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Revision 1

Mechanical Design for BWR Fuel Channels

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Framatome ANP, Inc.

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U.S. Nuclear Regulatory Commission
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Nature of Changes

Item	Section(s) or Page(s)	Description and Justification
1.	Throughout	Updated report format and included an Abstract. No technical changes were made other than described below.
2.	1.1	Added an introductory sentence briefly stating the purpose of describing the analysis methods and criteria.
3.	1.1	Deleted 5th paragraph on lead fuel channel experience. The information is now outdated. The advanced fuel channel design is now a standard design with extensive operating experience in reload quantities.
4.	1.1	Added a paragraph at the end of the section to briefly describe the reason for the report revision.
5.	1.3 and Tables 1.1 and 1.2	Under II.A.1, the wording was revised to change a "limit" analysis to a "plastic" analysis. Tables 1.1 and 1.2 were changed to describe a plastic analysis collapse load criterion instead of a limit analysis collapse load criterion. An additional criterion was added for normal operation to preclude permanent deformation from yielding. New analysis results are included in the table to address the revised criteria, updated tensile properties, and an increase in channel exposure that was previously communicated to the NRC. Also, corrected Table 1.2 to address an RAI comment in the Revision 0 report.
6.	1.4	Added a sentence for clarification that indicates the need for new analyses if the conditions change.
7.	2.2 and Table 2.1	Updated material properties according to current material specifications for fuel channels.
8.	3.2.1	Revised wording to indicate a plastic analysis instead of a limit analysis. An additional criterion was added to preclude permanent deformation from yielding during normal operation.
9.	3.3.2 and Table 3.2	Updated the numbers for the channel gusset strength because of the update to the material tensile properties.
10.	Table 3.1	The table heading in the second column was revised for clarification only to indicate that the plate and shell criteria are used.
		Revised wording to indicate a plastic analysis instead of a limit analysis.
11.	Table 3.2	Revised the allowable stress intensity values to be consistent with the updated tensile properties in Table 2.1.
12.	4.1.1	Revised wording to reference a plastic analysis instead of a limit analysis.

Item	Section(s) or Page(s)	Description and Justification
13.	6.1.1 Table 6.1	Added a reference to the ANSYS code because it is used for the plastic analysis. The section was generally revised to describe the plastic analysis, the stress-strain curve, and the additional calculation to show the lack of yielding under normal operating conditions. Included revised results.
14.	6.2.1 Table 6.4	2nd bullet: Revised wording to describe the plastic analysis similar to Section 6.1.1. Included revised results. Also, revised allowable membrane stress because of the updated material tensile properties.
15.	Figures 6.1, 6.2 and 6.3	Included updated model figures, stress-strain curve, and deformation results for the plastic analysis.
16.	7.2	Added a sentence indicating that new measurement data will be included as the data become available.
17.	Table 7.1	Included updated channel deformation results at 54 MWd/kgU exposure. Reference: Letter, J. F. Mallay to US NRC (Document Control Desk), “Assessment of Fuel Channel Design Calculations,” NRC:99:031, July 23, 1999.
18.	8.0	Added Reference 18 for the ANSYS code.

Contents

This document contains a total of 144 pages.

Tables

Figures

Abstract

The methods for analyzing the structural integrity of a Framatome ANP, Inc., BWR fuel channel are described. The topics covered are: 1) fuel channel stresses, 2) cyclic fatigue, 3) corrosion and hydrogen pickup, 4) channel deflection (bulge and bow), and 5) structural analysis under postulated seismic-LOCA loadings. In order to demonstrate the methods, analyses are provided for four fuel channel designs.

A finite element method is used to evaluate the pressure differential across the fuel channel wall caused by the coolant flow. Stress limits and allowable loads are derived from Section III, Division 1 of the ASME Boiler and Pressure Vessel Code.

The cyclic stresses from the pressure load are used in combination with a design fatigue curve to evaluate the allowable number of duty cycles. The resulting allowable is then compared to the expected number of cycles.

The stress analysis and the cyclic fatigue analysis take into account the expected amount of wall thinning due to oxidation. The hydrogen pickup is predicted based on the amount of oxidation and a pickup fraction in order to demonstrate that the hydrogen content remains relatively low in the fuel channel.

Fuel channel bulge and bow are evaluated by the use of a creep model for predicting bulge in combination with the use of channel bow measurement statistics. A statistical evaluation is performed to determine the maximum interference of four fuel channels in a control cell with the control blade. The maximum interference is compared to the allowable interference for avoiding a no-settle condition.

For evaluating fuel coolability and control blade insertion during postulated seismic-LOCA loads, a non-linear dynamic method is described for analyzing the maximum loads on the fuel channel. Acceleration response spectra are used to develop time histories for the core plate motions. A finite element model is used that includes gap elements for evaluating the impact of the spacer grids inside the fuel channel and the separation of the top ends of the fuel channels from the top fuel guide structure. The calculated maximum bending moment in the fuel channel is then compared to the allowable bending moment. The analytical model was developed using dynamic tests to confirm the stiffness, mass and damping properties. In addition, the dynamic analysis method was evaluated by solving the U. S. Nuclear Regulatory Commission standard five-assembly row problem.

The allowable bending moment was derived from analyses that were benchmarked to bending moment tests.

A more simplified response-spectrum method of analyzing the maximum bending moment in the fuel channel is presented as an alternative to the non-linear analysis.

1.0 INTRODUCTION AND SUMMARY

1.1 *Introduction*

This report describes the methods and criteria for evaluating a Framatome ANP, Inc.* (FANP) boiling water reactor (BWR) fuel channel design. To demonstrate the methods, four fuel channel designs were evaluated for acceptability for reactor operation in a BWR. The evaluations were performed to provide a basis for licensing applications. Included in this report are a design description, criteria, methods, and evaluation results. Results are provided for example reactor conditions and loadings. Allowable mechanical loadings are provided such that the applicability of the evaluations can be verified for specific plant application.

The four designs evaluated are:

- 80 mil FC (fuel channel), BWR/3,4 D-lattice & BWR/5 C-lattice
- BWR/6 100 mil FC, BWR/6 C-lattice
- BWR/3,4 AFC (advanced fuel channel), BWR/3,4 D-lattice, partial symmetry
- BWR/6 AFC, BWR/6 C-lattice

The first two fuel channels have a uniform wall thickness and the latter two have a non-uniform wall thickness. The 80 mil FC is conventional in design having the same configuration and dimensions as existing 80 mil FC designs in GE BWR/3,4, & 5 reactors. The BWR/6 100 mil FC is intended for the replacement of a 120 mil FC in a BWR/6 reactor. Both advanced fuel channels are configured with thick corners in relation to thinner sidewalls. Descriptions of the four fuel channel types are given in Section 2.0. The above listing also indicates the reactor lattice geometry, either D-lattice or C-lattice, in which the fuel channels were analyzed for creep deformation.

The motivation for introducing the AFC is to reduce the amount of zircaloy in the active region of the reactor core. In the case of the BWR/3,4 AFC, the thinner sidewalls permit the fuel assembly to be moved closer towards the control blade producing an effective symmetrization of a D-lattice core cell. To modify the D-lattice, the channelled fuel assembly is shifted towards the control blade. The amount of offset from the D-lattice geometry is selected to obtain up to [ ] of the total offset required to achieve complete symmetry.

Normal operation and accident condition design criteria formulated for the fuel channel evaluation are provided in Section 3.0. The criteria are based on USNRC regulatory requirements identified

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in Chapter 4 of the Standard Review Plan[1] and Section III of the ASME Boiler and Pressure Vessel Code.[2]

Section 4.0 describes the general methods for the evaluation. The FANP KWUSTOSS computer code is introduced as a method for analyzing the dynamic behavior of the fuel channels and fuel assemblies.

A reference set of loadings and operating conditions is given in Section 5.0. Normal operating conditions consist of the differential pressure across the fuel channel wall and the reactor exposure history. Accident loadings due to a seismic event and a postulated pipe break for a particular reactor are described along with their treatment.

Results from evaluations are presented in Section 6.0. In addition, Section 7.0 provides a probabilistic analysis of fuel channel deflection for compatibility with the control blade during normal operation.

Revision 1 of this report includes a correction to the method used in determining the maximum allowable pressure load across the fuel channel wall.

1.2 *Summary*

Evaluations were performed with the objectives of 1) assuring the fuel channel is not damaged as a result of normal operation and anticipated operational occurrences, 2) assuring fuel channel damage is never so severe as to prevent control blade insertion when it is required, and 3) maintaining coolability. The criteria and evaluations cover the following areas for normal operation:

- Fuel channel stresses due to normal operation loads (differential pressure)
- Cyclic fatigue from pressure fluctuations
- Oxidation and hydriding of the fuel channels

During a seismic/LOCA accident, the following areas are addressed:

- Fuel channel stresses due to normal operation and blowdown loads (differential pressure) and vertical accelerations
- Fuel channel bending moment due to horizontal excitations (seismic/LOCA loads)

Tables 1.1 and 1.2 summarize the key criteria and results. Reference sections of the report and applicable paragraphs of NUREG-0800 Standard Review Plan 4.2 are also listed in the two tables. The allowable loads in Tables 1.1 and 1.2 identify the criteria that must be examined to demonstrate the applicability of these analyses for plant specific usage.

To assess the compatibility of the fuel channels with control blade movement throughout their life, an evaluation of fuel channel deflection was made in addition to the analyses listed above.

1.3 *Standard Review Plan Summary*

In Section 4.2 of the Standard Review Plan,[1] acceptance criteria are given for core components. Each of the relevant criterion is reviewed and the FANP fuel channel evaluation results are summarized below. Paragraphs are numbered to agree with the corresponding paragraphs of the SRP. Normal operation criteria are included in Section II.A.1 of the SRP. Appendix A of SRP 4.2 describes the review for accident conditions.

II.A.1. Fuel System Damage

Design criteria for normal operation, including AOOs (anticipated operational occurrences), are given for known damage mechanisms. Each criterion is addressed to assure that the fuel system dimensions remain within operational tolerances and that functional capabilities are not reduced below those assumed in the safety analysis.

(a) Stress, strain, or loading limits for fuel channels should be provided. Stress limits that are obtained by methods similar to those given in Section III of the ASME code are acceptable.

Stress criteria for the fuel channels are directly in accordance with Section III of the ASME B&PV Code.[2] Stress analyses of the fuel channels under differential pressure loadings are accomplished using the finite element method to show compliance with the plastic analysis collapse load criterion. Results from the analyses satisfy Section III of the ASME Code for the allowable load. Channel wall deflection is limited to prevent interference with the control blade. The calculated amounts of deflection are small and within functional requirements.

(b) The cumulative number of strain fatigue cycles on the structural members mentioned in paragraph (a) above should be significantly less than the design fatigue lifetime, which is based on the appropriate data and includes a factor of 2 on stress amplitude or a safety factor of 20 on the number of cycles.

Cumulative damage is limited to the cyclic fatigue life of irradiated zircaloy based on test data which includes the recommended "2 or 20" factors. Cyclic stresses are mainly caused by pressure fluctuations during normal operation and AOOs. For all anticipated major pressure variations, one bounding stress amplitude is selected. Based on a "stress" versus "number of allowables cycles" design curve(3) for irradiated zircaloy and the stress amplitude, the number of anticipated cycles is much less than the allowable number of cycles. This analysis is done for the most limiting fuel channel (80 mil FC) thus demonstrating acceptable cyclic fatigue life for all four fuel channel types.

(c) Fretting wear at contact points on structural members should be limited. The allowable fretting wear should be stated and the stress and fatigue limits in paragraphs (a) and (b) should presume the existence of this wear.

Contact areas of interfacing components such as the upper core support guide beams, lower tie plate seal springs, and spacer grids are broad, and as such, do not produce noticeable wear on the fuel channel. This assertion is based on the observation of irradiated fuel channels and of irradiated fuel assemblies.

(d) Oxidation, hydriding, and the buildup of corrosion products (crud) should be limited. Allowable oxidation, hydriding, and crud levels should be discussed and shown to be acceptable. These levels should be presumed to exist in paragraphs (a) and (b) above.

Since the fuel channel has thicker walls as compared to other fuel components (e.g., fuel rod), oxidation and hydriding are not limiting for the fuel channel. In relation to the fuel channel wall thickness, the wall thinning from oxidation is small. Also, the hydrogen concentration levels are low due to the higher volume to surface area ratio for a fuel channel.

The oxidation and hydrogen absorption are a function of the material selection, water chemistry, and residence time. Wall thinning from oxidation and hydrogen pickup are estimated using available hydrogen concentration measurements and oxide thickness data on irradiated zircaloy-4 strip material. For the thinnest cross-section from among the four fuel channel types, the estimated oxide thickness and hydrogen concentration are at acceptably low levels. The amount of wall thinning is taken into consideration in the stress and cyclic fatigue analyses.

(e) Dimensional changes of the fuel channel such as bowing and irradiation growth need not be limited to set values (i.e., damage limits), but they must be included in the design analysis to establish operational tolerances.

Deformations experienced by fuel channels during normal operation do not impact the fuel channel analyses per se. Stress levels are reduced somewhat as the fuel channel walls bulge by creep under the differential pressure. Therefore, stress analyses are performed assuming no creep deformation. Deformation must be evaluated to assure that fuel channels do not cause operational difficulties with control blade movement. The initial dimensions and the manufacturing process are carefully controlled such that their effect on the overall in-reactor fuel channel deflection is minimal. Furthermore, FANP has evaluated the deformation of the fuel channels under irradiation by the use of a statistical procedure. Bulging due to the differential pressure is calculated from an incremental creep analysis. Lateral bowing is predicted by [

]. The maximum statistical deflections of the four fuel channel types in their appropriate lattice geometries are such that there is a 95% probability of no operating restriction to control blade movement with a 0.95 confidence level (>95/95).

APPENDIX A of SRP 4.2

A. Background

Earthquakes and postulated pipe breaks in the reactor coolant system result in external forces on the fuel channel. Fuel system coolability should be maintained and damage should not be so severe as to prevent control blade insertion when required for these low probability accidents. Appendix A to SRP 4.2[1] describes the review for accident conditions. The following summarizes each of the issues identified in this Appendix. Paragraph identification coincides with the numbering used in the Appendix.

B. Analysis of Loads

B.1. Input

Input for the channelled fuel assembly response to a LOCA includes (a) motions of the fuel support and top guide and (b) transient pressure difference applied directly to the fuel channel. SSE (safe shutdown earthquake) loads and the DBA (design basis accident) loads for a large pipe break are used in the form of displacement time histories at the fuel supports for a non-linear analysis. In addition, acceleration spectra at the fuel supports are used in a response spectrum analysis in conjunction with a linear analysis.

B.2. Methods

The fuel channels with fuel assemblies are modeled using the finite element method in a [

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A simplified response spectrum method is included [

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Important parameters such as fuel stiffness, spacer grid stiffness, and natural frequencies were verified by experimental means. Good agreement was obtained between experimental results and model predictions.

Verification of the computer code used for the analyses has been accomplished by the solution of the standard NRC sample problem (five-assembly core region problem with sine wave inputs). Also, simplified problems which resemble a channelled fuel assembly were solved and comparisons made between the analytical code and exact solutions. These sample problems exercised the major features of the code which are used for the fuel channel evaluation. Close correspondence was obtained between the code solutions and previously accepted solutions.

B.3 Uncertainty Allowances

A sensitivity analysis was performed by examining increases in resultant loads for ±10% variations in input amplitude and frequency. The variations in amplitude and frequency were applied separately. The resultant loads did not increase by more than [

].

B.5 Combination of Loads

Resulting loads on the fuel channels from the separate input loads produced from the SSE and LOCA were combined by the square-root-of-the-sum-of-squares method (SRSS). The combined loads were then compared to the allowable total load on the fuel channel according to the design criteria.

C.2. Determination of Strength

Fuel channel strength is derived from the specified minimum tensile properties in the unirradiated condition and the ASME B&PV Code procedures. The allowables for differential pressure and bending moment were determined using the ASME B&PV Code Section III, Appendix F criteria. A plastic analysis collapse load criterion is used to arrive at an allowable bending moment for each of the four fuel channel designs.

D. Acceptance Criteria

D.1 Loss of Coolant Accident

To demonstrate control blade insertability, combined loads on the fuel channel must remain below the allowable values defined above. If this is not the case, additional analysis is needed to show that deformation is not severe enough to prevent control blade insertion. FANP has analyzed the fuel channels in accordance with Appendix F of the ASME B&PV Code Section III. These analyses show the fuel channels meet the allowable values as described above. The effect of liftoff was included in the evaluation of stresses. (Note: The vertical liftoff analysis is performed as a part of the fuel assembly evaluation.)

D.2 Safe Shutdown Earthquake

Control blade insertability must be assured. This criterion is satisfied by combining the loadings coming from a LOCA with the SSE loads. The loadings were found to be within the allowables established for the fuel channel designs.

Fuel channel stresses due to the normal operating pressure and the added pressure during a blowdown event are evaluated in the same manner as for an AOO. The expected differential pressure load remains below the allowable collapse load, and the deformation is within acceptable limits.

An analysis of the axial stresses is presented for the case when the fuel assembly impacts the fuel support after liftoff. Since the fuel channel is supported by the fuel assembly which is a relatively flexible support, stresses in the fuel channel from the vertical accelerations are low.

The seismic/LOCA loads on the channelled fuel assembly are analyzed [

]. The FANP KWUSTOSS code is used to analyze the model and time history load inputs. The combined bending moments from the LOCA and SSE are within the allowable bending moments for the fuel channel designs.

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1.4 ***Plant-Specific Application***

Allowable loadings were obtained based on the design criteria for the purpose of determining the acceptability of the fuel channel designs for specific plant applications. To determine the applicability of the analyses of the fuel channel designs for a particular plant, the following areas are examined:

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If all of the above conditions are met, then the analyses and criteria presented in this report are applicable for the specific plant and channel design. Otherwise, new analyses are required that follow the methods and criteria described in this report.

Table 1.1 SUMMARY OF RESULTS FOR NORMAL OPERATION

Report Section, Criteria/ Results	Topic	Criteria	Allowable Loading	Results	Reference NUREG-0800 SRP Section 4.2
3.2.1/ 6.1.1	Stresses due to ΔP	[ ] according to ASME B&PV Code, Section III. Pressure load is also limited such that [ ].	Maximum ΔP for normal operation (+ AOO) [ ].	Normal operation + AOO pressure [ ]. Maximum deformation [ ] remains within function limits for normal control blade operation. Normal operation pressure of [ ].	II.A.1 (a)
3.2.2/ 6.1.2	Cyclic fatigue from pressure fluctuations	Cumulative cyclic loading to be less than design cyclic fatigue life for irradiated zircaloy.	Allowable no. of [ ].	Expected number of cycles [ ] is less than allowable.	(b)
3.2.3/ 6.1.3	Oxidation and hydriding	Oxidation shall be accounted for in the stress and fatigue analyses.	--	Maximum calculated wall thinning [ ] is low in relation to wall thickness. An account is made in the two preceding analyses.	(d)
7.0	Long-term creep deformation (bulging and bowing)	--	--	Maximum additional deflection [ ] is permitted prior to a stuck control blade condition.	--

Table 1.2 SUMMARY OF RESULTS FOR ACCIDENT CONDITIONS

Report Section, Criteria/ Results	Topic	Criteria	Allowable Loads	Results	Reference NUREG-0800 SRP 4.2 Section
3.3.1/ 6.2.1	Stresses from ΔP (blowdown) and vertical accelerations	Plastic analysis collapse load according to ASME B&PV code, Section III, Appendix F. Pressure load is also limited such that [ ].	Maximum allowable ΔP [ ].	Max. ΔP [ ] during blowdown is less [ ].	Appendix A, D.1.,D.2.
3.3.1/ 6.2.2	Channel bending from combined horizontal excitations	Allowable bending moment based on ASME Code, Section III, Appendix F plastic analysis collapse load.	[ ]	[ ].	
3.3.2/ 6.2.1	Channel gusset strength	ASME allowable load rating.	[ ] based on testing.	Vertical load [ ] from impact after liftoff is less than allowable and not limiting.	

2.0 DESIGN DESCRIPTION

2.1 *Description*

The BWR fuel channel is a square duct with rounded corners and it is open at both ends. It encloses the sides of each fuel assembly for the main purpose of providing a flow boundary between the active coolant flow and the core bypass flow. The fuel channel also lends considerable stiffness to the channelled fuel assembly and it provides a bearing surface for the guidance of the control blade during movement. Gussets are welded at two opposite corners of the top end of the fuel channel for support and attachment to the fuel assembly.

Four different fuel channel types are shown in Figure 2.1 through Figure 2.4:

- BWR/3,4,5 80 mil FC (fuel channel), uniform wall
- BWR/3,4 AFC (advanced fuel channel)
- BWR/6 AFC (advanced fuel channel)
- BWR/6 100 mil FC, uniform wall

The figures show the features and main dimensions of the fuel channels.

The 80 mil FC is conventional in design and it has a uniform wall. The two AFC types have thinner side-walls with reinforced corners in the active core region. [

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The BWR/3,4 AFC has the same inside dimensions as a standard 80 mil and 100 mil FC. [

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As compared to a regular BWR/6 120 mil FC, the BWR/6 AFC has an enlarged inside dimension. A standard 120 mil fuel channel has a nominal inside dimension of 5.215 inch (132.46 mm) while the BWR/6 AFC has a dimension of 5.278 inch (134.06 mm). This inside dimension of 5.278 inch is the same as for the other fuel channels types (e.g., 80 mil, 100 mil, and the BWR/3,4 AFC). The thinner side-walls and corners permit a larger interior while maintaining an exterior envelope which is compatible with the core internals and control blades. [

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Identical to the BWR/6 120 mil FC as far as internal dimensions, the BWR/6 100 mil FC is a thinner-walled replacement. Twenty mils are removed from the outer surface producing a uniform 100 mils. Enveloping dimensions at the upper end are the same as before such that the assembly pitch is maintained.

2.2 *Material Properties*

The material for the fuel channels may be either Zircaloy-4 or Zircaloy-2 sheet. The material is in the fully annealed condition. Table 2.1 lists the material properties which are used in the analyses. These properties are in the unirradiated condition and apply to both alloys. Minimum tensile strength values meet or exceed those in ASTM B352.

Table 2.1 FUEL CHANNEL MATERIAL PROPERTIES

Condition	Minimum Ultimate Strength, S_u ksi (MPa)	Minimum 0.2% Offset yield Strength, S_y ksi (MPa)	Modulus of Elasticity, E psi (MPa)	Coefficient of Thermal Expansion 1/°C
RT Transverse	[	[	[	[ ]
RT Longitudinal	]	]	]	
550°F Transverse	[	[	[	[ ]
550°F Longitudinal	]	]	]	

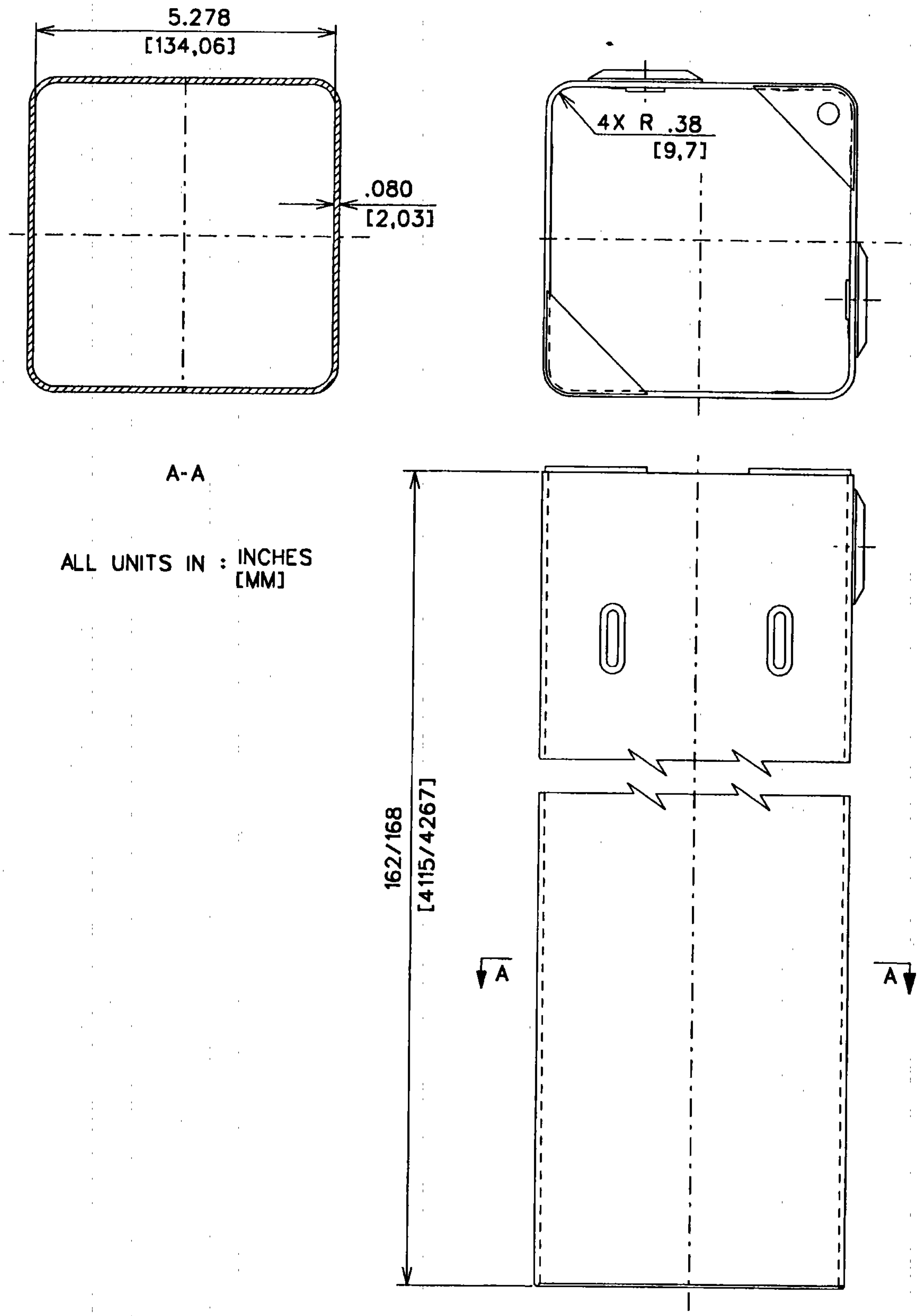

Figure 2.1 BWR/3,4,5 80 MIL FUEL CHANNEL

Figure 2.2 BWR/3,4 ADVANCED FUEL CHANNEL

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Figure 2.3 BWR/6 ADVANCED FUEL CHANNEL

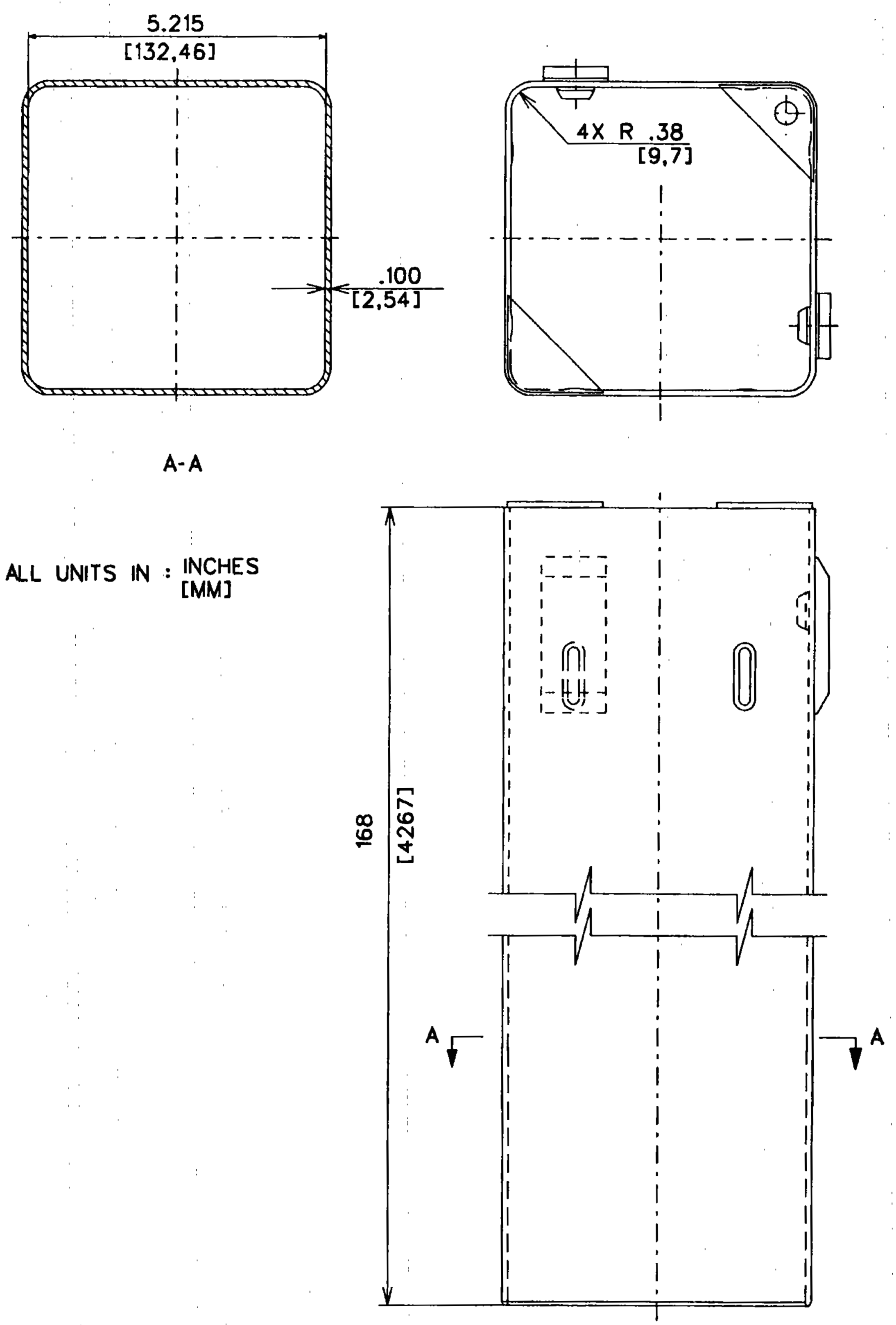

Figure 2.4 BWR/6 100 MIL FUEL CHANNEL

3.0 DESIGN BASES AND CRITERIA

3.1 *Design Objectives and General Criteria*

This section contains the design bases and general acceptance criteria for the fuel channel evaluation as defined in Section 4.2 of the Standard Review Plan.

"The objectives of the fuel system evaluation are to provide assurance that (a) the fuel system is not damaged as a result of normal operation and anticipated operational occurrences, (b) fuel system damage is never so severe as to prevent control rod insertion when it is required, (c) the number of fuel rod failures is not underestimated for postulated accidents, and (d) coolability is always maintained. "Not damaged", as used in the above statements ... {and in the context of the fuel channel evaluation, means that the fuel channel remains} within operational tolerances, and that functional capabilities are not reduced below those assumed in the safety analyses {i.e., flow blockage}."

The fuel channel contributes to meeting the fuel system objectives a, b, and d. These objectives are met when the combined loads on the fuel channel remain below the design criteria values. Component design criteria for the fuel channel were developed to be consistent with the criteria identified in the SRP to evaluate the structural integrity and functionality.

3.2 *Design Criteria for Normal Operation*

3.2.1 Steady State Stress Limits

The stress limits during normal operation are obtained from the ASME Boiler & Pressure Vessel Code, Section III, Division 1, Subsection NG for Level A Service.[2] The calculated stress intensities are due to the differential pressure across the channel wall. The pressure loading includes the normal operating pressure plus the increase during anticipated operational occurrences. The unirradiated properties of the fuel channel material are used since the yield and ultimate tensile strength increase during irradiation. Table 3.1 lists the stress criteria and Table 3.2 gives the allowable stress intensities. The allowables are based on the yield and ultimate strengths listed in Table 2.1.

As an alternative to the primary membrane plus bending stress intensity limits, a plastic analysis may be performed as permitted by paragraph NB-3228.3 of the ASME B&PV Code.

In the case of AOOs, the amount of bulging due to yielding is limited to that value which will permit control blade movement.

During normal operation, any significant permanent deformation due to yielding is precluded by restricting the maximum stresses at the inner and outer faces of the channel to be less than the yield strength.

3.2.2 Fuel Channel Fatigue

Cyclic changes in power and flow during operation impose a duty loading on the fuel channel. The cyclic duty from pressure fluctuations is limited to less than the fatigue lifetime of the fuel channel. The fatigue life is based on the O'Donnel and Langer curve[3] which includes a factor of 2 on stress amplitude or a factor of 20 on the number of cycles, whichever is most conservative.

3.2.3 Corrosion and Hydrogen Concentration

Corrosion reduces the material thickness and results in less load carrying capacity. The fuel channels have thicker walls than other components (e.g., fuel rods), and the normal amounts of oxidation and hydrogen pickup are not limiting provided: the alloy composition and impurity limits are carefully selected; the heat treatments are also carefully chosen; and, the water chemistry is controlled. Since the amount of corrosion and corresponding hydrogen pickup are relatively small, no specific limits are provided. The amount of thinning due to corrosion is taken into consideration in evaluating the fuel channel for the stresses and fatigue damage as required in the preceding two paragraphs.

3.3 *Design Criteria for Accident Conditions*

3.3.1 Fuel Channel Stresses and Limit Load

The criteria are based on the ASME Boiler and Pressure Vessel Code, Section III, Appendix F,[2] for faulted conditions (Level D Service). Component support criteria for elastic system analysis are used. Table 3.1 summarizes the applicable criteria used in the analyses for the fuel channel. Table 3.2 lists the allowable stresses and loads.

- Allowable Stresses

Primary membrane stresses and primary membrane plus bending stresses are limited in accordance with F-1332.1 and F-1332.2,[2] respectively. The allowable stresses are based on the yield and ultimate strengths listed in Table 2.1. The unirradiated properties of the fuel channel material are used since the yield and ultimate tensile strength increase during irradiation.

Primary membrane plus bending stresses are alternatively addressed by the plastic analysis collapse load criteria given in F-1332.2(b).[2] For the plastic analysis collapse load, the permanent deformation is limited to twice the deformation the structure would undergo had the behavior been entirely elastic. The stresses are caused primarily by bending from the horizontal excitations and from the differential pressure. Allowable bending moments for the four fuel channel types are derived in Appendix A.

3.3.2 Fuel Channel Gusset Load Rating

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Table 3.1 STRESS AND LOAD CRITERIA FOR NORMAL AND FAULTED CONDITIONS

	Limits for Level A Service for Elastic Analysis[(a)]	Limits for Level D Service for Elastic Analysis[(c)]/Plate and Shell Type Supports
P_m	$\leq MIN(2/3S_y, 1/3S_u)$	$\leq MAX(1.2S_y, 1.5S_m)$ & $<0.7S_u$
$P_m + P_b$	$\leq MIN(1.0S_y, 0.5S_u)$	$\leq MAX(1.8S_y, 2.25S_m)$ & $<1.0S_u$[(b)]

Definitions:

P_m - General primary membrane stress intensity
$P_m + P_b$ - General primary membrane plus primary bending stress intensity
S_m - ASME allowable stress intensity (if defined)
S_y - Specified yield strength
S_u - Specified ultimate strength

NOTES:

(a) Alternatively, a plastic analysis is permissible (NB-3228.3). The limits of general membrane stress intensity, local membrane stress intensity, and primary membrane plus primary bending stress intensity need not be satisfied at a specific location if it can be shown that the specified loadings do not exceed two-thirds of the plastic analysis collapse load determined by application of II-1430 to a load-deflection or load-strain relationship obtained by plastic analysis.

(b) As options, static or equivalent static loads shall not exceed 90% of the limit analysis collapse load using the yield strength which is the lesser of $1.2S_y$ and $0.7S_u$, or 100% of the plastic collapse load or test collapse load.

(c) Alternatively, the component may be qualified using the procedure for load rating (NF-3282).

Table 3.2 FUEL CHANNEL ALLOWABLE STRESS INTENSITY AND LOADS

Limit Category	Allowable Values
Normal Operation	
P_m, ksi (MPa)	[ ]
$P_m + P_b$, ksi (MPa)	[ ]
Faulted Conditions	
P_m, ksi (MPa)	[ ]
$P_m + P_b$ for ΔP, ksi (MPa)	[ ]
$P_m + P_b$, allowable lateral bending moment, in-lb, (Nm)	
80 mil FC	[ ]
BWR/3,4 AFC	[ ]
BWR/6 AFC	[ ]
BWR/6 100 mil FC	[ ]

[ ]

4.0 CALCULATION METHODS

4.1 *Calculations Methods for Normal Operation*

4.1.1 Stresses from Differential Pressure Loading

During normal operation, stresses are produced in the fuel channel principally from the ΔP (differential pressure) load across the wall. The ΔP results in primary membrane and bending stresses in the tangential direction and a bending stress component in the axial direction due to the plane strain condition. Following the criteria given in Section 3.0, the primary membrane plus bending stresses are evaluated by either a direct comparison to the stress intensity limits or by a plastic analysis collapse load method according to the ASME B&PV Code Section III, Subsection NB. The plastic analysis collapse load and deformation are determined by an elasto-plastic analysis using the finite element method.

4.1.2 Corrosion and Hydrogen Concentration

Corrosion and hydrogen concentration predictions are made using the MATPRO(4) correlation, the same as used in the approved RODEX2(5) code for fuel rod analysis. An enhancement factor and hydrogen pickup fraction in the model are selected to agree with available in-reactor measurement data on Zircaloy-4 strip material.

[

].

4.1.3 Fatigue Damage

The channel is subject to varying differential pressure loads during power level changes. Operational induced variations in the differential pressure produce cyclic stresses in the channel.

The stress results from the steady-state analyses are used to evaluate the channel fatigue damage through EOL due to the anticipated cyclic power variations defined in Table 5.1. For each of these repetitive operations, high and low differential pressure levels (corresponding to power level operations) are identified. Fatigue duty is evaluated for the specified number of repetitive operations as the reactor power (and differential pressure) is cycled back and forth between the two levels.

The fatigue life evaluation is based on the O'Donnel and Langer[3] design curve shown in Figure 4.1. This curve is conservative in that it is based on fatigue test data with a factor of safety of 2 on stress or 20 on the number of cycles, whichever is more conservative. The stresses used for the fatigue evaluation with this curve are the cyclic amplitudes of the maximum local stresses.

4.2 *Calculation Methods for Accident Conditions*

Calculations for accident conditions consist of determining fuel channel stresses from the differential pressure during a LOCA, vertical accelerations, and horizontal excitations [

]. For the dynamic analyses, time history excitations are generated from acceleration response spectra. Methods for these calculations are described below.

Major parameters used in establishing the input were based on component test values. Appendix C describes the types of tests performed in support of the analyses.

4.2.1 Stresses from Differential Pressure Loading and Vertical Acceleration

The stresses due to the pressure difference across the channel wall during blowdown are calculated in the same manner as described in Section 4.1.1. The stresses are judged according to the criteria given in Section 3.0.

Stresses from the vertical acceleration are calculated in the case when the channelled fuel assembly impacts the fuel support after liftoff. [

].

4.2.2 Generation of Core Support Synthetic Time History Excitations

Dynamic analyses are done in the time domain. The available loadings for the excitations are in the form of ARS (acceleration response spectra.) [

]. An example of the time history generation is given.

- <u>Acceleration Response Spectra</u>

Horizontal acceleration response spectra were converted to time histories for a BWR/4 plant with a Mark II containment. The loadings include those for SSE, AP FWLB (annulus pressurization - feedwater line break), AP RCLB (annulus pressurization - recirculation line break), chugging, condensation oscillation, and SRV (safety/relief valve) actuation. The ARS is shown in Figure 4.2 for the horizontal SSE load.

[

]

- Example Time History Generation

Using the starting target spectrum shown in Figure 4.2, acceleration, velocity, and displacement versus time excitation functions were generated. In addition, the recalculated ARS from the acceleration excitation function was compared to the original, target spectrum.

Figure 4.3 are plots of the acceleration, velocity, and displacement versus time. [

].

4.2.3 Dynamic Analysis and Model Description

Two different methods of accomplishing the dynamic analyses of the fuel channel (and fuel assembly) due to the horizontal excitations are presented - direct time integration of the equation of motion and RSA (response spectrum analysis). The direct time integration method is used in the case of the non-linear model of the channelled fuel assembly. [

]. The RSA method is to be used for demonstrating plant-specific applicability.

The analyses are carried out using the FANP computer code KWUSTOSS. KWUSTOSS is a finite element computer code with capabilities for solving non-linear dynamic problems. In addition, KWUSTOSS can account for FSI (fluid-structure interaction) effects. Solutions of sample problems are provided in Appendix B to demonstrate the adequacy of the code.

- General Model Description

Beam elements and non-linear spring elements are used to model [

]. Figure 4.4 depicts the configuration of two [ ]. The model representation of the configuration is also shown in Figure 4.4. The model is divided into discrete points with the mass and moment of inertia lumped at the nodes. [

]. The lower fuel support has a pinned boundary condition (no rotational constraint). The top end of the fuel channel is constrained to have the same translational and rotational displacements as the coincident fuel assembly node.

[

]. To analyze mixed core effects, the model is modified as shown in Figure 4.5. [ ]. Comparisons are made between a homogenous core (same fuel channels) or a mixed core (different fuel channel stiffnesses). [

] support [

].

- Model Characteristics

Since differences in fuel assembly designs may affect the fuel channel response, a parametric study was performed to bound fuel assembly characteristics. First, a channelled fuel assembly model (Figure 4.4) was established and shown to adequately represent a design by testing. Descriptions of tests for the verification of the model are given in Appendix C. Then, major parameters were varied individually to determine the model sensitivity in terms of the maximum fuel channel bending stress (or bending moment). From this investigation, a conservative "baseline fuel assembly" was created as a composite of the most conservative parameters (those which produce the highest bending stresses) from among the different fuel assembly designs. Subsequent calculations were then performed using this "baseline fuel assembly". [

]

Table 4.1 summarizes the results from the parametric analyses. Effects of the variables were judged [ ]. The parameters which were selected for the final calculations are indicated in the table. Aside from fuel assembly mass, the channelled fuel assembly response is dominated by the fuel channel [ ]. In addition, fuel assembly mass does not differ greatly from one design to another.

A discussion of the parameter study is provided below. The selection of damping factors and the inclusion of FSI effects are also covered in the following paragraphs.

- <u>Fuel Channel Stiffness</u>

[ ].

- <u>Lower Fuel Support Condition</u>

The fuel assembly lower tie plate rests on a 45° conical surface. Due to the weight of the fuel assembly on the fuel support, this interface gives some rotational restraint to the lower end and is not purely represented by either a pinned or fixed end condition. [ ]. This is the end condition which is selected for the analyses.

- <u>Fuel Assembly Mass</u>

A range of fuel assembly masses were considered for applicability to different FANP fuel assembly designs. Analyses show the [

] is used for the final calculations in Section 6.0.

- <u>Fuel Assembly Stiffness</u>

The fuel assembly stiffness was determined [

]

- Spacer Grid Stiffness

[

] was used for the final fuel channel calculations.

- Spacer Grid to Fuel Channel Gap Size

The gap between the spacer grid and inside wall of the fuel channel was [

] was selected for the subsequent analyses since the bending stress is slightly higher.

- Structural Damping

[

]

A damping factor, D, of [ ] was selected from the minimum of those values recommended in Reference (8). This damping factor is justified by the fact that [ ]. A lower damping factor has been determined to produce a larger response and the selection is therefore conservative. In this case, a value of [ ]. For the first mode, the amount of damping was less than [ ].

- Amplitude, Frequency, and Time Step Sensitivity

A study was conducted to evaluate the sensitivity of variations in frequency and load amplitude input on resultant loads from the non-linear analysis. Variations of ±10% excitation amplitude and ±10% frequency were considered separately. The KWUSTOSS model along with the fuel assembly parameters presented in Appendix C were used in the analysis. Loadings for the SSE cases from two plants (a Mark II BWR/4 plant and a Mark III BWR/6 plant) were varied.

Changes in the channel maximum bending moment were noted for the variations in frequency and amplitude as compared to the bending moment with no variation. The Table 4.2 lists the results for the BWR/4 SSE loading. These results show the increase in response to be [

]

For all analyses, the time step for the integration is [ ] second. To investigate the selection of the time step, a comparison was made to a smaller step of [ ] second. The results were approximately the same and no stability problems were encountered in any of the runs.

- <u>Fluid-Structure Interaction</u>

The FSI (fluid-structure interaction) has an effect on the natural frequencies which in turn, may affect the maximum response of the channelled fuel assembly. [

]:

[ ]

Table 4.1 RESULTS OF FUEL ASSEMBLY PARAMETER STUDY

Table 4.2 SENSITIVITY ANALYSIS OF AMPLITUDE AND FREQUENCY VARIATIONS

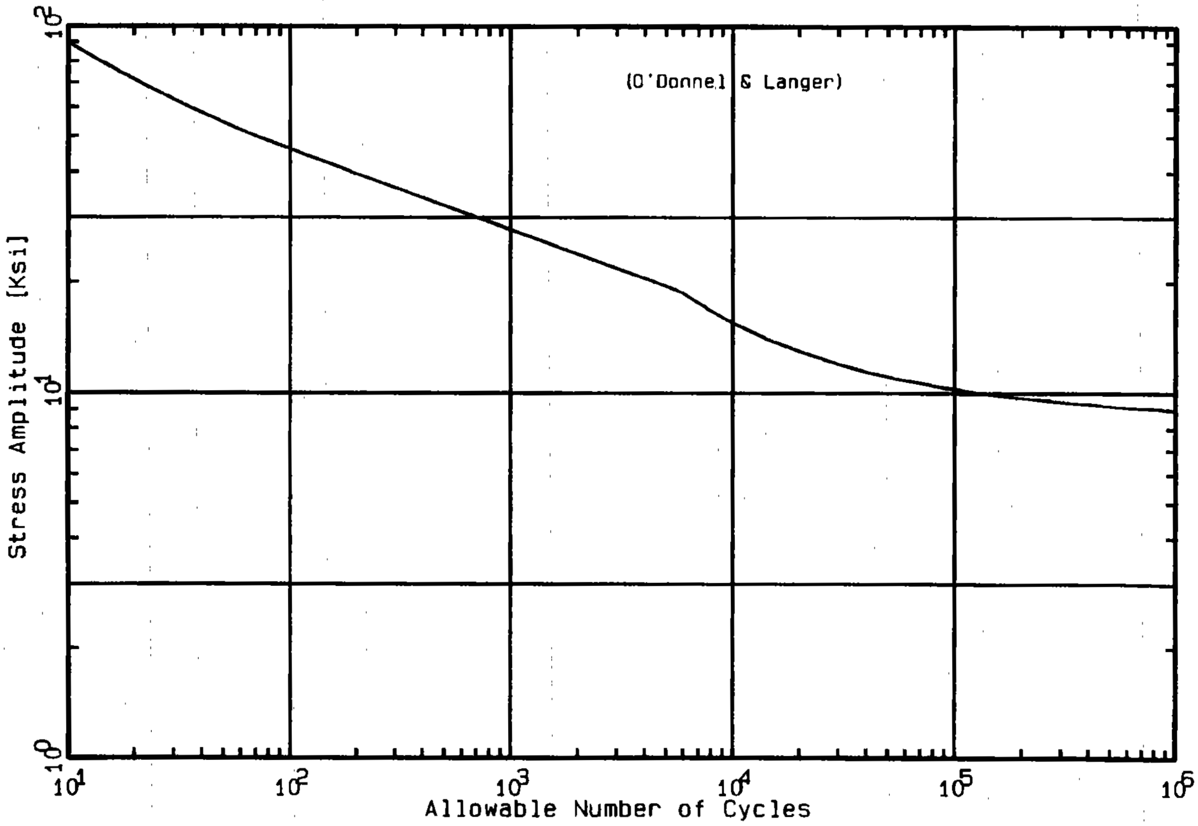

Figure 4.1 FATIGUE DESIGN CURVE FOR IRRADIATED ZIRCALOY

[ ]

Figure 4.2 SSE HORIZONTAL ACCELERATION RESPONSE SPECTRA AT FUEL SUPPORTS, BWR/4

Figure 4.3 ACCELERATION, VELOCITY, AND DISPLACEMENT TIME HISTORIES AT FUEL SUPPORTS

Figure 4.4 DYNAMIC MODEL OF TWO CHANNELLED FUEL ASSEMBLIES

Figure 4.5 DYNAMIC MODEL FOR MIXED CORE ANALYSIS

Figure 4.6 MEASURED LATERAL STIFFNESS OF FUEL ASSEMBLY

[ ]

Figure 4.7 MEASURED FUEL ASSEMBLY NATURAL FREQUENCIES VERSUS ACCELERATION

Figure 4.8 MODEL OF FUEL ASSEMBLY IMPACT TEST

Figure 4.9 CALCULATED AND MEASURED IMPACT FORCES AT MID-SPACER IN AIR

Figure 4.10 MODEL OF LATERAL DYNAMIC SPACER GRID IMPACT TEST

[ ]

Figure 4.11 MEASURED NATURAL FREQUENCIES OF CHANNELLED FUEL

5.0 LOADS

During normal operation, the primary load on the fuel channel is the operating ΔP (differential pressure) across the fuel channel wall. The channel wall experiences bending stresses due to the ΔP. Cyclic variations in differential pressure occur as a result of reactor power and flow changes.

The loadings on the fuel channel which may occur during a seismic/LOCA event consist of the following in addition to the normal operating ΔP:

- Increased ΔP across fuel channel wall during blowdown
- Core support motions due to SSE (safe shutdown earthquake)
- Core support motions due to AP (annulus pressurization) loads for the DBA (Design Basis Accident) pipe break
- Core support motions due to chugging loads
- Core support motions due to CO (condensation oscillation) loads
- Core support motions due to SRV (safety/relief valve) actuation loads

The differential pressure values presented in this section are intended to apply to all current FANP fuel and channel designs. A case is presented based on a set of seismic/LOCA loadings for a [ ].

The above loadings for accident conditions are combined as described in Section 5.2.3.

5.1 *Normal Operating Loads*

5.1.1 Fuel Channel Differential Pressure

The maximum ΔP value across the fuel channel wall for use in the normal operation stress analysis (including AOO) is [ ]. This pressure is the sum of the maximum normal operating ΔP [ ] plus the increase [ ] for AOO.

The steady state operating pressure was evaluated using the XCOBRA[10] code [ ]. The maximum ΔP value also applies to FANP fuel [ ]. The thermal/hydraulic analysis was done [ ]. The increase in pressure during an AOO is [

].

5.1.2 Fatigue Damage Analysis

The differential pressure used in the fatigue damage analysis reflects power level changes during typical normal operation and anticipated operational occurrences. These cyclic power variations are defined in Table 5.1.

5.1.3 Channel Design Life

The channel design residence life for the corrosion and hydride calculations is bounded by the fuel assembly calculations because of the higher temperature and thinner wall of the fuel rod cladding. Fuel channels are exposed for the lifetime of one fuel assembly.

Control cell loading is a variable in the statistical evaluation of the channel creep deflection. It is assumed that all four assemblies in one core cell are exposed to the discharge burnup. This configuration conservatively envelopes other possible fuel management schemes.

5.2 ***Accident Loadings***

5.2.1 Blowdown Load

[

].

5.2.2 Seismic and Core Support Excitations

During a seismic event, the motions of the ground are transmitted through the basemat of the containment structure through the RPV to the supports for the core. In addition, loads on the containment structure due to chugging, CO, and SRV are transmitted to the core supports through the RPV. Each fuel assembly is supported at the bottom by a fuel support casting and at the top by a grid of guide beams. Both horizontal and vertical excitations result on the lower fuel support and only horizontal excitations are exerted on the fuel at the upper guides.

Figure 5.2 shows the relevant horizontal ARS (acceleration response spectrum) at the core supports for a [ ] For the SSE, the loading is shown for the lower support only while the other plot indicates the average of the upper and lower supports. [ ]. To account for the higher loads at the upper guide beam during an SSE, [ ]. Only the horizontal ARS are shown since the vertical analysis is done separately based on maximum permissible liftoff (in Section 6.2.1).

[ ].

5.2.3 Load Cases

[

].

Table 5.1 DESIGN DUTY CYCLES FOR CYCLIC FATIGUE

Duty Cycle Description		Total Number of Cycles
1.	Startup following a refueling shutdown or major shutdown	[ ]
2.	Load follow - weekly reduction to 50% power	[ ]
3.	Load follow - daily reduction to 75% power	[ ]
4.	Control blade movements	[ ]
5.	Startup following a cold shutdown or minor shutdown	[ ]
6.	Recovery following a scram	[ ]
7.	Loss of feedwater heaters	[ ]
8.	Turbine trip	[ ]
Total no. of cycles		[ ]

Figure 5.1 FUEL CHANNEL DIFFERENTIAL PRESSURE VERSUS AXIAL LOCATION

Figure 5.2 HORIZONTAL ARS AT FUEL SUPPORTS, BWR/4

6.0 EVALUATION

Analysis results presented in this section for all four fuel channel designs and are divided into the two categories of normal operation and accident conditions. For normal operation, fuel channel stresses, cyclic fatigue, oxidation and hydrogen concentration are evaluated.

For accident conditions, the fuel channels are analyzed for the differential pressure during blowdown, vertical accelerations, and horizontal excitations. [

] in addition to the KWUSTOSS code. Only the first three types of fuel channel designs (excepting the BWR/6 100 mil FC) are analyzed under the plant horizontal loadings given in Section 5.0. Due to the higher allowable bending moment for the BWR/6 100 mil FC, analysis of the 80 mil FC is conservatively bounding.

Results are provided in comparison to allowables. In all cases, the calculations meet the design criteria.

6.1 *Normal Operation*

6.1.1 Fuel Channel Stresses

Finite element analyses are performed to evaluate the normal operating stresses in the fuel channels. Membrane stresses and membrane plus bending stresses are evaluated by a plastic analysis. To determine the stresses and deformations due to differential pressure, the ABAQUS(14) or ANSYS(18) finite element code is used.

Four fuel channel designs are considered in the analyses. All four fuel channels are evaluated by the use of two models. Under the same ΔP loading, the 100 mil FC has lower stresses than the 80 mil FC. The 80 mil FC analysis therefore conservatively applies to both fuel channels.

Both AFCs are evaluated with a second model. [

].

Due to symmetry in the cross-section geometry of any given channel, the two models for the uniform 80 mil FC and the AFCs are reduced to an octant configuration. [ ].

Figure 6.3 shows the deflection of the middle of the wall versus applied pressure load for the 80 mil FC model and the AFC model. In all cases, the deflection limit is achieved prior to reaching the collapse load criterion. [ ].

The maximum stresses occur just above the lower tie plate elevation where the ΔP is the greatest. At this location, the normal operating ΔP (including AOOs) is [ ]. The 80 mil FC satisfies the design criteria as the normal operating pressure is less than the allowable pressure.

The allowable pressure for the advanced channel case is higher than for the 80 mil FC. Table 6.1 summarizes the results with a listing of the maximum allowable pressures and deformations from the two cases. The advanced channels also satisfy the criteria.

An additional calculation was performed to determine the pressure at which [ ].

Creep deformation is addressed as part of the long-term evaluation of bulge and bow in Section 7.0

The maximum pressure load calculated at the [ ]. The maximum normal operating pressure of [ ]. The results for the AFC, as well as for the 80-mil FC, are listed in Table 6.1.

The above results apply to beginning of life conditions when the material strength is the lowest. Beginning of life conditions are limiting because the calculated increase in stress from wall thinning (oxidation) at end of life are offset by the increase in material strength from irradiation.

6.1.2 Fuel Channel Fatigue

The different duty cycles in Table 5.1 are evaluated by the use of [ ] is assumed to occur at a frequency corresponding to the total of [ ]. The wall was thinned according to the projected amount of oxidation at the end of life. From the stress versus allowable number of cycles curve given in Figure 4.1, the allowable number of cycles for such a stress amplitude is calculated to be greater [ ]. The anticipated number of cycles of [ ] lower than this value, and the criterion is satisfied.

[ ].

6.1.3 Corrosion and Hydrogen Concentration

Wall thinning due to oxidation is taken into account in the stress and cyclic fatigue analyses. The amount of wall thinning from oxidation is small relative to the wall thickness. Oxidation (one side) at the end of life is projected to be [ ].

Hydriding is greater for thinner-walled components. The fuel channel with the thinnest wall is the [ ]. Such a concentration will not impair the structural integrity of the fuel channel. For the same oxidation, smaller concentrations of hydrogen will occur in the thicker-walled cross-sections of the other fuel channel designs.

6.2 *Accident Evaluation*

Evaluation results for the four fuel channel types under faulted conditions are given along with a comparison to the criteria. Two independent analyses are presented: 1) a non-linear dynamic analysis of the fuel assembly and fuel channel is accomplished by the direct time integration method (using the KWUSTOSS computer code), and 2) an analysis using the RSA (response spectrum analysis) method. These methods are described in Section 4.0.

The calculated primary membrane stress intensity from the ΔP and vertical accelerations are shown to be small in comparison to the design criteria. The acceptability of the ΔP loading from normal operation plus the LOCA blowdown ΔP loads is evaluated using plastic analysis criteria in a manner similar to the analysis for the normal operation ΔP. The maximum combined lateral bending moments due to the horizontal excitations are less than the allowable bending moment loading for each fuel channel type.

Fuel channel bending moments calculated by [ ] obtained from the more accurate model representation used with the [ ].

6.2.1 Fuel Channel Stresses

- Membrane Stresses Due to Pressure and Vertical Accelerations

Membrane stress intensity caused by the normal operating ΔP plus the added ΔP during a blowdown is small. The membrane stress from the ΔP is calculated using a standard engineering mechanics formula for a thin-walled tube under internal pressure. For the total ΔP [ ], the membrane stress is less [

].

The highest stress occurs at the bottom of the fuel channel where the ΔP is the maximum.

The vertical accelerations produce a membrane stress in the axial direction. For the determination of these axial stresses, the maximum loads are expected to occur as the result of the channelled fuel assembly impacting the fuel support after liftoff. A maximum liftoff height of [ ] is selected. This amount is greater than the maximum allowable liftoff height for retaining the lateral position within the fuel support.

The impact problem is solved using basic principles [

].

The membrane stresses from the ΔP and vertical acceleration are combined by direct addition for a resultant stress intensity. The maximum stress intensity [ ] occurs at the top of the fuel channel and is equal to the axial membrane stress from the vertical acceleration. The criteria allows a membrane stress of up to [ ]. Calculated membrane stress is much less than the allowable. [

].

- <u>Primary Membrane Plus Bending Stresses From ΔP</u>

Stresses due to ΔP are evaluated in the same manner as given for the normal operation plus AOO evaluation (Section 6.1.1). According to the criteria, [

]. As described in Section 6.1.1, [ ] cases are considered which cover the four fuel channel designs.

As for the analyses of AOO, [

]. This allowable is greater than the maximum pressure during [
]. The design criterion is satisfied.

Table 6.4 lists the calculated allowable pressures and deformations for the two cases. Both AFCs and the BWR/6 100 mil FC also meet the design criterion.

6.2.2 Bending Moments Due to Horizontal Excitations

- KWUSTOSS Evaluation

The bending moments produced by the deflection of the fuel channel from each of the separate horizontal excitations (e.g., SSE, chugging and etc.) are calculated using the KWUSTOSS code as described in Section 4.0. These bending moments are then combined by the SRSS method for comparison to the allowable load. Table 6.5 lists the calculated maximum bending moments for SSE, AP FWLB (annulus pressurization feedwater line break), chugging, and SRVA.

In combining the loads, the following load cases are considered (refer to Section 5.0):

Case 1 (N + ΔP + SSE + AP)

Case 2 (N + ΔP + SSE + Chugging + SRV)

[

].

Table 6.5 shows the combined bending moments for three of the fuel channel types along with the allowables for comparison. The calculated total bending moments are well below the allowable bending moments.

- Response Spectrum Analysis (RSA)

The preceding results are obtained through a non-linear analysis using the direct time integration method. To assess the acceptability of the fuel channel designs under other seismic/LOCA loads, the simpler RSA method is also used. A comparison between the RSA method and the non-linear, direct time integration method indicates generally higher calculated bending moments with the RSA method.

Application of the RSA method is illustrated by the following example case using the SSE loading (Section 5.0) on the 80 mil fuel channel:

[

] Calculated bending moments by both methods meet the respective allowables.

Some observations are noted below in comparing the results given by the two methods:

[

]. The factors in the table permit the evaluation of specific plant horizontal loads for determining the acceptability of a fuel channel design. [

].

6.2.3 Mixed Core Evaluation

Use of different fuel channel designs within the same core will lead to differences in the response of the channelled fuel assemblies. The dominant factors controlling the channelled fuel assembly response [

].

[ ].

The mixed core case was investigated [

].

Table 6.1 FUEL CHANNEL PRESSURE ANALYSIS RESULTS (NORMAL OPERATION)

[ ]

Table 6.2 FUEL CHANNEL CYCLIC FATIGUE ANALYSIS RESULTS

[ ]

Table 6.3 FUEL CHANNEL OXIDATION AND HYDROGEN ABSORPTION RESULTS

[ ]

Table 6.4 FUEL CHANNEL PRESSURE ANALYSIS RESULTS (ACCIDENT CONDITIONS)

Table 6.5 FUEL CHANNEL BENDING MOMENT FROM KWUSTOSS (ACCIDENT LOADINGS)

Table 6.6 FUEL CHANNEL BENDING MOMENT FROM RSA (ACCIDENT LOADINGS)

Table 6.7 FUEL CHANNEL BENDING MOMENT – SPECTRAL ACCELERATION RELATIONS

[ ]

Figure 6.1 FINITE ELEMENT MODEL OF FUEL CHANNEL FOR ΔP STRESS ANALYSIS

Figure 6.2 STRESS-STRAIN CURVE FOR ΔP PLASTIC ANALYSIS

Figure 6.3 CALCULATED MID-WALL DEFLECTION VERSUS PRESSURE

7.0 FUEL CHANNEL CREEP DEFLECTION

Changes to the geometry of the fuel channel occur due to creep deformation during the long term exposure in the reactor core environment. Overall deformation of the fuel channel occurs from a combination of bulging and bowing. Bulging of the side walls occurs because of the differential pressure across the wall. Lateral bowing of the channel is caused primarily from the neutron flux and thermal gradients. Too much deflection may prevent normal control blade maneuvers and it may increase control blade insertion time above technical specification limits. For conventional fuel channels, which are irradiated for the life of a single fuel assembly, the deflections have not resulted in general problems with control blade interference. Since the advanced fuel channels have geometries which differ from the conventional designs, analyses have been performed for potential control blade interference.

The analyses are described in these basic steps:

1) Analyze bulging of the fuel channel by creep deformation.
2) Statistically characterize bulging, bowing and other parameters (e.g., control blade roller thickness). Correlate bulge and bow based on irradiated fuel channel measurement data.
3) Determine maximum probable interference between fuel channel and control blade.

7.1 *Fuel Channel Bulging by Creep*

For a given fuel channel and temperature, bulge rate due to creep is a function of time, operating stresses, and fast neutron fluence. Elastic deflection of the fuel channel is dependent on the stresses from the differential pressure. The stresses in the fuel channel are calculated from an elastic solution for [ ]. A creep law formulation is benchmarked to bulge measurements on irradiated fuel channels. The total bulge deformation is the elastic deflection plus the creep deformation accumulated over the life of the fuel channel.

Channel stresses for the bulge analysis are calculated [

] Because of symmetry, it is necessary to consider only one-eighth of the fuel channel cross-section. The cross-section extends from the middle of the side wall to the middle of the adjacent corner. The corner, included in a 45° angle, comprises one curved segment while the remaining half of the side wall is divided into three segments. [

].

Creep deflection of the fuel channel is calculated in time steps and the creep increments are accumulated over the residence life. [

].

The form of the creep law and the constants were selected to provide good agreement with measured bulge deformation of irradiated fuel channels. Figures 7.1 and 7.2 show calculated versus measured diametral bulge [

]. As shown in the figures, the creep expression and model give a conservative estimate of bulge.

7.2 *Statistical Characterization of Calculation Parameters*

The differential pressure histories, radial and axial fast flux gradient histories, tolerance variations in fuel channels, residual stresses, and initial clearances vary from channel to channel. Measurement data are used to characterize channel bulging and bowing. In addition, variations in fuel assembly spacing and control blade thickness due to fabrication tolerances should be considered. Therefore, a statistical approach was established to evaluate these variations on the control blade clearances.

The process described here establishes the mean and standard deviations for the bulge and bow along with the fabrication tolerances as input for a Monte Carlo analysis. Statistics on bulge and bow are derived from a measurement database on fuel channels* [

]

In addition, the axial location of the maximum bulge and bow values are available [ ]. These data include values for other channel manufacturers. It is assumed that the axial location of the maximum bulge and bow is not significantly affected by manufacturing processes. The bulge and bow statistics are updated as new measurements become available.

7.2.1 Axial Location of Maximum Channel Bulge

Figure 7.3 shows the distribution of the axial location of maximum channel bulge. [

* Fuel channels are primarily of the FANP design manufactured by Carpenter Technology Corporation.

].

7.2.2 Axial Location of Maximum Channel Bow

Figure 7.4 shows the distribution of the axial location of maximum channel bow. [

]

7.2.3 Axial Variation of Channel Bulge and Bow

To determine the channel bulge and bow at locations other than that of the maximum values, the variations in bulge and bow must be established over the channel length. The channel measurement database consists [

].

Figures 7.5 and 7.6 show examples of sample measurements and the [ ] comparison. Measurement data and the [ ] are in good agreement in the lower, most important channel region.

With this approach, the channel deformation over the entire length is established.

7.2.4 Maximum Channel Bulge

The maximum channel bulge occurs, as shown in Figure 7.3, [

]:

An average differential pressure is derived as described in Section 7.1 using the mean value of channel bulge. With this differential pressure, the average bulge for the advanced channels and the BWR/6 100 mil FC can be predicted from the creep bulge analysis.

Figures 7.7 and 7.8 show the mean and standard deviation for bulge as a function of the exposure. The standard deviation of bulge deformation measurements is used in determining the uncertainty in bulge deformation from the mean bulge calculated by the creep analysis. [

].

7.2.5 Maximum Channel Bow

Maximum lateral deflection is highly dependent on the core position and on the burnup of adjacent fuel, resulting in channel bow. The direction of the initial as-fabricated bow is determined and the channel is oriented such that the initial deflection is away from the control blade. Measurement data indicates that bow continues to increase away from the control blade and D-lattice plants experience significantly higher bow. Also, the standard deviation in bow is higher for a D-lattice plant.

Figures 7.9 and 7.10 show the mean and standard deviation of bow measurements for fuel channels in three plants. [

].

7.2.6 Miscellaneous Data Considerations

The effects of core component tolerances on channel gaps are included in statistical analyses. Control blade roller thickness, sheath thickness, control blade contact pad dimensions, and core cell tolerances are considered. The tolerance limits are taken to be [

].

7.3 *Statistical Analysis of Compatibility*

The statistical analysis used for channel design is based on the Monte Carlo method. Parameters are randomly selected to arrive at the amount of clearance or encroachment of the control blade by the fuel channels. This process is repeated a large number of times to obtain the maximum encroachment with a certain confidence level. The maximum encroachment is compared to the amount of control blade interference which can be tolerated.

For a specific Monte Carlo simulation of the gap conditions in a core cell, the following random values are generated:

[

]

The value, x, is determined by the amount of tolerable friction force between the control blade and the fuel channels. When the force between the control rod drive and control rod coupling during withdrawal is lower than the allowable force, a SCB (stuck control blade) condition may occur. In the case of a free movement of the control rod, i.e., no friction between channels and control blade, the magnitude of the force is equivalent to the control blade weight in water, disregarding inertial forces. In the case of an interference between channels and control blade, the force is reduced due to friction.

The permissible interference between channels and control blade depends on the following parameters:

[

]

The fuel channel stiffness is calculated [

].

7.4 *Channel Deflection Evaluation Results*

Using the methods described in the preceding sections, the deflections of the AFCs and BWR/6 100 mil FC were analyzed for compatibility with the control blade. The 80 mil FC was also analyzed to provide a reference point for comparison with the other fuel channels.

Table 7.1 summarizes the minimum margin without a SCB condition for the four fuel channel designs in their given core cell configurations. In all cases, positive margins remain throughout the channel lifetimes with a 95/95 confidence level. The 80 mil FC has the smallest remaining deflection without a SCB.

Table 7.1 FUEL CHANNEL DEFORMATION (NORMAL OPERATION)

* Results are at an exposure of 54 MWd/kgU, except for the BWR/6 100-mil FC, which is at an exposure of 50 MWd/kgU.

[ ]

Figure 7.1 CALCULATED VERSUS MEASURED BULGE FOR IRRADIATED FUEL CHANNELS (PLANT A)

Figure 7.2 CALCULATED VERSUS MEASURED BULGE FOR IRRADIATED FUEL CHANNELS (PLANT B)

Figure 7.3 AXIAL LOCATION OF MAXIMUM CHANNEL BULGE

Figure 7.4 AXIAL LOCATION OF MAXIMUM CHANNEL BOW

Figure 7.5 POLYNOMIAL APPROXIMATION OF CHANNEL BOW AND BULGE

Figure 7.6 POLYNOMIAL APPROXIMATION OF CHANNEL BOW AND BULGE

Figure 7.7 MEAN BULGE FOR DIFFERENT CHANNEL DESIGNS AND PLANTS

[ ]

Figure 7.8 STANDARD DEVIATION OF BULGE FOR DIFFERENT CHANNELS AND PLANTS

Figure 7.9 MEAN BOW FOR DIFFERENT CHANNEL DESIGNS AND PLANTS

[ ]

Figure 7.10 STD. DEVIATION OF BOW FOR DIFFERENT CHANNELS AND PLANTS

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9.0 LIST OF APPENDICES

Appendix A DERIVATION OF FUEL CHANNEL BENDING MOMENT ALLOWABLES

A.0 Summary

Allowable bending moments are derived using the ASME B&PV Code, Section III, Division 1, Appendix F criteria for a plastic analysis collapse load. These bending moments are used to assess the acceptability of the fuel channels under horizontal accident excitations. Four fuel channels were analyzed: 1) the 80 mil FC, 2) the BWR/3,4 AFC, 3) the BWR/6 AFC, and 4) the BWR/6 100 mil FC.

An elasto-plastic collapse analysis was performed using the finite element method. [

]. The maximum allowable bending moment was evaluated according to the method given in the ASME B&PV Code [ ]. The analyses were repeated for the other three fuel channel designs.

A.1 Finite Element Model

A detailed finite element model was created using MSC/NASTRAN. [ ]. The solution provides for the capability to analyze structures undergoing both geometric non-linearity (large displacement) and material non-linearity.

Due to symmetry, a half-length model was sufficient [

].

A.2 Test Verification

Testing was conducted on an instrumented, 80 mil full length fuel channel. [

].

Room temperature material properties were used. Samples from the cut-off ends of the test channel were tested to obtain the tensile values. The test curve was taken to be [ ]. Figure A.2 shows the material stress-strain curve for the test verification analysis.

To represent the test, the loading was applied in two stages. First a one g gravity force was applied in the downward direction. Then a concentrated load was prescribed in the upward direction as applied by the hydraulic cylinder. For a second run, the load was applied in the form of an enforced constraint in the upward lateral direction. The enforced constraint most closely resembles the test condition.

[ ].

Test results are overlaid on the same figure. The differences between the two curves are a result of the prior repeated loading during testing. Good agreement was reached with the test results in the elastic regime during initial load tests and the buckling failure load.

[ ].

A.3 Load Evaluation

To determine the allowable load, the maximum bending moment versus deflection was plotted for each of the four fuel channel designs. Figure A.5 is a plot of the results for the 80 mil FC. The output was evaluated using Article II-1000 of Section III, Division 1 of the ASME B&PV Code for the maximum allowable collapse load. Table A.1 summarizes the allowable loads for the four fuel channels.

Table A.1 FUEL CHANNEL BENDING MOMENT ALLOWABLES

Figure A.1 FINITE ELEMENT MODEL OF FULL LENGTH FUEL CHANNEL

Figure A.2 MATERIAL STRESS-STRAIN CURVES

Figure A.3 FULL LENGTH FUEL CHANNEL BENDING MOMENT TEST

Figure A.4 MODEL VERIFICATION RESULTS WITH CHANNEL TEST

[ ]

Figure A.5 BENDING MOMENT - DISPLACEMENT RESULTS FOR 80 MIL FC

Appendix B KWUSTOSS COMPUTER CODE SAMPLE PROBLEMS

B.0 Introduction and Summary

Four "sample" problems are solved with the KWUSTOSS to demonstrate that the code is capable of obtaining accurate results as compared to other methods. These sample cases serve to validate the results from the fuel channel analyses. The following problems are selected to exercise the capabilities used in the analyses, such as beam elements and nonlinear spring elements:

Sample Problem No.	Description
1	Simply supported beam with base excitation.
2 2a	Beam, one end pinned, other end supported by a linear spring, base excitation. Same as Case 2 except different excitation function
3 3a	Beam, one end pinned, other end supported by nonlinear springs, base excitation. Same as Case 3 except different excitation function
4 Case 1 Case 2 Case 2a	Solution of NRC standard problem, five-assembly row of PWR fuel assemblies, Reference (B.1). Case 1, 2, and 2a consist of differing excitation functions

The first problem is basic and a textbook solution is available for comparison. The next two problems introduce additional complexities to the first problem to show the effect of the spring elements. To show the sensitivity of the response to different degrees of nonlinearities, different gap sizes are studied in problem no. 3. These first three problems resemble the model used for the analysis of a channelled BWR fuel assembly.

The NRC standard sample problem, while not strictly relevant to the BWR analyses, has been studied in depth[B.1] in the past. It exercises the nonlinear capabilities of KWUSTOSS and results are presented as an additional comparison to prior work.

Solutions to the above problems are in close agreement with the answers obtained by other means.

B.1 Problems 1, 2, and 3

Figure B.1 shows diagrams of the models for problems 1 to 3. Problems 2 and 3 are variations of the first one to demonstrate the use of linear and nonlinear spring elements, respectively. Model parameters are also shown in Figure B.1 along with the excitation functions.

Results for the first two problems are tabulated in Table B.1. Theoretical solutions accompany the KWUSTOSS results.

A comparison of results for different gap sizes and excitation amplitudes is shown in Table B.2 for problem 3. This study shows that for a larger relative excitation amplitude, there is little change in the maximum response for different sized gaps.

B.2 Solution to NRC Standard Sample Problem

The NRC standard sample problem consists of five PWR fuel assemblies in a row bounded on both sides by the core shroud. Horizontal excitations are applied to the core supports and core shroud. Using parameters defined for the problem, the spacer grid impact loads are calculated. The direct time integration method as implemented in KWUSTOSS is used for the analysis of the NRC Standard Sample Problem.

B.2.1 Problem and Model Description

- Reactor Core and Input Loads

The reactor core for the sample problem consists of 13 fuel assemblies with five fuel assemblies on the major diameter. Figure B.2 shows the reactor core's plan view and cross section. The gaps between the peripheral fuel assemblies and the baffle or core barrel are 0.06 inch and the gaps between the fuel assemblies are 0.03 inch. Three cases which differ in excitations functions are considered. These three cases are listed in Table B.3.

For Case 1, the displacement function is a simple sine wave with a frequency of 3 Hz and an initial velocity of 9.425 inch/s which is imposed on the upper and lower core plates.

The displacement function for Case 2 is divided into two parts: Case 2a has three sine components with frequencies of 3.183, 15.9, and 86 Hz. A time delay of 0.006 s is imposed on the displacement functions applied to the upper and lower core plates. Case 2b has an amplitude four times greater than Case 2a. Figure B.2 shows the phasing difference for the baffle.

Figures B.3 and B.4 are plots of the excitation functions versus time.

- <u>Fuel Assembly and Core Model</u>

The five-assembly row is represented by the model shown in Figure B.5. The fuel assemblies have the dimensions and characteristics given in Figure B.6. [

].

B.2.2 Analysis Results

Maximum calculated spacer grid impact forces are summarized in Table B.3 for the three cases along with the locations of maximum impact forces. Table B.4 lists the maximum results in comparison to previous solutions of the problem.[B.1,B.2] The KWUSTOSS code results agree well with the other solutions.

B.3 REFERENCES

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Table B.1 SOLUTIONS FOR SAMPLE PROBLEMS 1 AND 2

Variable	Case		
	1	2	2a
f_1, Hz			
$\delta(f_1)$, m			
μ_1			
A_1, m			
y_{max}, theoretical			
y_{max}, KWUSTOSS			

Where

Table B.2 SOLUTIONS FOR SAMPLE PROBLEM 3

Gap size, m	y_{max}, m	
	Case 3 (A_1 = 0.01)	Case 3a (A_1 = 0.0025)
0.0		
0.00001		
0.0001		
0.001		
0.002		

Table B.3 LOCATIONS OF MAXIMUM IMPACT LOADS (SAMPLE PROBLEM 4)

Table B.4 MAXIMUM SPACER IMPACT LOAD COMPARISON (SAMPLE PROBLEM 4)

Figure B.1 MODEL DIAGRAMS FOR SAMPLE PROBLEMS 1, 2, & 3

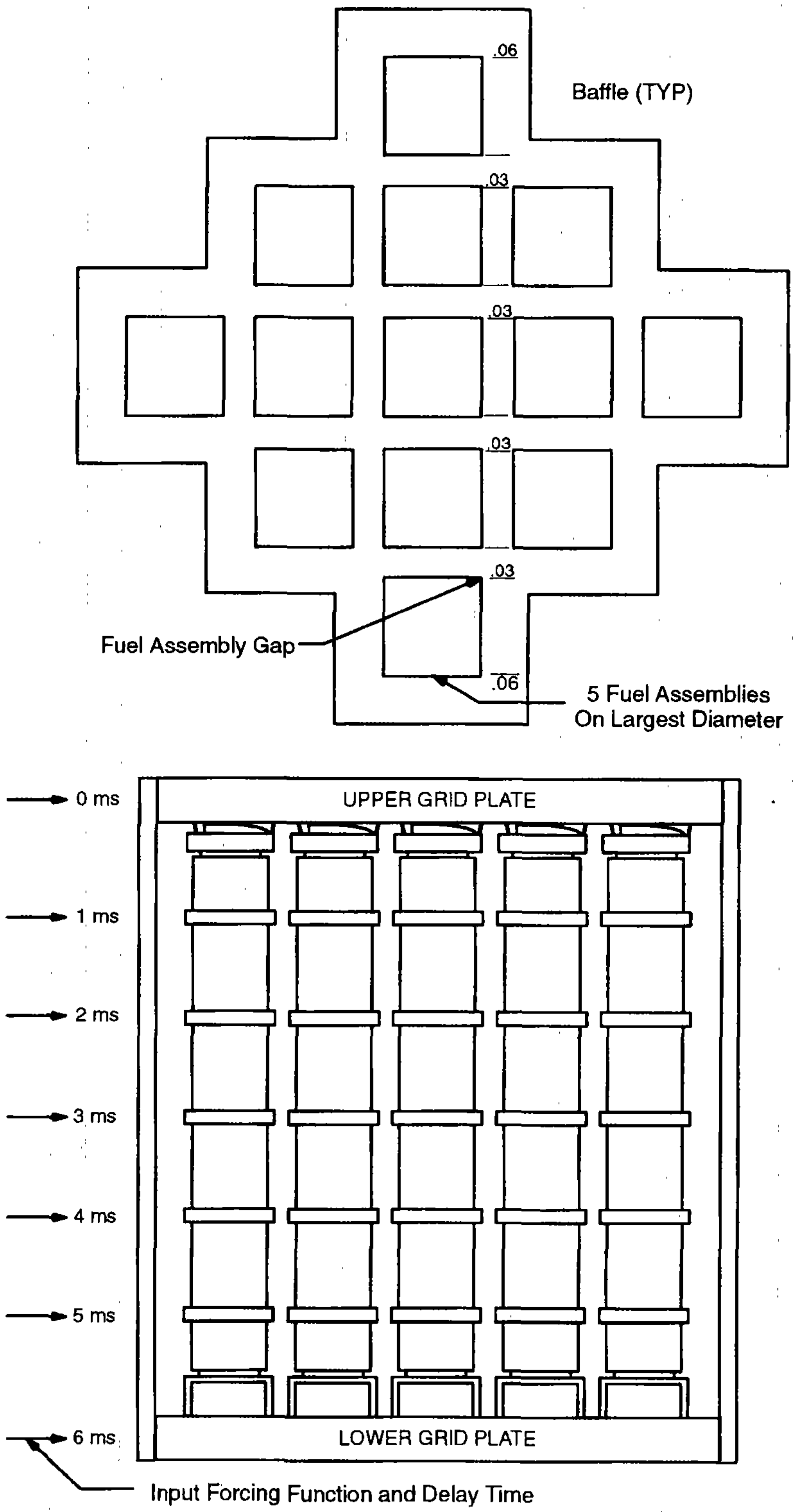

Figure B.2 REACTOR CORE CROSS SECTION (SAMPLE PROBLEM 4)

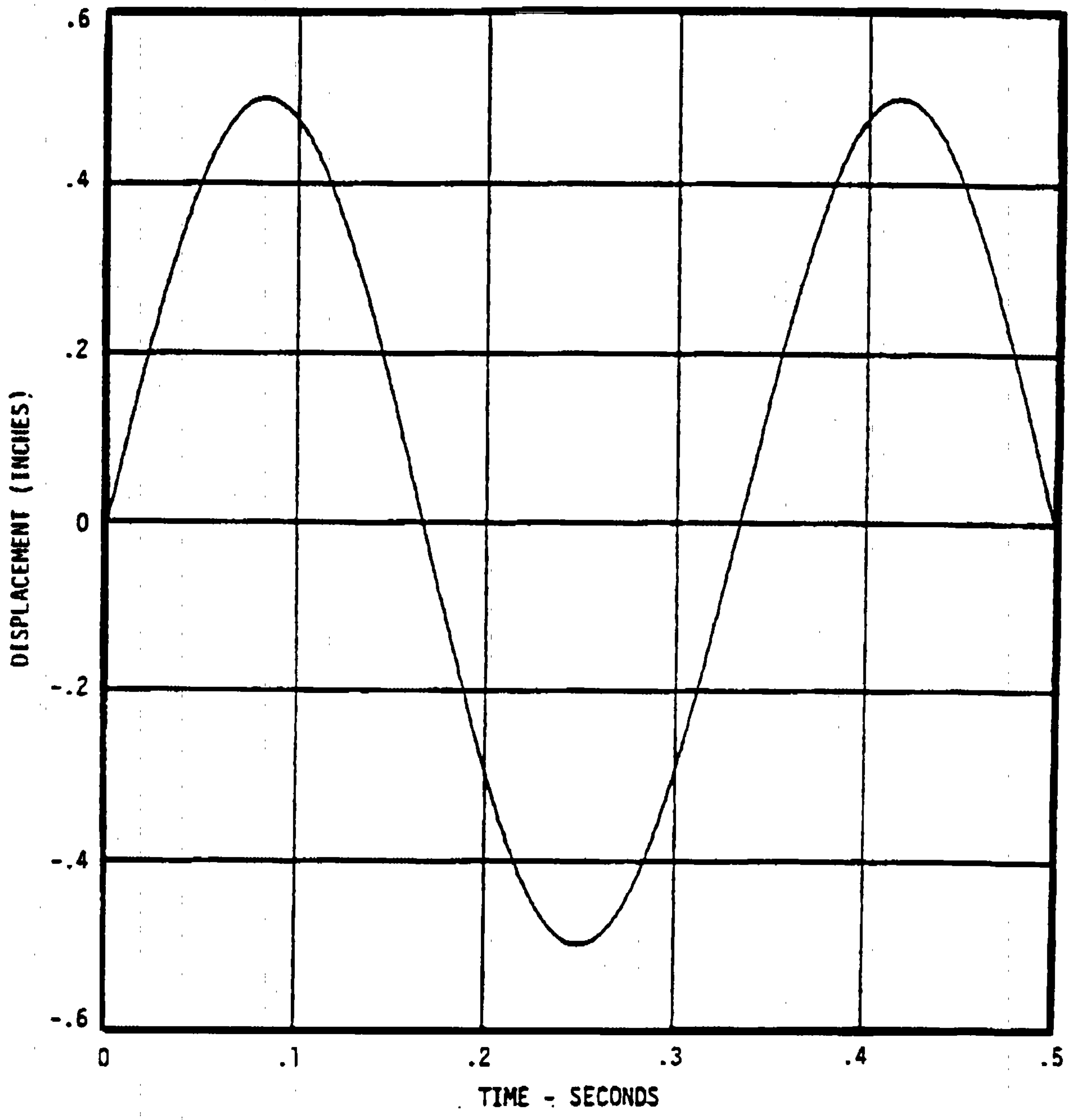

Figure B.3 CASE 1 SINE INPUT (SAMPLE PROBLEM 4)

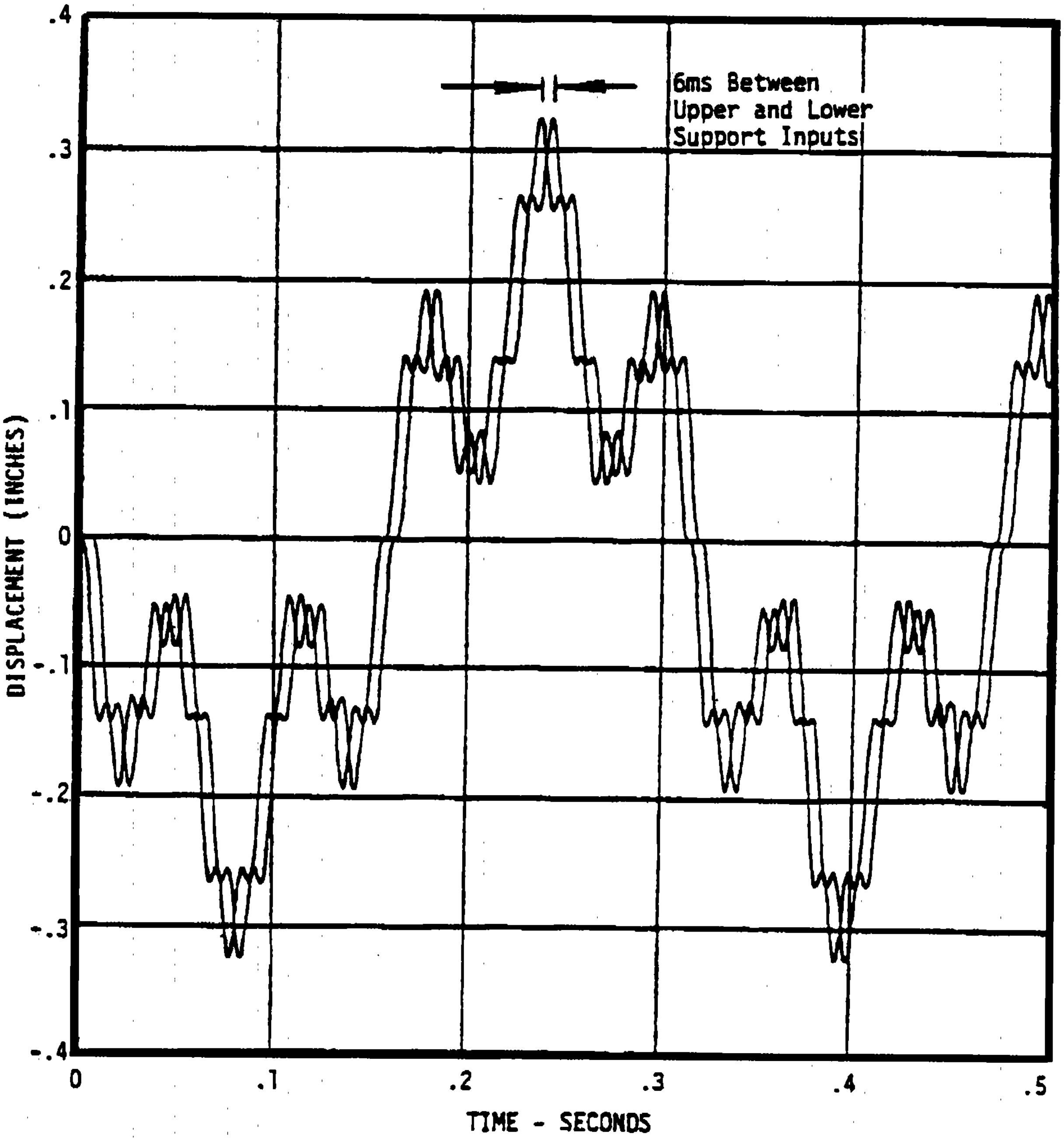

Figure B.4 CASE 2B THREE FREQ. SINE INPUT (SAMPLE PROBLEM 4)

Figure B.5 FIVE ASSEMBLY STRUCTURAL MODEL (SAMPLE PROBLEM 4)

Figure B.6 FUEL ASSEMBLY CHARACTERISTICS (SAMPLE PROBLEM 4)

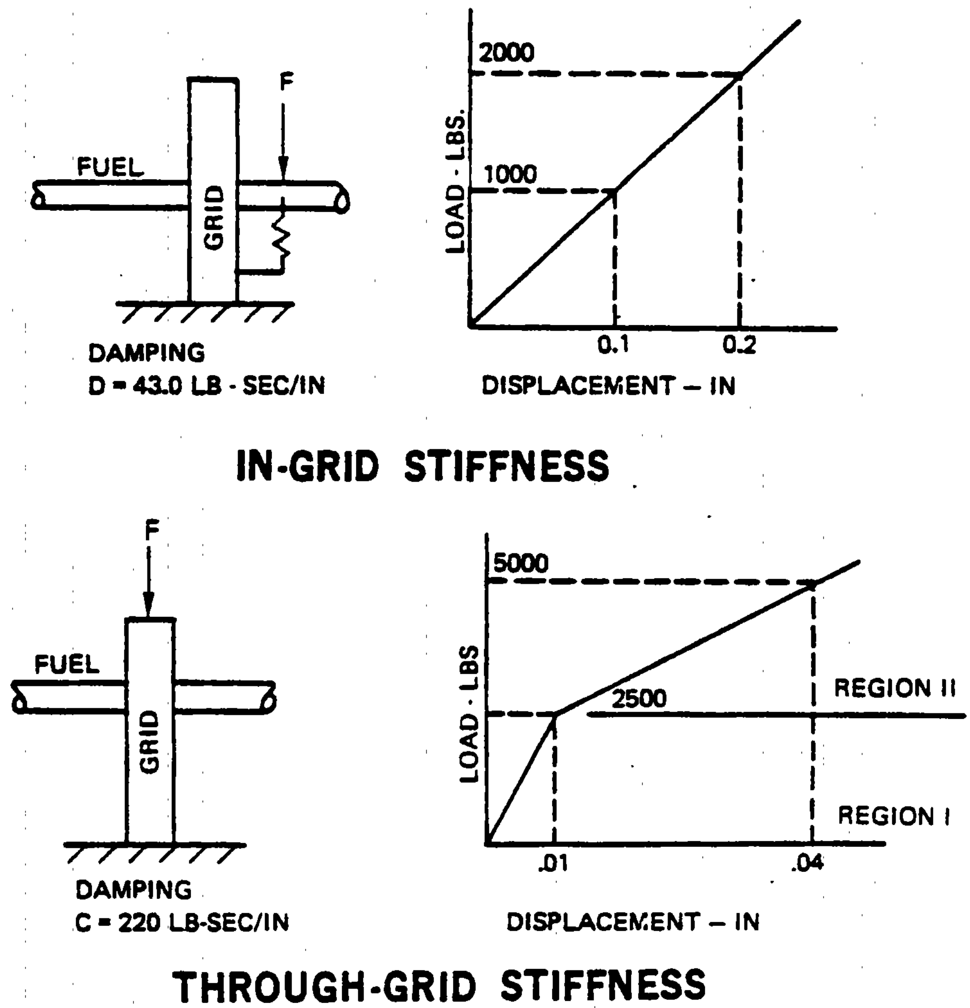

Figure B.7 SPACER GRID MODEL CHARACTERISTICS (SAMPLE PROBLEM 4)

Appendix C TEST VERIFICATIONS

C.0 Summary

Static structural tests and dynamic tests were performed on channelled fuel assemblies, fuel assemblies, and components to verify proper computer modeling in the analyses and to obtain certain characteristics for model parameters. The following tests were performed and analyzed:

[ ]

The above tests were performed for different FANP fuel assembly and fuel channel designs. In this appendix, the testing is primarily described for one particular fuel assembly in conjunction [ ] summarizes the different tests along with a brief description of the characteristics derived from the tests and the analytical modeling. A more detailed description of the test arrangements and results follow.

Table C.2 lists the characteristics for the test assembly. The model for this fuel channel and fuel assembly design are used in Section 4.2.3 in a sensitivity study to establish conservative parameters for subsequent calculations with the design loadings.

C.1 Fuel Assembly Static Lateral Deflection Test

Unlike a fuel channel, the fuel assembly structure is much more complicated and a lateral deflection test is used to determine the stiffness. The stiffness is obtained [

].

C.2 Lateral Vibration Tests

Testing of the BWR/6 advanced fuel channel along with a fuel assembly was carried out on the SHP1 (servo hydraulic test facility) in Erlangen, Germany. The vibration machine was used in determining the natural frequencies, damping, and spacer grid impact stiffness for a fuel assembly. Natural frequencies were also obtained for a channelled fuel assembly. Testing was performed in both air and water. Two principal tests were done in this vibration machine - lateral vibration tests and a fuel assembly impact test.

Figure C.2 shows the test arrangement. [

].

C.3 Fuel Assembly Impact Tests

These tests are conducted with the same vibration machine used for the lateral vibration tests except [

].

C.4 Spacer Grid Transverse Dynamic Load Tests

Measured impact loads from the spacer grid [

]. The test setup is illustrated in Figure C.7. The machine [

].

C.5 REFERENCES

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Table C.1 SUMMARY OF TEST VERIFICATIONS

Table C.2 TEST FUEL ASSEMBLY CHARACTERISTICS

[ ]

Figure C.1 MEASURED LATERAL STIFFNESS OF FUEL ASSEMBLY

Figure C.2 FUEL ASSEMBLY VIBRATION MACHINE (SHP 1)

Figure C.3 MEASURED FA NATURAL FREQUENCY VERSUS ACCELERATION (AIR & WATER)

Figure C.4 MEASURED CHANNELLED FA NATURAL FREQUENCY VERSUS ACCELERATION (AIR & WATER)

**Figure C.5 FUEL ASSEMBLY IMPACT TEST (AIR)
FORCE VERSUS FREQUENCY AT MIDDLE SPACER GRID**

**Figure C.6 FUEL ASSEMBLY IMPACT TEST (WATER)
FORCE VERSUS FREQUENCY AT MIDDLE SPACER GRID**

[ ]

Figure C.7 LATERAL DYNAMIC SPACER GRID IMPACT LOAD TEST SETUP

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