PPE-96-249

Preliminary Report

Incomplete RCCA Insertion

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1.0 Introduction/ History of Events

An RCCA insertion anomaly was experienced at Wolf Creek near the end of Cycle 8. During this trip, five RCCAs failed to fully insert. Wolf Creek performed cold drop tests after the anomaly and three additional RCCAs did not fully insert.

Since Wolf Creek was approximately one month from EOC shutdown, the utility decided to remain shutdown and go into their refueling outage.

A similar incident occurred at South Texas Unit 1 on December 18, 1995 when during a reactor trip, four RCCAs failed to fully insert. Subsequent to a review of the situation with the NRC, the unit returned to power with an agreement to conduct an RCCA trip/operability test on March 2, 1996. The RCCA tests on March 2 resulted in seven RCCAs failing to fully insert. Subsequent to satisfying technical specifications and safety evaluation limits, the unit returned to power until EOC when it shutdown. In accordance with NRC Bulletin 96-01, RCCAs were tripped and eleven RCCAs failed to fully insert. A calendar of events is shown below.

Calendar of Events

South Texas Event	12/95
Wolf Creek Event	01/96
NRC Contacted WOG/WOG Responded to 14 NRC Questions	02/96
Westinghouse/WOG/NRC Meeting	02/96
Bulletin 96-01 Issued	03/96
NRC/Westinghouse/WIG Meeting Susceptible Fuel 06/15/96 Root Cause 08/31/96	03/96
Westinghouse/WOG/NRC Meeting	05/96
Westinghouse Meeting with NRC on Susceptible Fuel	06/96
WOG/NRC Meeting	08/96
Westinghouse Root Cause Meeting with NRC	9/9/96

2.0 Summary of Plant Trip Information

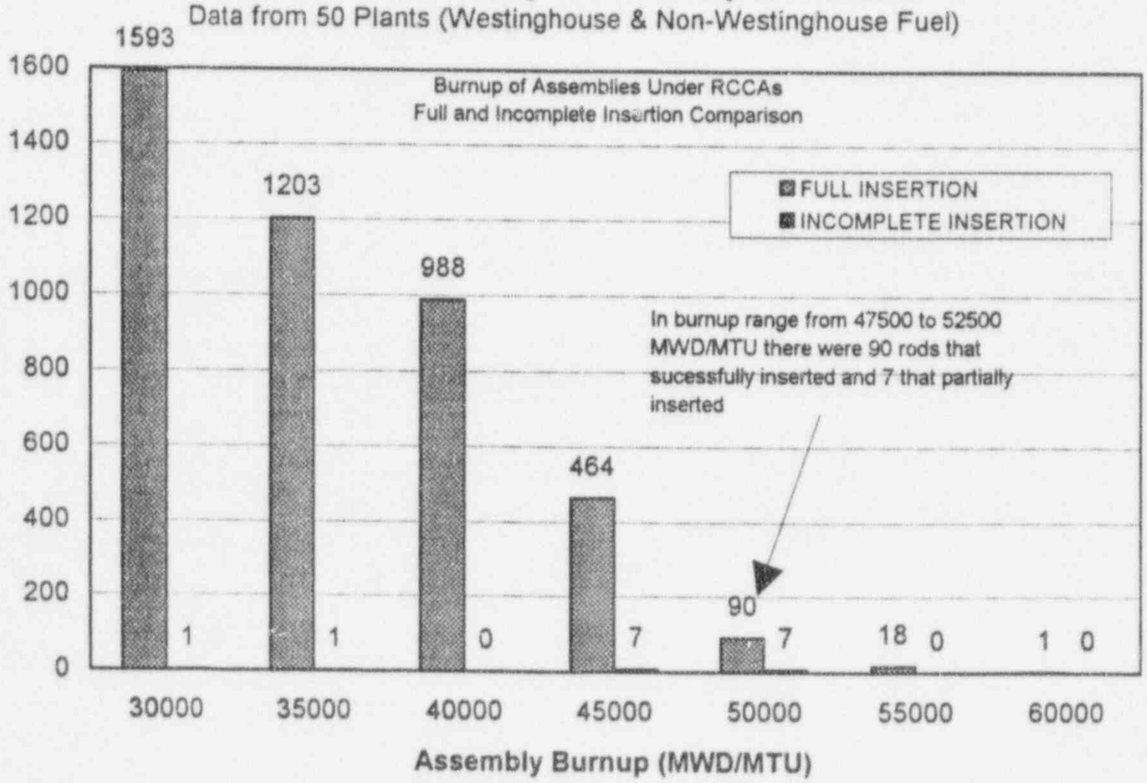
Figure 2.1 provides a graphical representation of plant trip information for full and incomplete RCCA insertion for 50 of the 51 Westinghouse designed domestic plants (the remaining plant, Watts Bar, is not included since its fuel assembly burnup is below 27,500 MWD/MTU). This figure has been developed based on information provided by the utilities in response to a request from the Westinghouse Owners Group (WOG). The data include information from both Westinghouse and non-Westinghouse supplied fuel of 12 foot, 10 foot, and 14 foot designs and

consists of the results of beginning of cycle and end of cycle rod drop tests, in cycle rod drop tests, and RCCA insertion observations during reactor trips. The table below provides a summary of this figure with information relative to the fuel assemblies at Wolf Creek and South Texas Unit 1 incomplete RCCA insertions.

BU (GWD/MTU) RANGE UNDER RCCA's	NUMBER FAs SHOWING FULL INSERTION	NUMBER FAs SHOWING INCOMPLETE INSERTION (WOLF CREEK)	NUMBER FAs SHOWING INCOMPLETE INSERTION (SOUTH TEXAS UNIT 1)
27.5 - 32.5	1593	0	1
32.5 - 37.5	1203	0	1
37.5 - 42.5	988	0	0
42.5 - 47.5	464	0	7
47.5 - 52.5	90	5	2
52.5 - 57.5	18	0	0
57.5 - 62.5	1	0	0

Figure 2.1: Summary of Plant Trip Information

Data from 50 Plants (Westinghouse & Non-Westinghouse Fuel)



As indicated above, the only instances of incomplete RCCA insertion below an assembly burnup of 47,500 MWD/MTU are associated with South Texas Unit 1, a plant utilizing a 14 foot fuel design. Additionally, with fuel of the 12 foot and 10 foot designs, there have been no incomplete RCCA insertions in fuel assemblies with an assembly burnup below approximately 49,000 MWD/MTU.

3.0 Root Cause Process

Several activities were planned/initiated to determine the root cause of incomplete RCCA insertion. These activities are shown pictorially in Figure 3.1. The objective/purpose of these activities are as follows (the detailed results will be discussed in later sections):

Plant Trip History Data
Determine the extent of the problem for all domestic plants that have experienced trips in the last 3-5 year period. The results were discussed in the previous section.

Detailed Manufacturing Review
Determine whether the thimble tube materials used in Wolf Creek and South Texas were unusual in any respects with regard to material specifications or process changes. Results showed no abnormalities in process or basic material properties.

Plant Operations and Fuel Management Review
Determine if there were any unique or unusual chemistry, fuel management, or core operating conditions which might suggest a cause. Both plants operated within the chemistry specifications. However, both plants have high operating temperature and Wolf Creek (Region H) appeared to operate with a somewhat unusual power history (3 cycle operation with high power in cycle 2 and 3).

Review of Available Worldwide Experience
Determine in a similar but less detailed fashion whether similar problems have been experienced in non-domestic plants. To date there are four European plants which have experienced incomplete RCCA insertions which appear to have the same symptoms as Wolf Creek and South Texas and therefore probably have the same or similar root cause. Information has and continues to be gathered on these plants and incorporated in the process to determine common root causes.

Westinghouse Testing at Plant Sites
Develop and implement a detailed testing program to gather information at ten plant sites (8, excluding Wolf Creek and South Texas Unit 1). The plants and particular fuel assemblies tested were identified to cover the range of most all Westinghouse designs as well as bracket the time history of thimble tube fabrication at Wolf Creek (see Figure 3.2).

The results suggested that the Wolf Creek H assemblies were unique in terms of fuel assembly growth. Wolf Creek and South Texas also displayed RCCA drag characteristics which were significantly larger than other plants tested.

Zircaloy Material Property Review
Performed a comprehensive review of all known Zircaloy properties information including work with outside consultants. This was done because Wolf Creek experienced unusually large fuel assembly growth. In addition, unirradiated material tests were performed to augment existing information on the effects of oxide and hydrogen on fully annealed tubing. This information was used to modify the Westinghouse growth model to account for these time and temperature effects. This information was also incorporated in our overall mechanical model.

Hot Cell Measurements
Determine the dimensional and material conditions/characteristics in irradiated Wolf Creek fuel assemblies to obtain basic information and insight into detailed thimble tube behavior. Fuel rods from two assemblies (H50 and H38) that had experienced incomplete RCCA insertion were removed, the skeletons sectioned and sent to the Westinghouse STC hot cell facility for detailed examination. Key information gathered was growth as a function of elevation, oxide/hydrogen as a function of elevation and detailed dimensional characteristics of thimble tubes (ovality, bow, diameter).

Detailed Mechanical Model
Develop a mechanical model based on prior experience and basic knowledge of fuel mechanical design criteria and incorporate all the information developed on growth mechanisms. The purpose of the model is to understand the interactions of various mechanisms, interpret test results and evaluate future design changes. The comparisons between the model and test results are reasonably good considering the complexity of the problems.

Figure 3.1: Root Cause Determination Process

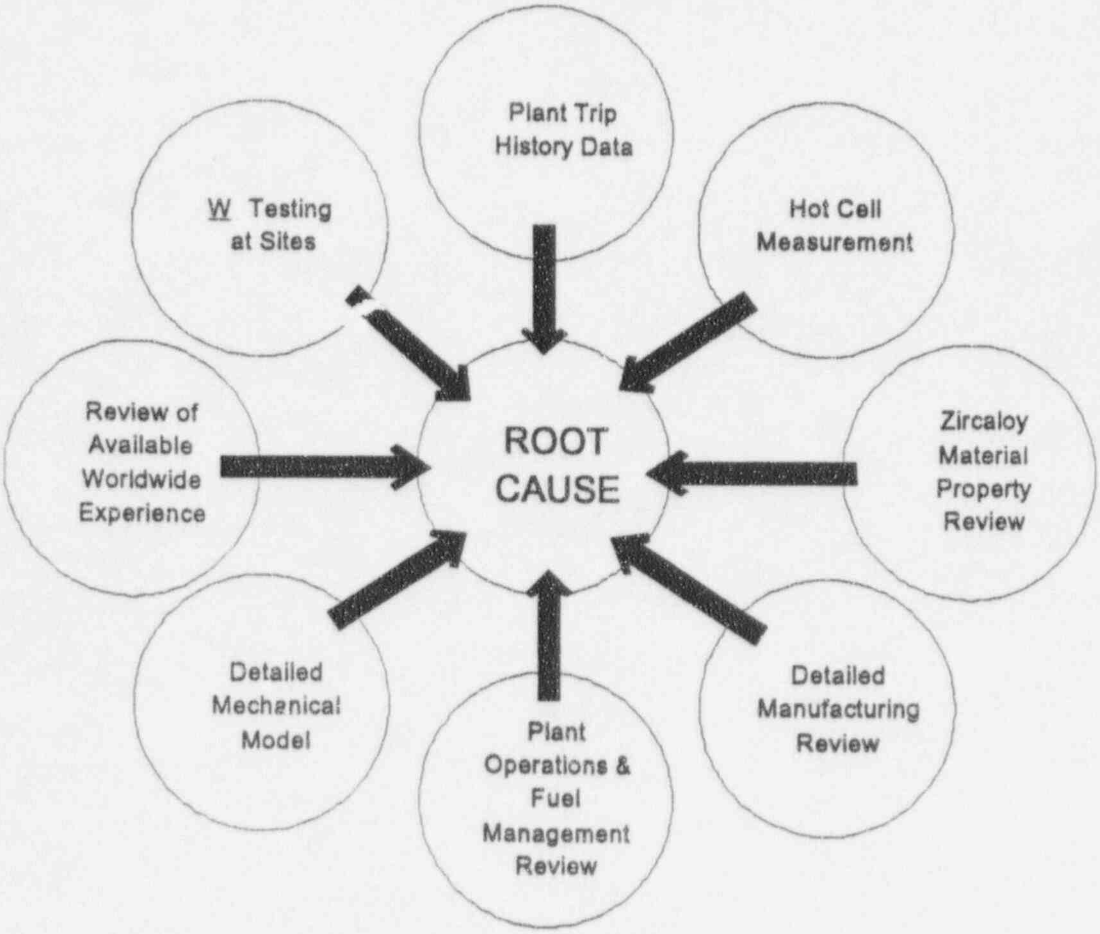


Figure 3.2: Program Status Overview

Isolation of the Population that may be Susceptible

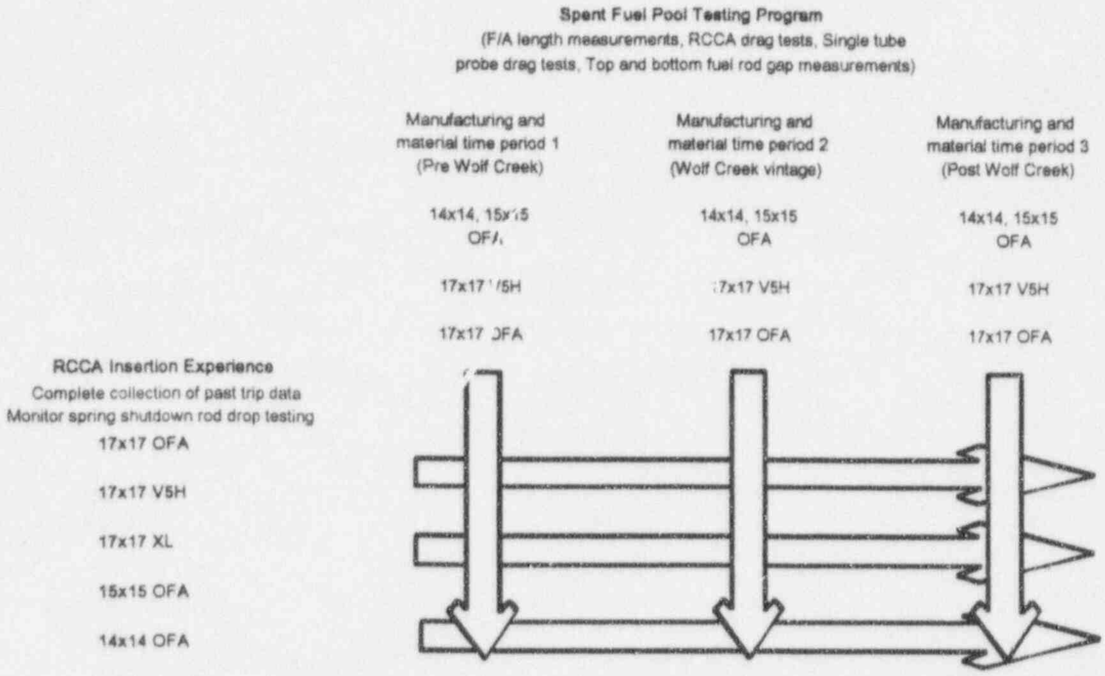


Figure 3.3: Process & testing logic used to determine root cause

Determine extent of problem
- Plant trip history data

Related to design (V5H) or manufacturing?
- Materials and process review
- Testing program at ten sites

Related to plant operations?
- Chemistry
- Temperature/flow/power
- Fuel management

Material property related?
- Unirradiated tests
- Hot cell exams
- Literature review
- Consultant experts including General Electric

Root cause hypothesis
- Data analysis
- Analytical model

4.0 Site Test Program/Logic

As previously discussed, the purpose of the Site Testing Program was to determine the susceptibility of various designs for the incomplete RCCA insertion anomaly. Manufacturing effects/contributions were also investigated by sampling assemblies which had thimble tubes that were manufactured before, during, and after the time period in which the thimble tubes for Wolf Creek were manufactured (Figure 3.2).

Table 4.1 shows the plants included in the program, their fuel design type and the nature of the tests performed. A summary of the results follows with the detailed data for each plant being included in the appendices.

Table 4.1: Completed Site Testing Programs

PLANT	FUEL TYPE	VISUAL	DRAG TESTING	GROWTH	PROBE	BORESCOPE	FA BOW
Wolf Creek	17x17 V5H	√	√	√	√	√	√
	17x17 V5H w/IFM	√	√	√	√	NP	√
	17x17 STD	√	√	√	NP	NP	NP
Millstone 3	17x17 V5H w/ IFM	√	√	√	√	NP	NP
South Texas	17x17 XL	√	√	√	√	√	√
Point Beach	14x14 OFA	√	√	√	√	NP	NP
Surry	15x15 OFA	√	√	√	√	NP	NP
VC Summer	17x17 OFA w/IFM	√	√	√	√	NP	NP
Sequoyah	17x17 V5H	√	√		√	NP	NP
Diablo Canyon	17x17 OFA w/IFM	√	NP	√	√	NP	NP
North Anna	17x17 V5H	NP	√	√	√	NP	NP
Vogtle	17x17 OFA w/IFM	√	√	√	√	NP	NP

NP = Not Planned

5.0 Site Testing

In this section of the report, the visual, drag test, fuel assembly growth, fuel rod growth, single tube probe, borescope and fuel assembly bow results are presented. In Table A.1, the design features for the different types of fuel assemblies that were tested are presented. In Table A.2, the drag, fuel assembly growth, fuel rod growth and single tube probe data is summarized for the assemblies that were tested. In Appendix C, the inspection report for the different programs is presented.

5.1 RCCA Drag Tests

The drag test results for two different programs are presented in this section. The two programs are the NRC Bulletin 96-01 tests and the root cause tests. The NRC Bulletin 96-01 tests were performed after it had been verified that the RCCAs would insert fully into the assemblies. The root cause tests were investigative tests on fuel assemblies that were stored in the spent fuel pool. The NRC Bulletin 96-01 tests are referred to as "drag measured after reactor trip" while the root cause tests are referred to as "spent fuel pool tests".

In response to NRC Bulletin 96-01, nuclear plants supplied either "incore drag data" or "spent fuel pool drag data" for either "withdrawal drag data" or "withdrawal and insertion drag data". The data was analyzed and based on the data trends, the Wolf Creek spent fuel pool withdrawal drag data was compared with the withdrawal drag data from other plants. This analysis revealed the following necessary conditions for incomplete RCCA insertions in 12' fuel assemblies: a) the fast fluence must be greater than 7.5 x 10^{21} nvt (~40 GWD/MTU) and b) the F-spec criteria for the a,b,c
[ ]

The "drag measured after reactor trip" results are presented in Figures 5.1.1, A.1 and A.2. The data in these figures support the IFM susceptibility conclusions.

The Wolf Creek plant drag data and the root cause drag data are presented in Table A.2 and in Figures 5.1.2, A.3 and A.4. The data in these figures support the 14x14 fuel assembly, 15x15 fuel assembly and IFM susceptibility conclusions. The drag test results from the different programs are discussed below.

Wolf Creek - Phase 1

1) Drag Test with Upper Internals in Place
A total of 27 RCCA positions were selected for drag testing with the upper internals in place. They included some assemblies which failed to fully insert, and a sample of assemblies with various burnups. Fuel assembly H16 (hafnium RCCA) was not selected because of the risk that the RCCA could not be reinserted. Since it was necessary to preserve "evidence" within some of the assemblies for future testing, fuel assemblies H03, H53 and H59 were not selected.

The reactor head was previously removed. The RCCA drive shafts remained attached to the RCCAs. A load cell and strip chart recorder were used in conjunction with the crane to withdraw the RCCA from the fuel assembly while recording total weight as a function of axial position of the RCCA in the fuel assembly.

Each of the thrice burned fuel assemblies (Region "H") showed a high drag in both the dashpot and the major diameter of the guide thimbles. With only one exception (assembly H69), all "H" assemblies would have failed the criteria in F-5.1. The twice burned assemblies (Region "J") showed an intermediate drag, and the once burned (Region "K") showed low drag.

On the "H" assemblies, although the highest drag was observed in the dashpot, a relatively high drag was observed over the entire length of the upper guide thimble. The "J" and "K" assemblies exhibited negligible drag in the upper guide thimble, and light to moderate drag in the dashpot.

2) <u>Drag Tests in the Spent Fuel Pool</u>
Sixteen fuel assemblies were selected for this test based on the results of the in reactor tests. The selected RCCAs were latched with a handling tool and withdrawn approximately 108 inches, then reinserted back into the fuel assembly.

In general, the highest drag was observed at the bottom of the dashpot (breakaway). The drag would then decrease to a constant (relatively high) value through the rest of the dashpot. There is usually a sharp decrease as the tips of the RCCA rodlets exit the dashpot. The drag typically a,b,c

[ ]

3) <u>Drag Tests of RCCAs in Reference Fuel Assembly</u>
Seventeen RCCAs were drag tested in a new fuel assembly (L54). In all cases, including hafnium a,b,c

[ ]

The RCCAs show no indications of damage or deformation; therefore, the problem resides within the fuel assembly.

<u>Wolf Creek - Phase 2</u>
Six additional fuel assemblies were selected for drag testing. Two 'G' region and four 'H' region assemblies were tested. The 'G' region assembly burnup values were 35 and 54 GWD/MTU. The 'H' region assembly burnup values were 37.2, 40, 44 and 49 GWD/MTU.

Both 'G' region assemblies showed low drag in the upper guide thimbles. Assembly G33 (35 GWD/MTU) showed low drag in the dashpot and assembly G68 (54 GWD/MTU) showed high drag in the dashpot. Because of the low upper guide thimble drag values it was judged that neither 'G' region assemblies were at risk for the insertion anomaly problem during operation.

The 'H' region assemblies also showed relatively low drag in the in the upper guide thimbles and intermediate to high drag in the dashpot. The drag in the four assemblies could not be differentiated by burnup. Based on the low upper guide thimble drag, it was judged that none of these 'H' region assemblies were at risk of an insertion anomaly during operation. It is noteworthy that even though the upper guide thimble drags were low, they were still on average higher than the 'G' region assemblies tested.

<u>Wolf Creek - H50 Skeleton Assembly</u>
After the fuel rods were removed from fuel assembly H50, a drag check measurement was performed with the dummy RCCA. The purpose was to determine what difference, if any, could be measured with the fuel rods removed. The measurements were taken in the new fuel elevator with the skeleton clamped down.

The drag measured in the empty skeleton was somewhat lower than the drag in the fuel assembly, but was still in the high range. The small decrease in drag indicates that the deformations in the fuel assembly skeleton are primarily plastic (i.e., permanent) rather than elastic or associated with fuel rod loading.

North Anna
Fuel assemblies fabricated for seven different contracts were drag tested in the spent fuel pool Drag test data was not obtained for assemblies 0A1, 0A2, 0A8 and 2A8 because the RCCA would not insert completely into the assembly.

Fuel assembly 3L4 was the only assembly to exceed the F5.1 dashpot and guide thimble drag criteria. Fuel assembly 3L4 (VGIF) displayed high dashpot drag similar to the fuel assemblies that experienced incomplete RCCA insertion at Wolf Creek. However, it should be noted that even the

[ ] a,b,c

at Wolf Creek.

VC Summer
Fuel assemblies fabricated for four different contracts were drag tested in the spent fuel pool. Fuel

[ ] a,b,c

drag has been attributed to the IFMs within these assemblies.

The VC Summer fuel assemblies that were tested had fast fluence values less than or equal to 8.001×10^{21} nvt. The VC Summer assemblies did not display characteristics similar to the Wolf Creek assemblies that experienced incomplete RCCA insertion for comparable fluences.

Point Beach
Fuel assemblies fabricated for four different contracts were drag tested in the spent fuel pool. Fuel

[ ] a,b,c

pounds.

Vogtle
Fuel assemblies fabricated fo: five different contracts were drag tested in the spent fuel pool. Fuel

[ ] a,b,c

upper guide thimble drag has been attributed to the IFMs within these assemblies.

Surry
Fuel assemblies fabricated for six different contracts were drag tested in the spent fuel pool. Two assemblies from region VPIF (0F3 and 0F6), standard design, were drag tested as part of the inspection plan. These assemblies had burnups greater than 49,000 MWD/MTU and showed negligible upper guide tube and dashpot drag.

[ ] a,b,c

South Texas

Fuel assemblies fabricated for four different contracts were drag tested in the spent fuel pool.. In contrast to the Wolf Creek fuel, none of the South Texas Unit 1 fuel assemblies exceeded the F-5.1 upper guide thimble drag criteria. All the significant drag is attributable to the dashpot interference.

a,b,c [ ]

examining the duration and location of distortions (in addition to the drag magnitude) within the fuel assembly guide tubes.

Sequoyah

Fuel assemblies fabricated for seven (7) different contracts were drag tested in the spent fuel pool. Assemblies S74 and F61 exceeded the 100 pound dashpot drag criteria. The fast fluence value for

[ ] a,b,c

Millstone

Fuel assemblies fabricated for two different contracts were drag tested in the spent fuel pool. Nine of the ten fuel assemblies that were tested were fabricated with Vantage 5H fuel features and have burnups of approximately 47 GWD/MTU. All of the Millstone 3 drag data is within the guideline limits.

Figure 5.1.1: Dashpot and Upper Guide Thimble Drag Data
(Drag Measured after Reactor Trip)

a,b,c

Figure 5.1.2: Dashpot and Upper Guide Thimble Drag Data
(Spent Fuel Pool Testing)

a,b,c

5.2 Fuel Assembly and Fuel Rod Growth

Fuel assembly growth data is obtained by using a measuring device that has a dial indicator and comparing the measurement to a standard of known length. The data is corrected for the spent fuel pool water temperature.

a,b,c

[ ]

In Figures 5.2.1 and 5.2.2, the recent assembly growth data is shown for Zircaloy-4 and Inconel [ ] a,b,c

Inconel grids. The assembly and rod growth data summaries are provided below.

<u>Wolf Creek - Phase 1</u>

Twenty-six fuel assemblies were measured for fuel assembly growth. The thimble tube material of [ ] a,b,c

[ ] a,b,c

Rod growth data was obtained on eleven (11) assemblies. Almost all peripheral rods in the "H" [ ] a,b,c

[ ] a,b,c than average growth at higher burnup levels.

Wolf Creek - Phase 2

The fuel assembly length measurements were performed on an additional 8 assemblies. The 'G' assemblies use standard Zircaloy-4 as the thimble tube material, but improved Zircaloy-4 is used for the 'J' and 'H' assemblies.

[ ] a,b,c cycles. Assemblies H35, H67 and H83 were irradiated for two cycles. The assembly growth of the 'H' assemblies is higher than other plant data (including Wolf Creek J assemblies). This also occurs in the lower fluence range.

Rod growth data was obtained for 10 additional assemblies. None of the rods came in contact with [ ] a,b,c

growth values are within the expected limits at comparable burnup levels.

North Anna

Fuel assembly length measurements were performed on 16 assemblies. The thimble tube material for assemblies 2A8, K17, K32, Y08, and X09 is standard Zircaloy-4; the remaining assemblies have thimbles made from Improved Zircaloy-4.

[ ] a.b.c

VC Summer

Fuel assembly length measurements were performed on a total of 8 assemblies. The thimble tube material in assemblies H46 & H51 is Improved Zircaloy-4; assemblies H47 & H50 have standard Zircaloy-4 thimbles; assemblies J09, J10, J13, and J22 have ZIRLO™ thimbles.

[ ] a.b.c

growth. The "J" assembly growth data confirms that ZIRLO™ thimble growth is significantly less than Zircaloy-4 thimble growth.

Point Beach

Assembly length and rod growth measurements were performed on a total of 10 assemblies. The thimble tube material of assemblies V75, V76, V77, V78, Y11, and Z11 is Improved Zircaloy-4. Standard Zircaloy-4 is the thimble tube material for assemblies V17, V20, V22, and V26.

[ ] a,b,c

Vogtle

Fuel assembly length and rod growth measurements were performed on a total of 14 assemblies. The thimble tube material of assembly 5D28 is standard Zircaloy-4; all thimbles in the "F", "G" and "R" assemblies contain Improved Zircaloy-4.

a,b,c

[ ] 0.24 to 0.59% for the "R" assemblies, and 0.20 to 0.55% for the "G" assemblies. The Vogtle rod growth values are slightly lower than the expected results at the higher burnup levels.

Surry

Fuel assembly length measurements were performed on a total of 10 assemblies. Assemblies 0F3, 0F6, 1G0, and 4G1 use standard Zircaloy-4 thimble material, while all of the "H", "J", and "V" F/A thimbles use Improved Zircaloy-4.

[ ] a,b,c

[ ] a,b,c

South Texas

Fuel assembly length measurements were performed on a total of 24 assemblies. The measured

[ ] a,b,c

shows that the South Texas rod growth values are within the expected limits at comparable burnup levels.

<u>Millstone</u>

Fuel assembly length and rod growth measurements were performed on a 10 assemblies. The a,b,c

[ ]

assemblies. The data shows that the Millstone rod growth values are within the expected limits at comparable burnup levels.

<u>Diablo Canyon</u>

Fuel assembly length and rod growth measurements were performed on 16 assemblies. The a,b,c

[ ]

growth values are within the expected limits at comparable burnup levels.

Figure 5.2.1: Recent Fuel Assembly Growth Data - Zr-4 Grids

a,b,c

Figure 5.2.2: Recent Fuel Assembly Growth Data - Inconel Grids

a,b,c

5.3 Single Tube Probe

Fuel assemblies that show relatively high drag in the RCCA test have been selected for this test. Therefore, it is known that there is an interference between the RCCA rodlets and thimble tubes. The objective of this test was to determine the condition of the thimbles with respect to the following:

-Are the dashpots and/or major diameters distorted?
-Are the distortions "bows" or "kinks"?
-Are the distortions localized at a particular elevation?
-Are all the thimble tubes within an assembly distorted?

[ ] a,b,c

Wolf Creek - Phase 1

[ ] a,b,c

Wolf Creek - Phase 2

[ ] a,b,c

North Anna

[ ] a.b.c

a,b,c

[ ]

It is noteworthy that these assemblies had been placed in the spent fuel pool some 18 months prior to the test. No problems were reported in removing RCCAs from these assemblies when they were removed from the core 18 months earlier. It has been experienced from other testing work that assemblies can increase in bow as a function of cooling time. It has been proposed that this is caused by differences in cooling rates between the fuel rod and thimble tubes.

Point Beach

Assemblies Z11 and Y11 have upper guide thimble distortion. The distortion in the dashpot in these assemblies is small when compared to 17x17 fuel designs at similar burnups.

Vogtle

The probe data shows that the fuel assembly upper guide thimbles are only mildly distorted, and [ ] a,b,c

Surry

Single tube probing was conducted on four fuel assemblies at Surry. Assembly 5H1 showed the [ ] a,b,c

a,b,c

Assembly 0V7 has approximately the same burnup as assembly 3J1, but the drag recorded is [ ]

South Texas

Assembly F26 showed the greatest amount of upper guide tube and dashpot distortion. This is consistent with it not allowing complete RCCA insertion and with the very high dashpot drag forces recorded. Assemblies F01, F25, F26, F53 and F64 were not drag tested since the RCCA [ ] a,b,c

Sequoyah

[ ] a,b,c

[ ] a,b,c

Millstone

Single tube probing was conducted on fuel assembly F02 at Millstone 3. Based on the RCCA drag a,b,c

[ ]

Diablo Canyon

Single tube probing was conducted on two fuel assemblies at Diablo Canyon Unit 1. The assemblies (T78H and T80H) were selected based on their containing the same thimble tube material lot as the assemblies at Wolf Creek which experienced the RCCA insertion anomaly.

[ ] a,b,c

5.4 Guide Thimble Borescope Examinations

Borescope examinations were conducted on all guide thimbles based upon the results of their RCCA drag force measurements and their burnup. Every guide thimble in the selected assemblies was examined to determine:

-The presence of obvious physical anomalies and the general condition of the tube;
-The presence of debris or debris-related scarring on the thimbles; and
-The quantity and severity of wear marks believed to be present in the guide thimbles based upon their drag force results.

Wolf Creek

[ ] a,b,c

South Texas

a,b,c

5.5 Assembly Bow

The bow measurements were performed at Wolf Creek and South Texas 1. At Wolf Creek during phase 1, the plumb bob method was used to measure assembly bow. During the Wolf Creek phase 2 and the South Texas 1 campaigns, alternative methods were used to obtain an indication of the distortion within the assemblies.

Wolf Creek - Phase 1

a,b,c

The string is fixed at the top and bottom nozzles for the profile view and direct view methods. In both methods, the corrected bow is also obtained from the measured distance between the string and the grid's edge. The profile view and the plumb bob methods are similar since the bow is measured parallel to the assembly face. In the direct view method the bow is measured normal to the assembly face.

a,b,c

Figure 5.5.1: Fuel Assembly H50, Face 3 Bow Data - Direct View

Figure 5.5.2: Fuel Assembly H50, Face 4 Bow Data - Direct View

a,b,c

[ ]

South Texas

The bow for assemblies F26, F32, F37 and F41 was measured by two methods (direct view & profile view). Care must be used when interpreting the data because the data inaccuracy is greater than .1 inch.

a,b,c

[ ]

a,b,c

Figure 5.5.3: South Texas 1 Assembly Bow Data - (Vector Added)

6.0 Empirical Observations of Growth Data

A statistical analysis was performed on the assembly growth and thimble tube and dashpot drag data. The correlations were made to power history data for each assembly, which is found in Appendix B. This history data is for 127 assemblies from 12 different plants. The data includes growth and individual cycle properties for each assembly such as relative power, EFPY, burnup, coolant inlet temperature, delta temperature across the core, and the core average power density.

It is difficult to draw any unequivocal conclusions in a "statistical sense" primarily since the data base was based on information gathered from the site tests. In the site tests the focus was on high burnup, design variety and manufacturing chronology. The focus was not on "designing an experiment" which would yield statistically significant results.

In Figure 7.1, the relationship between growth and fluence as a function of core average outlet Temperature (T_{HOT}) for three cycle fuel. The data is separated into two populations, T_{HOT} greater than and less than 615°F. Figure 7.2 shows similar information for two cycle fuel.

The following trends were observed:

[(1) There is higher growth associated with higher drag force in the thimble tubes.

] a,b,c

(3) This accelerated growth occurred only at Wolf Creek and predominantly in H assemblies.
(4) G assemblies also showed accelerated growth, but this began at a higher fluence.
(5) The accelerated growth can be associated with high coolant outlet temperature plants. However, there are other factors which influence growth besides temperature, since high temperature plants exist that do not have high growth.
(6) This outlet temperature effect seems to be a plant effect and not an individual assembly effect.
(7) This accelerated growth is associated with three cycle operation. However, there are factors which influence growth besides the number of cycles, since many three cycle assemblies do not have high growth.
(8) Low first cycle and high second cycle power is associated with high growth, but only at Wolf Creek.
(9) Low first cycle and high second cycle power is associated with high drag values.

Growth Vs Fluence

a,b,c

[ ]

Figure 7.1: Three cycle assembly Growth as a function of average fluence that the assembly has seen. The plant average coolant outlet temperature is either greater or less than 615°F.

Growth Vs Fluence

[ ] a,b,c

Figure 7.2: Two cycle assembly Growth as a function of average fluence that the assembly has seen. The plant average coolant outlet temperature is either greater or less than 615°F.

7.0 Susceptibility Conclusion

Based on plant trip information, site test results and observations of growth data, Westinghouse presented the following susceptibility conclusions to the NRC on June 27, 1996:

- Based on the data and analysis to date, fuel with IFMs are not susceptible to incomplete insertion.
- The manufacturing period does not affect the susceptibility to incomplete insertion.
- Twelve foot Westinghouse fuel is not susceptible below a burnup of 40,000 MWD/MTU.
- Based on the data to date, while it does appear that 14x14 and 15x15 fuel are less susceptible, it is difficult at this time to make a definitive conclusion.

8.0 Materials Investigations

8.1 Unirradiated Materials Testing

The objective of these tests were to characterize archived samples of tubes from the same lots used in the fabrication of the Wolf Creek "H" assemblies. After the materials properties were characterized it could be determined if the thimble tubing was typical or if there were some anomalous tube conditions.

Dimensions
The dimensions of the thimble tubes used in the Wolf Creek assemblies had been inspected prior to their release for use in skeleton fabrication. To verify that the dimensions did not have significant deviations, the 36 inch long archive samples from eleven thimble tube lots were retrieved and dimensionally inspected using the standard production ultrasonic inspection units. The outer diameter, inner diameter, and the wall thickness of the tubes were measured and recorded on charts. All dimensions were found to be well within the drawing limits and close to nominal. The wall thickness variations were less than 50% of the in-house limits and the diameters were typically within 50% of the allowable tolerance range around the nominal drawing dimension.

It is concluded that there are no dimensional anomalies in the tubes and that there would be no abnormal impact on the tube performance from a dimensional perspective.

Tensile Testing
Sections were taken from six of the archive tubes and a room temperature tensile test was performed on the samples. The 0.2% yield strength and ultimate strength were recorded and compared to the average of 104 production lot tests. The mechanical properties of the archive tubes were near the average for the production lots and within the normal range of values obtained from past and current tube lots. Samples from the thimble tube lots are tensile tested prior to the lot release and the original lot values were reviewed and found to be typical.

It is concluded that there are no anomalous conditions in the tensile properties of the Wolf Creek thimble tubes and that the material was typical of recrystallized annealed tubing.

Crystallographic Texture
It is generally agreed that the crystallographic texture can influence the degree of irradiation growth. The irradiation growth is related to texture by the (1-3F) term where "F" is the texture factor or Kearns number for a specific tube direction; axial, radial, or circumferential. The axial texture influences the irradiation growth along the thimble tube length. The texture was measured on 2 samples from the Wolf Creek archive tubes and compared to results from three samples taken from tubes produced in the same time frame, three lots made over two years prior to the Wolf Creek production and one current lot. The direct pole method was used to determine the tubing texture. The Wolf Creek results were equivalent to and within the range of the other samples.

It is concluded that the texture in the wolf Creek thimble tubes is typical of normal production and that texture differences are not present or a factor in the observed high growth of the Wolf Creek "H" assemblies.

Material Chemistry
The chemistry or alloying and impurity element levels are measured at the ingot stage. The ingot chemistry certifications were reviewed and no deviant chemistry conditions were observed. To further verify the material chemistry, samples were taken from eleven archive tubes and tested for alloy element levels. The tin, iron, and chrome levels in all the samples were well within the specification limits and at nominal levels.

It was concluded that there were no deviant chemistry conditions associated with the thimble tube lots.

Conclusion
The unirradiated material testing performed on the archive tube samples representing the thimble tube lots used in the fabrication of the Wolf Creek "H" assemblies indicates that there are no anomalous conditions present that would contribute to increased irradiation growth or thimble tube distortion.

8.2 Manufacturing Process

The thimble tube manufacturing process was reviewed to determine if there was any changes made that would contribute to an increase in the thimble tube irradiation growth rate.

Timeline

[ ] a,b,c

Ingot Processing
The "H" assemblies thimble tubes were fabricated from material produced from twelve ingots. These twelve ingots were melted over an eight month time span; thus, there is no single ingot source or small production time window in which an anomalous condition could have occurred and contributed to the observed thimble tube growth. The data reported for each ingot was reviewed and all met the specification requirements and deviations were observed.

Tube Lot Processing
There are 23 thimble tube lots associated with the "H" assemblies. The lots were produced over a six month time frame and two separate production runs were involved. There was no single or small group of lots or a small production window in which an anomalous condition could have occurred and contributed to the observed thimble tube growth.

A thimble tube lot nominally contains 240 tubes. About 40% of the tubes in the 23 lots were used in the Wolf Creek assemblies and the remaining were used to fabricate fuel for other reactors.

Table 8.2.1 lists the thimble tube lots made in the same time frame and that are of equivalent design to the "H" assembly thimble tubes. About 85% of the thimble tubes produced in the 54 lots from the two thimble tube runs were used in skeleton fabrication for other, non-Wolf Creek fuel.

During recent reactor site examinations, the assemblies at two sites which had thimble tubes from the same lots as Wolf Creek were evaluated. The irradiation growth of the assemblies at Diablo Canyon and Vogtle have normal growth and do not show the accelerated growth observed at Wolf Creek. Figure 5.2.1 shows a plot of the assembly growth of the various reactors and the specific assemblies at Vogtle and Diablo Canyon with the same thimble tube lots as Wolf Creek are noted.

It is concluded that there was no thimble tube processing anomaly associated with the Wolf Creek thimble tubes that would impact the observed high growth.

8.3 Hot Cell Examination and Tests

The hot-cell examination scope for the RCCA insertion anomaly included the following:

1. Visual examination of the skeletons (H38 and H50)
2. Spanwise growth measurements for the selected spans
3. Thimble tube diameter and bow measurements
4. Metallography
5. Hydrogen content

The table below shows the relationship between assembly span number and section numbers.

Span		Section
Top	7	1-1
	6	1-2
	4	2-2
	2	4-1
Bottom	1	4-2

Visual Examination

Components of both skeletons were visually examined through the hot cell windows and selected features were examined through a periscope at magnifications up to 4x. The major purpose of these inspections were to assess both the overall mechanical integrity and the corrosion appearance of the visible portion of the components. These inspections then provided a basis for selecting metallographic and mechanical test specimens. Specific components which were visually examined included thimble tubes, grids, bulge joints, and sleeves.

a,b,c

The initial examination of the skeletons as seen through the hot cell windows, indicated that they [ ]

corrosion on skeleton components.

Table 8.2.1: Thimble Tube Lots of equivalent Wolf Creek "H" Assembly Design

Ingot	Lot Number	W/C "H" Assembly
2240	W30-6561	12
	W30-6556	
	- -6564	
2204	W30-6588	3
	W30-6589	
2246	W30-6638	
	W30-6639	26
	W30-6640	
	W30-6777	
	W30-6778	31-32-35-41-42-43
	W30-6779	28
	W30-6780	1-2-6-9-15-22-27-30-37-38
	W30-6781	21
2273	W30-6815	
	W30-6816	5-7-8-11-13-16-20-39-40
	W30-6817	
	W30-6818	
	W30-6819	4-10-14-17-18-19-23-24-25
	W30-6820	
2332	W73-7179	34-36
2333	W73-7226	33
	W73-7222	
	- -7231	
2304	W73-7263	
	W73-7264	
	W73-7265	44
	W73-7266	
2304	W73-7267	
	W73-7280	
	W73-7281	
	W73-7282	59
	W73-7283	46-51-66-75-(80)
	W73-7284	53-58-74-82-(80)
2336	W73-7311	
	W73-7312	61-71-76-77-78-81
	W73-7313	
	W73-7314	54-56-57-63-64
	W73-7353	
2344	W73-7354	
	W73-7355	49-55
	W73-7356	47-48-69
	W73-7357	52-62-72-73-79
	W73-7358	
2379	W73-7543	
	W73-7544	45-60-65-67-68-70-84
	W73-7545	83
2381	W73-7556	50
	W73-7557	
	W73-7558	
	W73-7559	
	W73-7560	
	W73-7561	
	W73-7566	
	W73-7724	

[ ] a,b,c

Spanwise Growth Measurements

Spanwise growth measurements were performed on three sections with two grids in place and in

[ ] a,b,c

Thimble Tube Diameters and Bow Measurements

These measurements were made using a laser micrometer and a translation/rotation system controlled by a PC. The measurements were made at 15° rotation azimuthally and at 1 inch increments along the length on selected tubes from spans 7, 6, 4, 2, and 1. The selected tubes represent the extremes of the burnup, interference, and the individual probe profiles from the site examination. The measured average diameters are tabulated in Table 8.3.3.

[ ] a,b,c

Table 8.3.1: Skeleton Assembly H38 Spanwise Growth Data

a,b,c

[ ]

Table 8.3.2: Skeleton Assembly H50 Spanwise Growth Data

a,b,c

Table 8.3.2: Skeleton Assembly H50 Spanwise Growth Data (continued)

a,b,c

Figure 8.3.1: Skeleton Assembly H50 Measured Span Growth

a,b,c

[ ]

Note: Parenthesis show estimated growth

Table 8.3.3: Measured Average Diameters

a,b,c

Figure 8.3.2: Assembly H50 Profile with Oxide, Hydrogen and Dimensional Changes

a,b,c

[ ]

Note: % values are based on nominal drawing dimensions

Figure 8.3.3: Assembly H50 Bow Vectors

a,b,c

Figure 8.3.4: Assembly H50 Maximu and Average Bow for the Measured

a,b,c

Figure 8.3.5: Assembly H50 Thimble Tube Outside Diameter vs Axial Position

[ ] a,b,c

Figure 8.3.6 : Assembly H50 Thimble Tube Outside Diameter Change vs Axial Position for Spans 6 & 7

a,b,c

Figure 8.3.7: Assembly H50 Thimble Tube Ovality vs Axial Position for Spans 6 & 7

a,b,c

Metallography (H50)
Selected transverse and longitudinal sections of the thimble tubes from assembly H50 were metallographically examined to determine the oxide thickness on the OD and ID of the specimen. The samples were then etched with a suitable chemical reagent to observe the hydride morphology.

Initial thimble tube results showed that the OD and ID oxide thickness were the same, although there may be a slight trend for ID oxide to be thicker than the OD oxide. A definitive conclusion [ ] a,b,c

Hydrogen Content (H50)
Hydrogen content in the thimble tube specimens was determined by LECO Corporation Hydrogen Determinator equipment. The method consists of fusing a small specimen with a flux and driving the released hydrogen using Argon carrier gas. The hydrogen content is determined by change in the conductivity of the carrier gas. Special standards were prepared by hydriding Zircaloy-4 thimble tubes to known levels of hydrogen content to calibrate the equipment. The hydrogen samples were taken from tube sections adjacent to the metallographic specimens to correlate the oxide thickness and hydrogen content. The measured values are shown in Table 8.3.5 with corresponding oxide thickness values. The measurement technique has an accuracy of about ±15% and therefore, an average of several measurements at each location should be used to obtain an estimate of the hydrogen content. Since the measurements are still continuing, the data shown in Table 8.3.5 should be considered preliminary.

Table 8.3.5: Hydrogen Content of Assembly H50 Samples

a,b,c

[ ]

9.0 Materials Growth Models

9.1 Oxide/ Hydrogen Growth

The objective of these tests was to determine the impacts of surface oxide and internal hydride formation on the thimble tube growth. It is known that there is about a 50% volume expansion when the zirconium metal is converted to oxide. As the oxide is formed on the inner and outer surfaces of the thimble tubes this volume expansion produces stresses and resultant creeping of the base material. These dimensional changes have been documented by Donaldson in ASTM STP 1132 and Hillner in WAPD-TM-307 to list a few.

During the oxide formation in a water or steam environment, there is some hydrogen released during the reaction and a portion of the hydrogen is absorbed into the base metal. This hydrogen forms hydrides which have nominally a 16% volume expansion over the metal that it replaces. This volume expansion also produces stresses which result in material growth/creep.

Testing was performed and is continuing to determine the specific impacts on thimble tube growth from the formation of the oxide and hydrides during reactor operation. Specifically some thimble tube samples were exposed to an accelerated corrosion test in 600°F and 680°F water with 700 PPM lithium and the length and diameter changes were measured as a function of the surface oxide thickness. Figures 9.1.1 and 9.1.2 are plots of the results. The dimensional changes are significant and are due both to the oxide and hydride formation.

a,b,c

Figure 9.1.1: Corrosion Impacts on Length Changes in Zircaloy-4 Thimble Tube Samples (680degF, 700 ppm Li Water Tests)

a,b,c

[ ]

Figure 9.1.2: Corrosion Impacts on Diameter Changes in Ziracoloy-4 Thimble Tube Samples (680 degF, 700 ppm Li Water Test)

[ ] a,b,c

Figure 9.1.3: Hydrogen/ Hydride Impact on Growth

a,b,c

Figure 9.1.4: Oxide Impact on Growth

[ ] a,b,c

Figure 9.1.5: Estimate of Oxide and Hydride Impact on Assembly H50 Measured Growth

a,b,c

Note: Values in parenthesis represent growth difference between measured and estimated oxide/hydride impacts

From the hot cell examination of thimble tubes from assembly H50 the oxide thickness and hydrogen levels are know at various locations along the assembly length. Applying the unirradiated hydrogen and oxide growth factors developed from the autoclave and hydride tests an estimate of the oxide/hydride contributions to the measured assembly growth has been made and is summarized in Figure 9.1.5. The estimated growths are compared to the measured growth in the a,b,c

9.1.2 Accelerated Growth

A number of factors combine to produce the observed thimble tube growth. Simplified, the total a,b,c

particular there are numerous industry reports that correlate c-loop dislocation densities with accelerated growth. The c-loop dislocations increase at the higher temperature and at the higher fluences.

Temperature and fluence are reported to be significant factors in both the formation of the c-loops and their stabilization by dissolution of iron/chrome precipitates into the matrix. Temperature and exposure time are also significant factors in the oxide and hydride formation rates. It is postulated that the c-loop dislocation increase combined with vacancy/interstitials formed and the stresses from the oxide/hydride formation result in an increase in the growth rate observed at the higher fluences and temperatures.

There is not much published information on the accelerated growth rates for the specific temperature/fluence/material represented by the Wolf Creek assemblies. The information that is available was reviewed and industry experts were consulted regarding the observations of the accelerated growth. From the available information an empirical model for irradiation growth with an accelerated growth factor for the higher temperature and fluence was extrapolated for use in the mechanical model development (see Section 10).

10.0 Mechanical Model - Thimble Tube Distortion

Description

A mechanical model has been developed to calculate thimble tube distortion. Input to the model includes:

a,b,c

[ ]

[ ]a,b,c

Typical outputs at each time step include:

- Assembly growth
- Assembly holddown spring load
- Assembly lateral bow per grid
- Clad elastic modulus per span
- Fuel rod axial load per span
- Fuel rod growth per span
- Grid drag per grid
- Thimble oxide thickness per span
- Thimble axial creep per span
- Thimble axial growth due to oxide per span
- Thimble axial load per span
- Thimble axial stress free irradiation growth per span
- Thimble elastic modulus per span
- Thimble lateral bow per span

Model Benchmarking

With any model of this nature and complexity, one must perform sufficient benchmarking to assure that the code can adequately address a range of designs and empirical observations. First, the model was checked against Wolf Creek assembly H50. This assembly was chosen since it had the longest growth, highest drag, and significant hot cell data available for comparison.

[ ] a,b,c

Table 10.1 and 10.2 show the measured versus predicted span lengths and bows. Notice the order/relative magnitude of the span lengths are predicted, as well as the absolute magnitude. The

[ ] a,b,c

Table 10.1: Measured and Predicted Span Length
H50

[ ] a,b,c

Table 10.2: Measured and Predicted Span Bow (mils)
H50

[ ] a,b,c

Additional "Qualitative" Model Assessments

In order to test the models credibility against criteria other than fuel assembly growth, three assembly types were analyzed with respect to span bow predictions. H50, which was previously

discussed, as well as Wolf Creek assembly J32 and South Texas assembly F26. The following observations of the results (Figures 10.3 - 10.5) are of interest.

[ ] a,b,c

Conclusions

As illustrated in Figures 10.1 and 10.2, the model predicts the fuel assembly growth differences between Wolf Creek "H", "J", and South Texas reasonably well.

Figure 10.1: Measure vs Predicted Assembly Growth

a,b,c

Figure 10.2 : Predicted and Measured Assembly Growth

a,b,c

Figure 10.3: Wolf Creek F/A H50
Span Bow vs Fast Fluence

a,b,c

Figure 10.4: Wolf Creek F/A J32
Span Bow vs Fast Fluence

a,b,c

Figure 10.5: South Texas F/A F26

Span Bow vs Fast Fluence

a,b,c

11.0 Root Cause Conclusions

The following conclusions were drawn based on the results of the detailed test programs and analysis:

1. The trip history data from the plants demonstrated that there were a significant number of assemblies operating at high burnup levels under control rod locations without showing insertion problems.

2. Review of the available worldwide experience indicated that in almost all cases that RCCA insertion problems have been reported (other than those cases that have been attributed to debris of Control Rod drive mechanism problems), the causes were related to excessive compressive loads on the fuel assembly guide thimble tubes.

3. The detailed manufacturing review indicated that this problem was not related to a manufacturing anomaly. Additionally, thimble tubes in other plants from the same lot and similar burnups as Wolf Creek did not show unusual growth, thereby confirming that this was not a manufacturing related issue.

4. A detailed review of plant operations and fuel management showed that the Wolf Creek assemblies that showed incomplete insertion were somewhat unique in their power history behavior. These assemblies operated for three cycles with relatively high power in the second and third cycles in a high temperature environment.

5. The results of the growth measurements showed that fuel assemblies that showed high growth were only seen in the high temperature plants. However, high temperature seemed to be a necessary but not a sufficient condition for high growth. For high temperature plants, specific power histories seemed to influence growth, especially those that have long residence times and high power in the later stages of operation.

6. The hot cell results from the two incomplete insertion assemblies showed that a significant portion of the growth was related to oxide formation. As well known, oxide formation is a strong function of temperature and residence time. Also, the remainder of the growth was greater than what would be expected for normal saturation growth. This component was attributed to accelerated growth, a phenomenon that is reported in the literature and is shown to be very temperature sensitive.

7. Data from the literature on Zircaloy growth suggested that depending on the temperature and fluence level, accelerated growth could occur. This growth would proceed after an incubation period. The point at which this growth would initiate, as well as the slope of the growth versus fluence curve was very temperature dependent. It is postulated that the high temperature in the later cycles of operation (consistent with the incubation period theory) would exacerbate the accelerated growth mechanism.

8. The detailed mechanical model predicted the growth differences between the Wolf Creek incomplete insertion assemblies, the Wolf Creek complete insertion assemblies and the South Texas assemblies reasonably well. In addition, the model was able to reasonably reproduce the span dependent bow measurements that were obtained from the hot cell on the Wolf Creek incomplete insertion assemblies. This model used a free growth correlation with the

accelerated growth component normalized to the actual growth measurement from one of the Wolf Creek incomplete insertion assemblies.

Based on the above information for Westinghouse data and models for Westinghouse fuel, the root cause conclusions are as follows:

- The incomplete RCCA insertions observed at Wolf Creek have been caused by excessive compressive loads on the fuel assembly guide thimble tubes leading to excessive thimble tube distortion.
- For Wolf Creek, the increased compressive load was caused by unusual fuel assembly growth over and above what would normally be expected as a result of irradiation exposure.
- The unusual growth component is a combination of growth due to oxide accumulation and accelerated growth, both of which are temperature sensitive.
- The unusual growth is observed only in high temperature plants on those high burnup fuel assemblies that have certain types of power histories.
- The apparent cause of the incomplete Rod Cluster Control Assembly insertion at the South Texas Project is fuel assembly thimble tube distortion resulting from high, in-vessel, compressive loading imparted on the assembly skeleton. The problematic distortion is limited to the assembly dashpot area of the thimble tubes which prevents complete control rod insertion. Westinghouse will continue to work with the South Texas Project to identify the root cause, along with short and long term corrective actions. The final conclusions of this control rod insertion anomaly will be documented in future Nuclear Regulatory Commission Bulletin 96-001 correspondence.

Appendix A

Site Test Data

Table A.1: Fuel Features of Root Cause Test Assemblies

a,b,c

Table A.2: Summary of Plant Data

a,b,c

Table A.2: Summary of Plant Data

a,b,c

Table A.2: Summary of Plant Data

a,b,c

Table A.2: Summary of Plant Data

a,b,c

Table A.2: Summary of Plant Data

a,b,c

Table A.2: Summary of Plant Data

a,b,c

Figure A.1: Dashpot Drag and Fast Fluence Data
(Drag Measured after Reactor Trip)

a,b,c

Figure A.2: Upper Guide Thimble Drag and Fast Fluence Data
(Drag Measured after Reactor Trip)

a,b,c

Figure A.3: Dashpot Drag and Fast Fluence Data
(Spent Fuel Pool Testing)

a,b,c

Figure A.4: Upper Guide Thimble Drag and Fast Fluence Data
(Spent Fuel Pool Testing)

[ ] a,b,c

Appendix B
Power History Data for the Statistical Analysis

The data used to draw Figures 7.1 and 7.2 in this report and on which the statistical analysis is based is presented in this Appendix. The following list gives an explanation of each of the columns in the data table and how they were determined. The actual data table starts on the next page.

a,b,c

Appendix B (continued): Power History Data for Statistical Analysis

a,b,c

Appendix B (continued): Power History Data for Statistical Analysis

a,b,c

Appendix B (continued): Power History Data for Statistical Analysis

a,b,c

Appendix C

Plant Reports