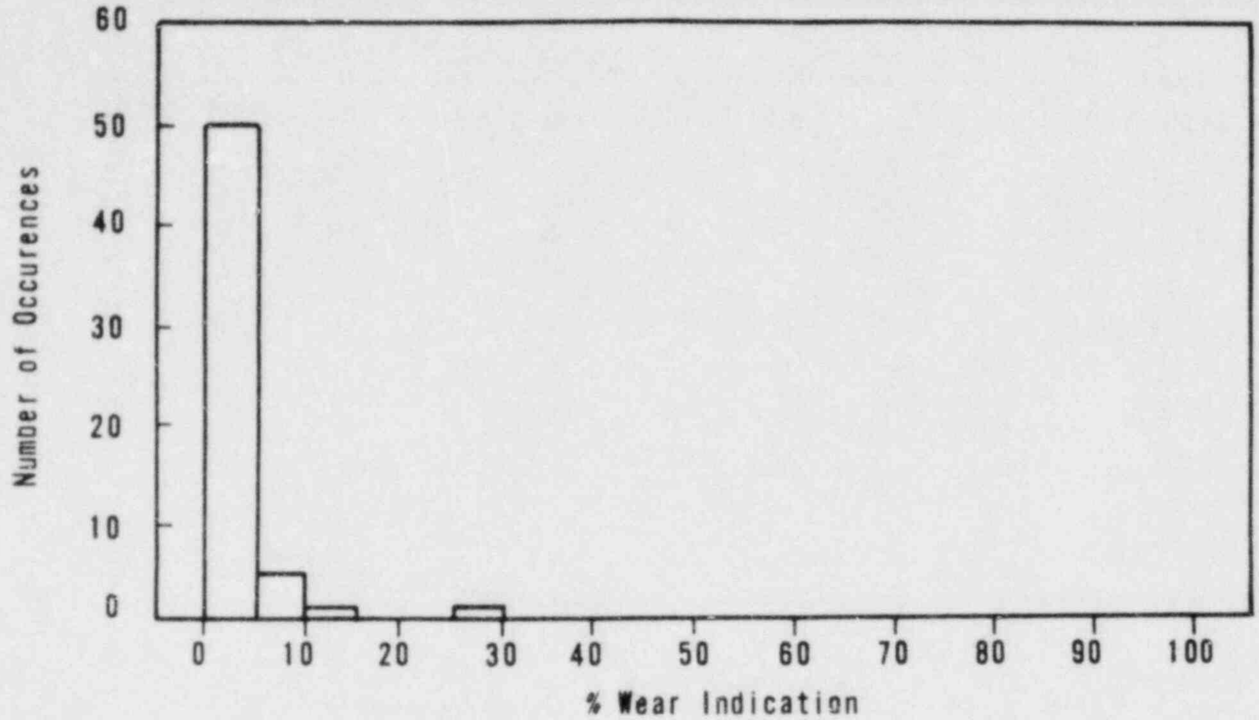
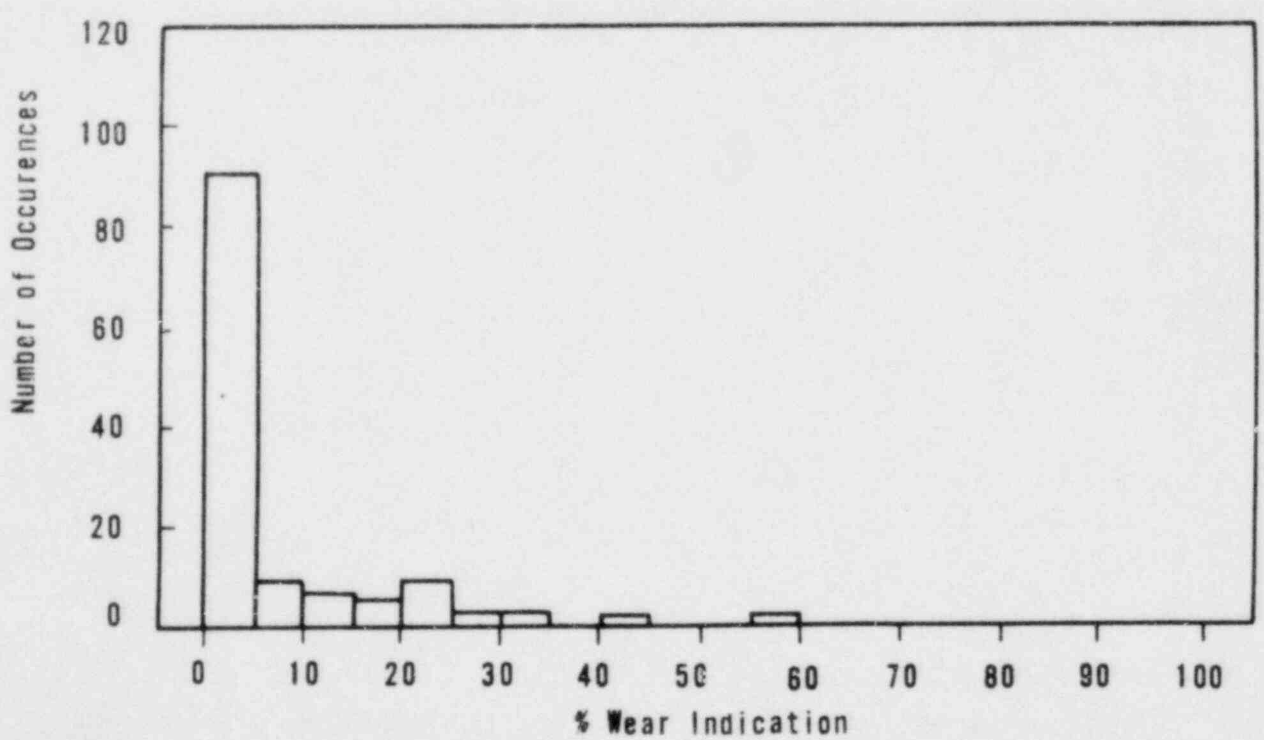


Figure 4-2. Rancho Seco Wear Amplitude



5. STRESS ANALYSIS

A stress analysis was performed to determine the amount of wear that would still result in positive design margin. The loads considered included normal operating, handling, and LOCA plus seismic loads. Of these, the highest loads are due to handling (tension) and LOCA plus seismic (buckling) effects.

Uniform, one-sided, and two-sided wear was considered in the analysis. The wear pattern was assumed to have the same radius of curvature as the control rod for both the one-sided and the two-sided wear (diametrically opposed). Wear was assumed constant over the length of the span where it was observed on the withdrawn control rods. For the one-sided wear case the shift in neutral axis was considered.

The allowable wear based on the assumptions above, conservatively considering the unirradiated strength of unhydrided Zircaloy-4, is as follows:

Wear type	Load condition	Design criterion	Allowable* wear, %
Uniform Circular	Handling	Stress	60
	LOCA+seismic	Buckling	55
One-sided	Handling	Stress	100
	LOCA-seismic	Buckling	100
Two-sided	Handling	Stress	100
	LOCA+seismic	Buckling	80

*100% wear is defined as wear depth equal to the wall thickness.

The controlling design condition is 55% wear. This value is used as a limiting value in the statistical analysis to determine the probability of not having a positive design margin.