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BRAIDWOOD UNIT 1
TECHNICAL SUPPORT FOR CYCLE 5
STEAM GENERATOR
INTERIM PLUGGING CRITERIA

FEBRUARY 1995

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1.0 INTRODUCTION

This WCAP revision modifies Section 4.7 of Revision 1 of this document, issued in August of 1994. Section 4.7 identifies tubes that are to excluded from the IPC criteria due to the potential for tube deformation under combined LOCA + SSE loads in the vicinity of wedges that react the tube bundle load. Further details of the loading mechanism and plate response under the LOCA + SSE loads follow in Section 4.7.

Since none of the other sections of the WCAP are being modified, only the modified Section 4.7 is included as part of this document. Because the modified Section 4.7 contains a different number of tables and figures than in the Revision 1 document, table and figure numbers in this revision start with the number 4-1 and continue successively to the end of the section.

There are two principal changes made in the revision to Section 4.7. The first concerns the applied loads used in performing the calculations. In the analysis documented in Revisions 0 and 1 of the WCAP, the calculations to define the tubes potentially susceptible to deformation under LOCA plus SSE loads were performed on a conservative upper bound basis, such that there were no specific loads specified for the tube support plates. As part of this revision, however, calculations were performed to approximate plate loads for the Byron Unit 1 and Braidwood Unit 1 steam generators. A summary of the analysis methodology and results is presented.

The second change in Section 4.7 from the prior WCAP revisions deals with the criteria used for excluding tubes from the IPC. In the prior versions of the report, tubes were excluded that could potentially collapse under the post LOCA secondary to primary pressure gradient. For the present analysis, a more limiting criteria is used. Tubes are now excluded if the change in tube diameter resulting from the plate deformation is greater than [ ]^{a,c} inch.

The results of the revised analysis show that the prior upper bound methodology resulted in a conservative estimate of the number of tubes to exclude for the lower plates (B(2C) - K(7C))[1], even using a more limiting criteria for the present analysis. Thus, the revised analysis results in a reduction of the number of tubes to exclude for these plates. For Plates L(8) - N(10), the number of excluded tubes is nearly the same for this analysis ([ ]^{a,c} versus [ ]^{a,c}), as in the earlier analysis. Results for the top plate, which experiences significant LOCA forces, show a significant increase in the number of excluded tubes. For the limiting wedge locations, the number of excluded tubes has increased from [ ]^{a,c} in the prior analysis to [ ]^{a,c} in this evaluation.

It should be noted that the results presented below do not affect the summary of results and overall conclusions presented in Section 2 of Revision 1. The only affect of the revised analysis is to modify the number and location of the tubes to be excluded from the IPC due to the potential of tube deformation under combined LCOA plus SSE loads.

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1 Numbers in parentheses correspond to plate numbering scheme used by Byron / Braidwood

4.0 ACCIDENT CONSIDERATIONS

4.7 Tubes Subject to Deformation in a SSE + LOCA Event

This section deals with accident condition loadings in terms of their effects on tube deformation. The most limiting accident conditions relative to these concerns are seismic (SSE) plus loss of coolant accident (LOCA). For the combined SSE + LOCA loading condition, the potential exists for yielding of the tube support plate in the vicinity of the wedge groups, accompanied by deformation of tubes and subsequent loss of flow area and a postulated in-leakage. Tube deformation alone, although it impacts the steam generator cooling capability following a LOCA, is small and the increase in peak clad temperature (PCT) is acceptable. Consequent in-leakage, however, may occur if axial cracks are present and propagate through wall as tube deformation occurs. This deformation may also lead to opening of pre-existing tight through wall cracks, resulting in primary to secondary leakage during the SSE + LOCA event, with consequent in-leakage following the event. In-leakage is a potential concern, as a small amount of leakage may cause an unacceptable increase in the core PCT. Thus, any tubes that are defined to be potentially susceptible to significant deformation under SSE + LOCA loads are excluded from consideration under the IPC.

4.7.1 SSE Analysis

Seismic loads result from motion of the ground during an earthquake. The SSE excitation of the steam generator is defined in the form of acceleration response spectra at the steam generator supports. To perform the non-linear time history analysis, it is necessary to convert the response spectra input into acceleration time history input. Acceleration time histories for the nonlinear analysis are synthesized from El Centro Earthquake motions, using a frequency suppression / raising technique, such that the resulting spectrum in each of the orthogonal axes closely envelopes the original specified spectrum. The resulting three orthogonal time histories are then applied simultaneously at each steam generator support to perform the analysis.

The analysis is performed using the WECAN finite element computer program. The mathematical model consists of three-dimensional lumped mass, beam, and pipe elements as well as general matrix input to represent the specific steam generator piping stiffnesses. The TSP-shell interaction is represented by a rotating, concentric gap-spring dynamic element, using impact damping to account for energy dissipation at these locations. The primary loop piping and the lower column support stiffnesses are input as 6x6 matrices. The upper and lower lateral support restraints are represented by compression-only (single-acting) spring elements, with the shell flexibility included for the upper support stiffnesses. At the lower elevation, the support structure is connected to a relatively rigid channel head-foot combination. In modeling the tube bundle internals-to-shell interface, the TSP local shell stiffness, obtained from detailed finite element analyses, is also included.

The tube bundle geometry is shown in Figure 4-1, with the flow baffles and support plates identified. The flow baffles (B(2C), E(4C), H(6C)) are typically not included in the seismic model, both due to the difficulty in representing them accurately in the model, and also because it is conservative in terms of tube stresses to exclude them from the model. If the baffles were included in the model, it is anticipated that contact impact loads for the

lower plates would be distributed among the various plates and baffles resulting in reduced loads. However, it is difficult to estimate these loads, due to the flexible nature of the partition plate which forms one of the support members for these plates. For the flow baffles, it is concluded to be conservative to use the loads developed for the support plates (C/D(3), F/G(5), J/K(7)).

In the absence of a plant specific seismic analysis for Byron Unit 1 and Braidwood Unit 1, a conservative estimate was made of the tube support plate loads using results from two non-linear analyses for plants having similar model steam generators. The spectra for these two plants were selected because of similar frequency content in one case, and because of a bounding acceleration level in the other. For the plant with the similar frequency content, the acceleration levels were not as high as for Byron / Braidwood, so the plate loads were scaled by the ratio of the acceleration levels. Plate loads were then selected for each plate using the higher of the results for these two plants. A summary of the resulting plate loads is provided in Table 4-1. It is observed that the plate load for the bottom plate is quite low, and would not produce any significant deformation of the plate. Thus, Plate A (1) is not considered further. For the remaining plates, the seismically induced load is approximately [ ][a,c] kips. To provide some additional conservatism to account for possible geometrical and support variations, and for spectra frequency content effects, [ ][a,c] kips is used for the seismically induced plate load in calculating the resulting plate deformations.

4.7.2 LOCA Analysis

LOCA loads are developed as a result of transient flow, and temperature and pressure fluctuations following a postulated primary coolant pipe break.[2] As a result of a LOCA event, the steam generator tubing is subjected to the following loads:

1) Primary fluid rarefaction wave loads.

2) Steam generator shaking loads due to the coolant loop motion.

3) External hydrostatic pressure loads as the primary side blows down to atmospheric pressure.

4) Bending stresses resulting from bow of the tubesheet due to the secondary-to-primary pressure drop.

5) Bending of the tube due to differential thermal expansion between the tubesheet and first tube support plate following the drop in primary fluid temperature.

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[2] Based on the prior qualification of the Byron / Braidwood steam generators for leak before break requirements for the primary piping, the limiting LOCA event is one of the branch line breaks. However, bounding LOCA load calculations for Byron Unit 1 / Braidwood Unit 1 are not available for the smaller breaks. As a conservative approximation, the available LOCA loads for the primary piping breaks are used to bound the smaller pipe breaks. The large pipe break loads have been shown for other model steam generators to be several times larger than the smaller pipe breaks, and thus, it is judged that these loads form a conservative basis for the small pipe breaks for Byron Unit 1 / Braidwood Unit 1.

Loading mechanisms (3) through (5) above are not an issue since they are a non-cyclic loading condition and will not result in crack growth, and/or result in a compressive membrane loading on the tube that is beneficial in terms of negating cyclic bending stresses that could result in crack growth.

<u>LOCA Rarefaction Wave Analysis</u>

The principal tube loading during a LOCA is caused by the rarefaction wave in the primary fluid. This wave initiates at the postulated break location and travels around the tube U-bends. A differential pressure is created across the two legs of the tube which causes an in-plane horizontal motion of the U-bend. This differential pressure, in turn, induces significant lateral loads on the tubes.

The pressure-time histories input to the structural analysis are obtained from transient thermal-hydraulic (T/H) analyses, using the MULTIFLEX computer code. A break opening time of 1.0 msec of full flow area, simulating an instantaneous double-ended rupture is assumed to obtain conservative hydraulic loads. The fluid-structure interaction effect due to the flexibility of the divider plate between the inlet and outlet plenums of the primary chamber is included in the analysis. Pressure time histories are calculated for two tube radii, identified as the average and maximum radius tubes. A plot showing the tube representation in the T/H model is provided in Figure 4-2. Typical primary pressure time-histories following a LOCA are shown in Figure 4-3 for nodes 8 through 15 (in Figure 4-2) on the cold leg of the largest radius U-bend. For the structural evaluation, the tube loads result from the hot-to-cold leg ΔP. Plots showing the hot-to-cold leg ΔP for the maximum and average radius tubes are provided in Figures 4-4 and 4-5, respectively.

For the rarefaction wave induced loadings, the predominant motion of the U-bends is in the plane of the U-Bend. Thus, the individual tube motions are not coupled by the anti-vibration bars. Also, only the U-bend region is subjected to high bending stresses. Therefore, the structural analysis is performed using single tube models limited to the U-bend and the straight-leg region over the top two TSP's. The tube structural model, shown in Figure 4-6, consists of three-dimensional straight and curved pipe elements. The mass inertia is input as effective material density and includes the weight of the tube, weight of the primary fluid inside the tube and the hydrodynamic mass effects of the secondary fluid. Damping coefficients are defined to realize a maximum damping of 4% at the lowest and highest significant frequencies of the structure.

To account for the varying nature of the tube/TSP interface with increasing tube deflection, three sets of boundary conditions are considered. For the first case, the tube is assumed to be laterally supported at the TSP, but is free to rotate. This is designated as the "continuous" condition, as the finite element model for this case models the tube down to the second TSP. As the tube is loaded, it moves laterally and rotates within the TSP. After a finite amount of rotation, the tube will become wedged within the TSP and is no longer able to rotate. The second set of boundary conditions, therefore, considers the tube to be fixed at the top TSP location, and is referred to as the "fixed" case. Continued tube loading causes the tube to yield in bending at the top TSP and eventually a plastic hinge develops. This represents the third set of boundary conditions, and is referred to as the "pinned" case.

For the average radius tube, only the continuous case is analyzed. Results for the continuous case analysis indicate that both the tube rotations and moments at the TSP nodes are small compared to those required to cause the locking-in or plastic hinge, respectively, at the support locations. Since the main objective in analyzing the average radius tube is to determine the maximum reaction load on the TSP due to the overall response of the tube bundle, the continuous configuration is the most appropriate for the average radius tube analysis. Each of the dynamic solutions results in a force time history acting on the TSP. These time histories show that the peak responses do not occur at the same time during the transient. However, it is assumed for this analysis that the maximum reaction forces occur simultaneously. Using these results, a TSP load corresponding to the overall bundle is then calculated.

<u>LOCA Shaking Loads</u>

Concurrent with the rarefaction wave loading during a LOCA, the tube bundle is subjected to additional bending loads due to the shaking of the steam generator caused by the break hydraulics and reactor coolant loop motion. However, the resulting TSP loads from this motion are small compared to those due to the rarefaction wave induced motion.

To obtain the LOCA induced hydraulic forcing functions, a dynamic blowdown analysis is performed to obtain the system hydraulic forcing functions assuming an instantaneous (1.0 msec break opening time) double-ended guillotine break. The hydraulic forcing functions are then applied, along with the displacement time-history of the reactor pressure vessel (obtained from a separate reactor vessel blowdown analysis), to a system structural model, which includes the steam generator, the reactor coolant pump and the primary piping. This analysis yields the time history displacements of the steam generator at its upper lateral and lower support nodes. These time-history displacements formulate the forcing functions for obtaining the TSP loads due to LOCA shaking of the steam generator.

To evaluate the steam generator response to LOCA shaking loads, the computer code WECAN is used. The model used is similar to the one used for the seismic analysis, discussed previously. The steam generator support elements are removed, however, as the LOCA system model accounts for their influence on the steam generator response. Input to the WECAN model is in the form of acceleration time histories at the tube/tubesheet interface. These accelerations are obtained by differentiation of the system model displacement time histories at this location. Acceleration time histories for all six degrees of freedom are used. Past experience has shown that LOCA shaking loads are small when compared to LOCA rarefaction loads.

4.7.3 Combined Plate Loads

A summary of the resulting LOCA and seismic loads is provided in Table 4-2. In combining loads, the LOCA shaking and LOCA rarefaction loads are combined algebraically, while LOCA and SSE loads are combined using the square root of the sum of the squares.

In reacting the load among the various wedge groups, a cosine distribution is assumed among the wedges that are loaded. Typically, only half of the wedge groups are loaded at any given time. In determining the distribution of load for seismic and LOCA loads, the

directionality of the load is considered. LOCA loads are uni-directional, in that they only act in the plane of the U-bend. Seismic loads on the other hand are random, and can act in any direction. Calculations are performed to determine load factors for the various plates, grouping the TSP by commonality of their wedge group locations. The load factors are not a function of the wedge group size, only of location.

Applying these load factors to the overall TSP loads in Table 4-2, loads for each of the wedge groups are determined. A summary of the individual wedge loads is provided in Table 4-3.

4.7.4 Tube Deformation

In estimating the number of deformed tubes, the results of TSP crush tests for Model D steam generators are used. The deformation criteria for establishing a tube as being susceptible to in-leakage has been defined to be [ ]^{a,c} inch. In reporting the crush test results, tube deformations were reported for various deformation magnitudes. This is the smallest deformation reported. Although test data is not available for leak rate as a function of tube deformation, it is judged that deformation levels of this magnitude will not result in significant in-leakage.

Using the crush test data, a correlation is developed between elastic plate load and the number of tubes that would have a deformation of [ ]^{a,c} inch or greater. It is this correlation, summarized in Table 4-4, that is used to approximate the number of affected tubes. A summary of the number of potentially affected tubes for each of the wedge groups is provided in Tables 4-5.[3]

4.7.5 Tube Maps / Summary Tables for Potentially Affected Tubes

Byron Unit 1 and Braidwood Unit 1 are four-loop plants. As such, there are two loops with "left-hand" steam generators and two loops with "right-hand" steam generators. These designations refer to the orientation of the nozzles and manways on the channel head. For the purpose of this analysis, "left-hand" units are defined to be those loops where the primary fluid flows from the reactor to the steam generator to the pump and back to the reactor vessel in a counter-clockwise direction. Conversely, for the "right-hand" units, the flow is in the clockwise direction. The left- versus right-hand designation affects the location of the nozzles and manways, and the manner in which the columns are numbered for tube identification purposes. Reference configurations used in identifying wedge locations are shown in Figures 4-7 and 4-8 for the left-hand and right-hand units, respectively. As shown in the figures, for left-hand units, the nozzle and tube column 1 are located at 0°, while for right-hand units they are located at 180°.

Tabular summaries of the tubes that are potentially susceptible to collapse and subsequent in-leakage are summarized in Tables 4-6 to 4-12 for the left-hand units, and in Tables 4-13 to 4-19 for the right-hand units. It should be noted that separate summary tables are provided for the lower TSPs, B(2C)-K(7C) (except E(4C) and H(6C) where a

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3 The [ ]^{a,c} tubes noted for the limiting wedges for Plate P(11) is based on LOCA forces for a primary pipe break event. It is estimated that use of a secondary pipe break, consistent with the qualification of Byron / Braidwood for leak before break for their primary piping, would reduce the number of tubes to be excluded to approximately [ ]^{a,c}

table common to both is used), and a single table for the upper TSPs L(8) - N(10). A separate table is also provided for the top plate, Plate P(11). This is due to the orientation of wedge groups for each of the TSP. For the lower TSPs, the wedge groups are rotated in some instances relative to the other TSPs, while for the upper TSPs, the wedge groups have the same angular orientation.

Maps showing the location of the potentially susceptible tubes are provided in Figures 4-9 to 4-22. The maps provide row and column designations relative to the left-hand units. Column numbers for the right-hand units are shown in brackets. Identification of the potentially susceptible tubes is based on crush test results for both Model D and Series 51 steam generators. For both sets of tests, however, wedge / tube configurations identical to those for the Byron Unit 1 and Braidwood Unit 1 steam generators were not tested. As such, it was not possible to identify exactly the tubes that might be limiting at each wedge group. Thus, due to the uncertainties involved, there are more tubes identified at each wedge group as being limiting.

Finally, Table 4-20 provides an index of the applicable tables and figures identifying the potentially susceptible tubes for each TSP.

Table 4-1

Summary of Maximum Plate Loads
SSE Seismic Condition
Byron Unit 1 / Braidwood Unit 1 Steam Generators

a,c

Table 4-2

Summary of Maximum Plate Loads
Combined LOCA Plus SSE Transient Conditions
Byron Unit 1 / Braidwood Unit 1 Steam Generators

a,c

Table 4-3

Summary of Individual Wedge Loads
Combined LOCA Plus SSE Transient Conditions
Byron Unit 1 / Braidwood Unit 1 Steam Generators

a,c

Table 4-4

Number of Tubes with ΔD > [ ]^{a,c} inch Versus Load
Byron Unit 1 / Braidwood Unit 1 Steam Generators

a,c

Table 4-5

Summary of Number of Tubes with ΔD > [ ]^{a,c} inch
Byron Unit 1 / Braidwood Unit 1 Steam Generators
LOCA Plus SSE Loading Conditions

a,c

Table 4-6

Tubes Potentially Susceptible to Collapse and In-Leakage
TSP C(3H), D(3C)
Left-Hand Unit

a,c

Table 4-7

Tubes Potentially Susceptible to Collapse and In-Leakage
TSP F(5H), G(5C)
Left-Hand Unit

a,c

[ ]

Table 4-8

Tubes Potentially Susceptible to Collapse and In-Leakage
TSP J(7H), K(7C)
Left-Hand Unit

a,c

Table 4-9

Tubes Potentially Susceptible to Collapse and In-Leakage
TSP L(8) - N(10)
Left-Hand Unit

a,c

Table 4-10

Tubes Potentially Susceptible to Collapse and In-Leakage
TSP P(11)
Left-Hand Unit

a,c

Table 4-11

Tubes Potentially Susceptible to Collapse and In-Leakage
TSP B(2C)
Left-Hand Unit

a,c

Table 4-12

Tubes Potentially Susceptible to Collapse and In-Leakage
TSP E(4C), H(6C)
Left-Hand Unit

a,c

Table 4-13

Tubes Potentially Susceptible to Collapse and In-Leakage
TSP C(3H), D(3C)
Right-Hand Unit

a,c

Table 4-14

Tubes Potentially Susceptible to Collapse and In-Leakage
TSP F(5H), G(5C)
Right-Hand Unit

a,c

Table 4-15

Tubes Potentially Susceptible to Collapse and In-Leakage
TSP J(7H), K(7C)
Right-Hand Unit

a,c

Table 4-16

Tubes Potentially Susceptible to Collapse and In-Leakage
TSP L(8) - N(10)
Right-Hand Unit

a,c

Table 4-17

Tubes Potentially Susceptible to Collapse and In-Leakage
TSP P(11)
Right-Hand Unit

a,c

Table 4-18

Tubes Potentially Susceptible to Collapse and In-Leakage
TSP B(2C)
Right-Hand Unit

a,c

Table 4-19

Tubes Potentially Susceptible to Collapse and In-Leakage
TSP E(4C), H(6C)
Right-Hand Unit

a,c

Table 4-20

Table and Figure Index for TSP Row/Column Identification

TSP	Summary Tables		Tube Map Figures
	Left-Hand SG	Right-Hand SG	
B	4-11	4-18	4-9, 4-10
C	4-6	4-13	4-9, 4-10
D	4-6	4-13	4-11, 4-12
E	4-12	4-19	4-13, 4-14
F	4-7	4-14	4-15, 4-16
G	4-7	4-14	4-17, 4-18
H	4-12	4-19	4-13, 4-14
J	4-8	4-15	4-9, 4-10
K	4-8	4-15	4-9, 4-10
L	4-9	4-16	4-19, 4-20
M	4-9	4-16	4-19, 4-20
N	4-9	4-16	4-19, 4-20
P	4-10	4-17	4-21, 4-22

a,c

Figure 4-1. Tube Bundle Geometry

a,c

Figure 4-2. Thermal / Hydraulic LOCA Tube Model

a,c

Figure 4-3. LOCA Pressure Time Histories
Maximum Radius Tube
Nodes 8-15

a,c

**Figure 4-4. LOCA Pressure Time History
Hot-to-Cold Leg Pressure Differential
Maximum Radius Tube**

a,c

Figure 4-5. LOCA Pressure Time History
Hot-to-Cold Leg Pressure Differential
Average Radius Tube

a,c

Figure 4-6. Structural LOCA Tube Model

a,c

[ ]

Figure 4-7. Reference Configuration Looking Down on Steam Generator Left-Hand Unit

a,c

Figure 4-8. Reference Configuration
Looking Down on Steam Generator
Right-Hand Unit

a,c

Figure 4-9. Tubes Potentially Susceptible to Collapse and In-Leakage
Braidwood Unit 1
TSP C(3H), J(7H)
Quadrant 1

a,c

Figure 4-10. Tubes Potentially Susceptible to Collapse and In-Leakage
Braidwood Unit 1
TSP C(3H), J(7H)
Quadrant 2

a,c

Figure 4-11. Tubes Potentially Susceptible to Collapse and In-Leakage
Braidwood Unit 1
TSP D(3C)
Quadrant 3

a,c

Figure 4-12. Tubes Potentially Susceptible to Collapse and In-Leakage
Braidwood Unit 1
TSP D(3C)
Quadrant 4

a,c

Figure 4-13. Tubes Potentially Susceptible to Collapse and In-Leakage
Braidwood Unit 1
TSP E(4C), H(6C)
Quadrant 3

a,c

Figure 4-14. Tubes Potentially Susceptible to Collapse and In-Leakage
Braidwood Unit 1
TSP E(4C), H(6C)
Quadrant 4

a,c

Figure 4-15. Tubes Potentially Susceptible to Collapse and In-Leakage
Braidwood Unit 1
TSP F(5H)
Quadrant 1

a,c

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Figure 4-16. Tubes Potentially Susceptible to Collapse and In-Leakage
Braidwood Unit 1
TSP F(7H)
Quadrant 2

a,c

Figure 4-17. Tubes Potentially Susceptible to Collapse and In-Leakage
Braidwood Unit 1
TSP G(5C)
Quadrant 3

a,c

Figure 4-18. Tubes Potentially Susceptible to Collapse and In-Leakage
Braidwood Unit 1
TSP G(5C)
Quadrant 4

a,c

Figure 4-19. Tubes Potentially Susceptible to Collapse and In-Leakage
Braidwood Unit 1
TSP L(8) - N(10)
Quadrant 1

a,c

Figure 4-20. Tubes Potentially Susceptible to Collapse and In-Leakage
Braidwood Unit 1
TSP L(8) - N(10)
Quadrant 2

a,c

Figure 4-21. Tubes Potentially Susceptible to Collapse and In-Leakage
Braidwood Unit 1
TSP P(11)
Quadrant 1

14

a,c

Figure 4-22. Tubes Potentially Susceptible to Collapse and In-Leakage
Braidwood Unit 1
TSP P(11)
Quadrant 2