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WESTINGHOUSE CLASS 3

SOUTH TEXAS PLANT (TGX) REACTOR INTERNALS
FLOW-INDUCED VIBRATION ASSESSMENT

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1.0 INTRODUCTION

Flow-induced vibrations of pressurized water reactor internals have been studied at Westinghouse over a number of years. The objective of these studies is to assure structural integrity and reliability of reactor internal components. These efforts have included in-plant tests, scale-model tests, bench tests of components, and various analytical investigations. The results of scale-model and in-plant tests indicate that the vibrational behavior of 2, 3 and 4 loop plants is essentially similar; and that the results obtained from each of the tests compliment one another and make possible a better understanding of the flow-induced vibration phenomena.

The TGX reactor internals design incorporates the major features of an original 4-loop plant configuration such as that of Indian Point Unit 2. The successive hardware changes from the original 4-loop configuration of thermal shield to neutron pads and deep beam upper internals to (UHI-style) inverted top hat configuration have been successfully tested in scale model and plant measurement programs [1-7]. The justification and adequacy of these modifications for the TGX plant is presented in Section 2.0.

The purpose of this report is to assess the structural adequacy of 4-loop XL (TGX) reactor internals with regard to flow-induced vibrations. Internals flow-induced vibrations are determined on the basis of scale model tests, tests on instrumented reactors and the results of analtyical calculations. Based on analytical evaluations and the available test data applicable to 4-loop XL plants, it is demonstrated that the vibratory behavior of TGX reactor internals is well characterized, and that the vibration amplitudes are sufficiently low to assure structural adequacy of the components.

It should be noted that the approach taken here is similar to the one previously adopted by Westinghouse to demonstrate the structural integrity of reactor internals of 2, 3, and 4 loop plants.

2.0 JUSTIFICATION OF TGX DESIGN CHANGES FROM ORIGINAL 4-LOOP CONFIGURATION

As discussed earlier, the significant design changes in the TGX reactor internals from the original 4-loop configuration are those involving upper and lower internals. Both of these design changes have been successfully tested and qualified; and the vibration measurement programs completed. For example, the thermal shield core barrel design of the original 4-loop configuration has been replaced by the neutron pad core barrel design in TGX. The in-plant and the scale model vibration measurement programs [ ] of the neutron pad core barrel have been completed and the design change is shown to be adequate. Also, the in-plant and scale model vibration measurement programs [ ] of the (UHI style) inverted top hat upper internals in TGX have been completed and the design change is proven to be adequate. Furthermore, the in-plant testing of Paluel [ ], a 4 loop XL plant configuration, has demonstrated structural adequacy of its internal components with regard to flow-induced vibrations.

In summary, Table 2-1 gives a partial list of domestic and foreign operating plants for which these design changes have successfully been incorporated and the plants licensed.

TABLE 2-1

CHANGES TO ORIGINAL PROTOTYPE

IPP-II	INSTRUMENTED	IPP-II LICENSED
LOWER INTERNALS (NEUTRON PADS)	SCALE TESTS, ANALYSIS PLANT TESTS, OPERATING EXPERIENCE	TROJAN-1 LICENSED MCGUIRE 1 & 2 LICENSED CATAWBA 1 & 2 LICENSED OHI* LICENSED FARLEY LICENSED DOEL* 3 & 4 LICENSED TWP* LICENSED
UPPER INTERNALS (INVERTED TOP HAT)	SCALE TESTS, ANALYSIS PLANT TESTS, OPERATING EXPERIENCE	SEQUOYAH LICENSED MCGUIRE 1 & 2 LICENSED CATAWBA 1 & 2 LICENSED DOEL* 3 & 4 LICENSED PALUEL* LICENSED OHI* LICENSED
14 FOOT CORE	SCALE TESTS, ANALYSIS, PLANT TESTS	PALUEL* LICENSED DOEL* 4 LICENSED

*FOREIGN PLANTS

3.0 CORE BARREL RESPONSE

Results from the scale model and in-plant tests [·] indicate that the primary cause of core barrel excitations is due to flow turbulence generated by the expansion and turning of the flow at the transition from the inlet nozzles to the barrel vessel annulus. Test results of [ ] indicate that the vibration levels of a neutron pad core barrel are lower than the corresponding vibration levels of a core barrel with thermal shield. Vibratory response of the TGX core barrel is deduced from the 1/7-scale model test of 4-loop XL [ ], test data of a 4-loop standard neutron pad core barrel (e.g., in-plant test of POR [ ], the test data of 1/24 - scale model) and in-plant testing of Paluel [ ], a 4-loop XL core barrel.

It should be noted that the test results of the 4 loop neutron pad core barrel such as that of POR are applicable to TGX because the diameter and thickness of both TGX and POR core barrels are the same; difference in the lengths of the core barrels is insignificant (i.e., less than 1/2%). Furthermore, the reactor vessel diameter, neutron pad size, and the core cavity cross-section also are unchanged. In view of these similarities, the down-comer annulus remains the same and, therefore, the core barrel forcing function and the core barrel excitations are the same. The only design difference between TGX and POR lower internals is the change of lower support structure to accommodate additional fuel length. It is shown here that this change has insignificant effects on the vibrational characteristics of TGX core barrel and the change is justified by 1/7 - 4XL scale model measurements [ ], in-plant testing of Paluel-1 [ ] and the analytical evaluations.

3.1 Effects of Replacement of 12 Foot Core with 14 Foot Core

The design difference of TGX lower internals from that of POR internals is the modification resulting from the use of a 14 foot core. This modification involves the elimination of the lower core plate to accommodate additional fuel length and a slight reduction in thickness of the lower support plate.

In the 12 foot core design, the fuel assemblies rest on the lower core plate, whereas, in the 14 foot core design the fuel assemblies rest directly on the lower support plate as shown in Figure 3-1. It is seen

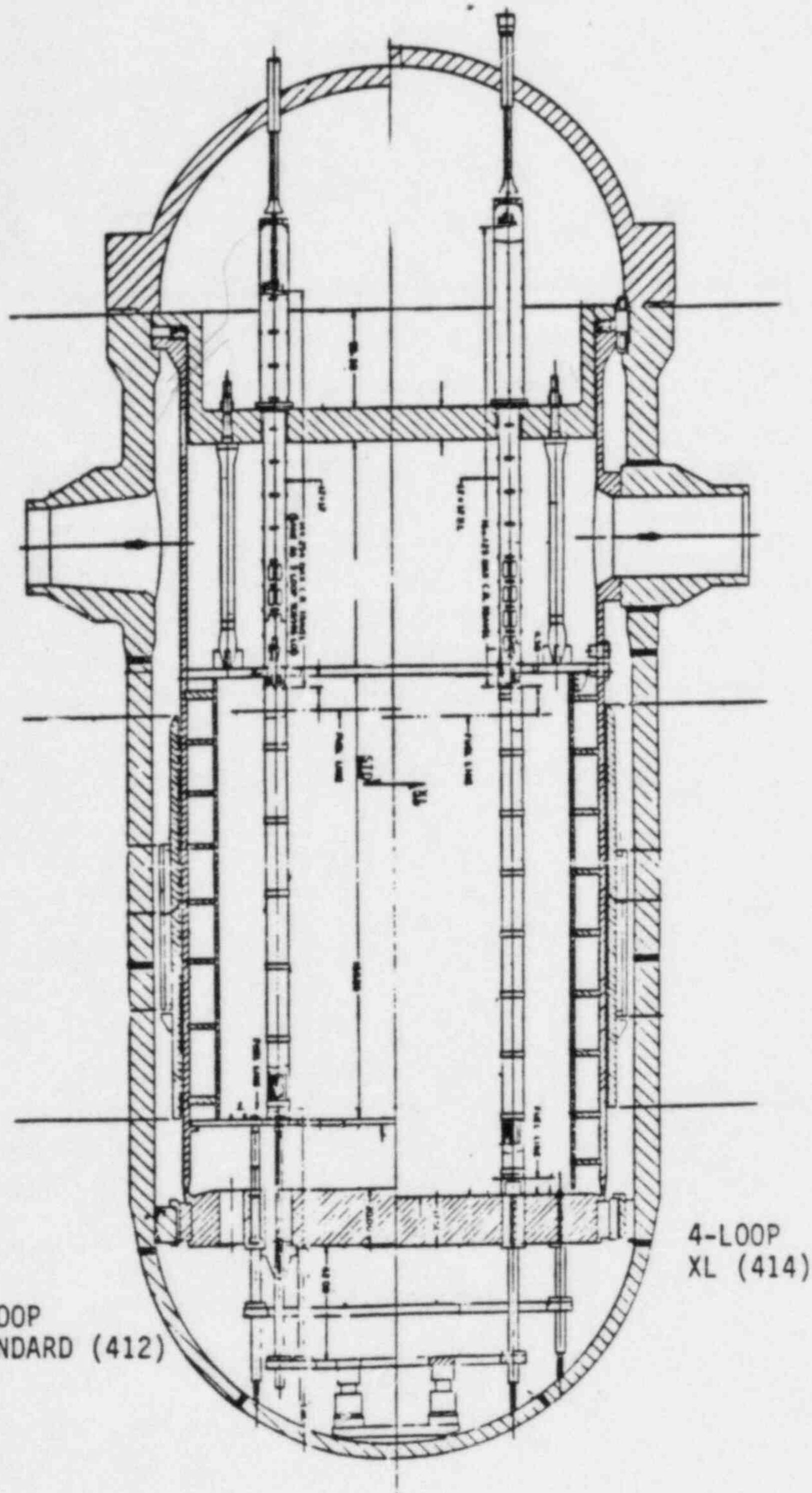

FIGURE 3-1 DESIGN DIFFERENCES BETWEEN 4-XL AND 4-LOOP STANDARD (412) LOWER INTERNALS

from the analysis that the effects of this change on the vibrational characteristics are insignificant. Tables 3-1 and 3-2 presents the results of detailed finite element analysis of 4XL (TGX) and 4-loop standard (412) system models using WECAN [ ] computer code. Table 3-3 shows the comparison of the ratio of (4XL) and (412) core barrel normalized amplitudes in cantilever beam mode for equal excitations. These tables indicate that the effects of this design change on the 4XL vibrational characteristics are not significant.

The WECAN system finite element models of 4XL and 4-loop standard (412) plants used in the analytical investigations are shown in Figures 3-2 and 3-3 respectively. Figures 3-4 and 3-5 show typical mode shapes in cantilever beam mode for the two system models.

3.2 Core Barrel Beam Mode Response Due to Flow-Induced Vibrations

The primary cause of core barrel excitations is the flow turbulence in the downcomer annulus which is independent of upper internals design. Scale model and in-plant test results show that the vibration amplitudes of neutron pad core barrel are less than that of thermal shield core barrel.

The 4XL core barrel cantilever beam mode response obtained from the 1/7-scale model test is shown in Figure 3-6. This figure represents the core barrel vibration spectrum (strain $\mu\varepsilon$ versus frequency) measured by axial strain gages located near the core barrel flange level and azimuth θ = 270°. Table 3-4 presents a comparison of core barrel cantilever beam mode frequency results obtained from the 4XL - 1/7 scale model test, 1/24 scale model test and the in-plant test results of Trojan (POR). The comparison of Table 3-4 shows a good agreement in the test frequency results.

The test results (i.e., rms vibration amplitude versus inlet nozzle flow velocity) obtained from 1/24 scale model of 4 loop neutron pad and thermal shield core barrels are shown in Figure 3-7. It is seen from Figure 3-7 that for a given inlet nozzle velocity, U_n, the vibration amplitudes of neutron pad core barrel are less than that of thermal

TABLE 3-1

4XL (TGX) vs. 4LSTD. (412)

WECAN ANALYSIS

(With Core)

	4XL (TGX)	4LSTD. (412)
Fuel Assembly Natural Frequency 1st Mode	[ ]	[ ]
Core Barrel		
Cantilever Beam Mode		
- Natural Frequency	[ ]	[ ]
- Normalized(1) Amplitude	[ ]	[ ]

(1) Amplitude Normalized by (TGX) Amplitude

TABLE 3-2

4XL (TGX) vs. 4L STD. (412)

WECAN ANALYSIS

(Without Core)

	4XL (TGX)	4LSTD. (412)
Core Barrel Cantilever Beam Model		
f_n	[ ]	[ ]
Normalized[1] Amplitude	[ ]	[ ]

(1)Amplitudes Normalized by (TGX) Amplitudes

TABLE 3-3

RATIO OF 4XL vs. 4LSTD. (412) BARREL

RESPONSE FOR EQUAL EXCITATION

(WECAN ANALYSIS)

	WITH CORE	WITHOUT CORE
$\frac{(4XL)_{Response}}{(412)_{Response}} =$	[ ]	[ ]

FIGURE 3-2 FINITE ELEMENT MODEL OF 4-LOOP XL PLANT

FIGURE 3-3 FINITE ELEMENT MODEL OF 4-LOOP STANDARD (412) PLANT

FIGURE 3-4 MODE SHAPES FOR 4XL WITH AND WITHOUT CORE

FIGURE 3-5 MODE SHAPES FOR (412) WITH AND WITHOUT FUEL

FIGURE 3-6 CORE BARREL SPECTRA FROM 4XL 1/7 SCALE MODEL TEST

TABLE 3-4

FREQUENCY COMPARISON OF 4XL (TGX) vs. 4LSTD. (412)

USING TEST DATA

	4XL - 1/7 SCALE	1/24 SCALE	TROJAN-1 (POR)
Core Barrel Beam Mode Frequency	[ ]	[ ]	[ ]

*With Simulated Core

FIGURE 3-7 INLET NOZZLE VELOCITY, Un (ft/sec) vs. CANTILEVER BEAM MODE AMPLITUDE

shield core barrel. Since the downcomer annulus configuration and the core barrel structures of 4 loop-XL (TGX) and 4-loop standard are nearly identical, their vibration levels will be essentially the same. The TGX core barrel cantilever beam mode response predictions made from three different tests (i.e., 4XL 1/7-scale model test, 1/24 scale model test of a 4-loop neutron pad core barrel, and the in-plant test of Paluel-1) are presented in Appendix A and the results are summarized in Tables 3-5 and 3-6.

The test results presented in Table 3-4 through 3-6 show that the 4XL (TGX) core barrel cantilever beam mode response is similar to 4-loop standard core barrel with 12 foot core configuration.

3.3 Core Barrel Shell Mode Response Due to Flow-Induced Vibrations

In this section the results of shell mode response are presented. Table 3-7 shows a very good agreement of shell mode frequencies for the 1/7 scale model, 1/24 scale model and the inplant test data of Trojan-1 and Paluel. Table 3-8 shows a very good agreement of shell mode deformation obtained from the scale model and in-plant test as discussed in Appendix B.

3.4 Core Barrel Deformations and Stresses

Table 3-9 gives the 4XL (TGX) core barrel deformations and stresses. It is seen from Table 3-9 that the core barrel deformations for the beam and shell modes are extremely small and the corresponding stresses are insignificant. The TGX core barrel finite element model used to calculate the stresses is discussed in Appendix C.

TABLE 3-5

CORE BARREL CANTILEVER BEAM MODE RESPONSE

AMPLITUDES (INCH)

PLANT	CORE BARREL CONFIGURATION	MAXIMUM AMPLITUDE (IN)	INLET NOZZLE FLOW-RATE (GPM)	COMMENTS
Indian Point-2	Thermal Shield			1/24 Scale Model Measurement
Paluel-1 (4XL)	Without Neutron Pads+			Plant Test Measurement*
Trojan-1	Neutron Pads			1/24 Scale Model Measurement
South Texas ([illegible]GX)	Neutron Pads			1/24 Scale Model Measurement
South Texas (TGX)	Neutron Pads			1/7 Scale Model Measurement**

* Without Neutron Pads

**With Simulated Core

\+ Tested Without Neutron Pads

TABLE 3-6

TGX CORE BARREL AMPLITUDE

PREDICTED FROM	AMPLITUDE
1/24 SCALE MODEL	[ ]
1/7 SCALE MODEL*	[ ]
PALUEL**	[ ]

*With Simulated Core

**Neutron Pads Effects Considered

TABLE 3-7

COMPARISON OF CORE BARREL SHELL MODE FREQUENCY (HZ)

Shell Modes (n)	1/24 Scale Model 4 Loop Std. (412)	1/7 Scale Model 4 Loop XL (414)	Plant Test Trojan-1 (412)	Plant Test Paluel-1 (4XL)
n = 2	[ ]	[ ]	[ ]	[ ]
n = 3	[ ]	[ ]	[ ]	[ ]

TABLE 3-8

TGX CORE BARREL SHELL MODE AMPLITUDES

DEDUCED FROM TEST DATA	AMPLITUDE (MILS - RMS) n = 2	AMPLITUDE (MILS - RMS) n = 3
1/24 Scale Model Test		
1/7 Scale Model Test of 4XL		
Paluel Plant Test		

TABLE 3-9

TGX CORE BARREL DEFORMATIONS AND STRESSES

MODE	DEFORMATIONS MILS (RMS)	PEAK STRESSES* (PSI)
Beam Mode		
n = 1	[ ]	[ ]
Shell Modes		
n = 2	[ ]	Negligible
n = 3		Negligible

* σ_{peak} = (4σ) rms

Note that the code allowable stress for high cycle fatigue evaluations is conservatively taken to be 13,200 psi for 10" cycles (40 years life); whereas the calculated maximum peak stress is only [.]. Thus the fatigue usage factor, U is essentially zero $(U = \frac{n}{N} = 0)$.

4.0 TGX UPPER INTERNALS QUALIFICATION WITH RESPECT TO FLOW-INDUCED VIBRATIONS

The TGX upper internals assembly design shown in Figure 4-1 has an inverted top hat design configuration. The upper internals components are excitated by flow turbulences generated by axial and cross-flows that converge on the outlet nozzles. Therefore, the more highly loaded components are those guide tubes and support columns which lie within the vicinity of the outlet nozzles. Thus, the results presented for the TGX upper internals components as shown in Figure 4-2 correspond to those guide tubes and support columns which are within the vicinity of the outlet nozzles.

Since the TGX upper internals design is identical to that of Paluel-1, and since the source of excitations is the same in both cases, the same general vibrational behavior is expected. Note that the flow-rates for the Paluel-1 in-plant test (hot functional) are higher than that of the TGX mechanical design flow-rates; and, therefore, the response obtained from the Paluel-1 plant tests is conservative for the evaluation of TGX upper internals.

It should also be noted that in addition to Paluel-1 plant test data, the test results from 1/7 - scale model of 4XL [ ], 1/7 - scale model of UHI upper internals [ ] and the in-plant tests of Sequoyah [ ] and Doel 3 [ ] are also reviewed to demonstrate the structural adequacy of TGX upper internals.

4.1 Comparison of Test Results for Upper Internal Components

The test results applicable to upper internals of similar design are summarized in Tables 4-1 through 4-3. These tables show comparisons of results between the UHI scale model and the Sequoyah-1 plant. The main purpose of this comparison is two fold; firstly to show the validity and applicability of the scale model test data to predict the in-plant results, and secondly to show that the UHI 1/7 scale model, in general, predicts conservative response of upper internal components as compared to the Sequoyah-1 plant results.

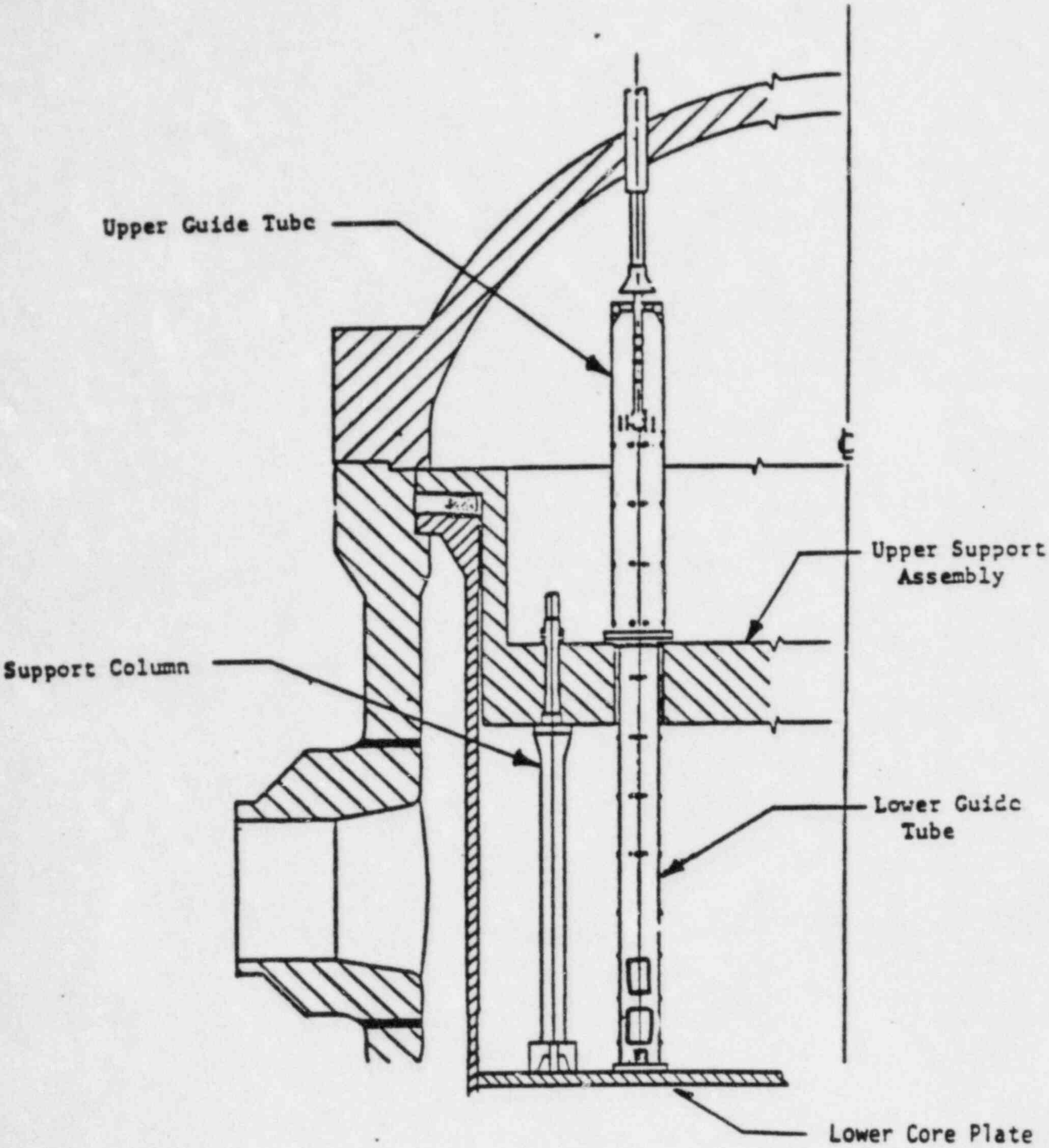

FIGURE 4-1 4 LOOP XL UPPER INTERNALS

FIGURE 4-2 UPPER INTERNALS COMPONENTS (G.T. AND S.C.) IN THE DIRECTION OF CROSS FLOW AT OUTLET NOZZLES

TABLE 4-1

UHI-SCALE MODEL vs. SEQUOYAH-1

UPPER INTERNALS FREQUENCIES

COMPONENT	UHI 1/7 SCALE MODEL (HZ)	SEQUOYAH-1 PROTOTYPE (HZ)
Lower Guide Tube		
0° - 180° 90° - 270°	[ ]	[ ]
5" Support Column	[ ]	[ ]
4" Support Column	[ ]	[ ]

TABLE 4-2

UHI-SCALE MODEL vs. SEQUOYAH-1

UPPER INTERNALS STEADY FLOW LOADS

COMPONENTS	UHI 1/7 SCALE MODEL (LB_f)	SEQUOYAH-1 PROTOTYPE (LB_f)
S.C. L-2	[ ]	[ ]
S.C. N-2	[ ]	[ ]
S.C. K-1	[ ]	[ ]
G.T. K-2	[ ]	[ ]
G.T. M-2	[ ]	[ ]

S.C. = Support Column

G.T. = Guide Tube

TABLE 4-3

UHI-SCALE MODEL vs. SEQUOYAH-1 UPPER INTERNALS

RANDOM FLOW-INDUCED VIBRATORY RESPONSE

COMPONENT	UHI 1/7 SCALE MODEL (MILS)	SEQUOYAH-1 PROTOTYPE (MILS)
S.C. L-2	[ ]	[ ]
S.C. N-2	[ ]	[ ]
S.C. K-1	[ ]	[ ]
G.T. K-2	[ ]	[ ]
G.T. M-2	[ ]	[ ]

Table 4-1 shows a very good agreement between the UHI scale model and Sequoyah-1 plant frequencies. Tables 4-2 and 4-3 show the comparisons for steady flow loads and random flow-induced vibratory responses, respectively. From the response of these tables (i.e., 4-2 and 4-3) it is seen that for the most highly stressed (loaded) components among the upper support columns and guide tubes, the UHI scale model tests yield conservative flow loads and vibration amplitudes. Therefore, use of the 1/7 - scale model test data to predict plant data is conservative and adequate to characterize Sequoyah-1 plant vibrational behavior. Table 4-4 shows the comparison of Doel 3 and Sequoyah-1 plant vibration test data. The purpose in presenting Table 4-4 results is to show the similarities in the response of guide tubes and support columns even though there exist certain differences in the design of these components (e.g., Sequoyah-1 has thicker support columns than those of Doel 3). In both the cases, the magnitude of the measured strains are extremely small.

4.2 Results Applicable to TGX Upper Internals

As discussed earlier, the TGX upper internals design is identical to Paluel-1 and, therefore, the Paluel-1 plant test data is used to calculate the response of TGX upper internals. The TGX guide tube and upper support column vibrational loads obtained from the Paluel-1 plant measurements are discussed in Appendix D. The flow-induced vibrational response of guide tubes and upper support columns is determined from the considerations of:

- Low frequency response due to flow turbulence
- Beam modes response due to random turbulence
- Response due to pump-induced loads

The total response from 0 to 200 Hz, which consists of low frequency response and the 1st and 2nd beam modes responses, is calculated using hot functional test data of PALUEL plant [ ]. The response due to pump induced loads was inferred using the hot functional test data of SEQUOYAH [ ].

Table 4-5 shows the frequency comparison of Paluel-1 plant test data with other available tests for the similar guide tubes and upper support columns; and the results show a very good agreement.

TABLE 4-4

COMPARISON OF DOEL 3 AND SEQUOYAH 1

PLANT VIBRATION DATA

Guide Tube	Sequoyah 1 (0-100 Hz)	Doel 3 (0-200 Hz)
Natural Frequency (Hz)		
RMS Strain (μ in/in)		

Support Column	Sequoyah 1 (0-179 Hz)	Doel 3 (0-200 Hz)
Natural Frequency (Hz)		
RMS Strain (μ in/in)		

TABLE 4-5

UPPER INTERNALS FREQUENCY COMPARISON

COMPONENT	4XL PALUEL-PLANT (HZ)	4XL 1/7 - SCALE MODEL (HZ)	DOEL-3 PLANT (HZ)
Lower Guide Tubes			
m = 1			
0° - 180°	[	[	[
90° - 270°	]	]	]
m = 2			
0° - 180°	[	–	[
90° - 270°	]	–	]
Support Column			
m = 1			
0° - 180°	[	[	[
90° - 270°	]	]	]

4.2.1 Guide Tube Response

The maximum vibrational response of the TGX guide tubes for 0 to 200 Hz frequency range is compared with that of PALUEL as shown below:

	Strain (rms)	Force (rms)	Peak Strain (4 σ)	Peak Force (4 σ)
PALUEL-1				
TGX				

It is to be noted that the effects of core outlet temperature, water density and flow-rates at the outlet plenum are taken into account in calculating the guide tube loads. The hot functional test data of SEQUOYAH [5] plant indicates that the predominant reactor coolant pump frequencies of the guide tubes are 19.7 Hz (pump shaft frequency) and 277 Hz second harmonic of the blade passing frequency and that the levels at these frequency components are less than [ ] and therefore negligible.

It should also be noted that the 17 x 17A lower guide tubes have been analyzed in Reference [11] for a maximum vibrational load of 750 lb_f (against 328 lb_f for TGX), and the analysis show that the guide tubes have adequate margins of safety.

4.2.2 Upper Support Columns Response

Similar to Section 4.2.1 on guide tubes response, the maximum vibrational response of the TGX upper support columns from 0 to 200 Hz frequency range is also compared with the Paluel results, i.e.:

	Strain (rms)	Force (rms)	Peak Strain (4 σ)	Peak Force (4 σ)
PALUEL-1				
TGX				

In addition to the above calculated loads for 0 to 200 Hz frequency range, the 2nd beam mode response at 285 Hz was obtained using SEQUOYAH [5] test data. The SEQUOYAH test data for the 277 Hz second harmonic of the blade passing frequency inferred a uniform pressure of [ ] distributed along the length of the support columns. It is shown in [11] that for a maximum load of [ ] along with the [ ] pressure distribution, the upper support columns have adequate margins of safety.

5.0 PUMP/INDUCED VIBRATIONS

The pump induced vibrations of the reactor internals are due to:

a. Low frequency forcing functions due to pump shaft rotations.

b. High frequency forcing functions due to pump blade passing motions.

In the following, the upper and lower support plates which have relatively low vertical frequencies are analyzed due to low frequency pump excitations. Similarly, for the guide tubes and upper support columns which have relatively high natural frequencies (see, e.g. Section 4.0) are investigated due to high frequency pump blade forcing functions.

5.1 Upper Support Assembly

The TGX upper-support-plate's, Figure 5.1-1, responses to the pump induced pulsations were assessed using a 2-D axisymmetric finite element model as shown in Figure 5.1-2.

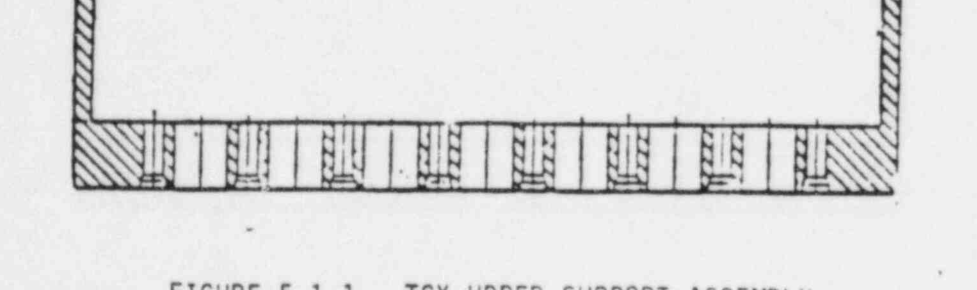

FIGURE 5.1-1 TGX UPPER SUPPORT ASSEMBLY

FIGURE 5.1-2 TGX UPPER SUPPORT ASSEMBLY MODEL

Uniform pressure of 1 psi was statically applied on the plate to simulate pump induced pressure loadings. The maximum stress was 91 psi [10] at the skirt-plate joint region as shown in the following figure:

FIGURE 5.1-3 RESULTS OF UNIT PRESSURE LOADING

Assuming [ ] damping and, conservatively, resonant condition, the statically obtained stresses were scaled by the acoustically calculated maximum pressure amplitude of [ ] and the dynamic amplification factor of [ ] Finally, fatigue strength reduction of [ ] was used for the weld region:

[ ]

It is seen that the magnitude of the alternating stress, S_{ALT}, is negligible compared to the ASME Code allowable of 13, 200 psi.

5.2 Lower Core Support Plate

The TGX lower core support plate's response to the pump induced pulsations were investigated the same way as for the upper support plate in Section 5.1. The lower core support plate and the 2D axisymmetrical model are shown in the following figures.

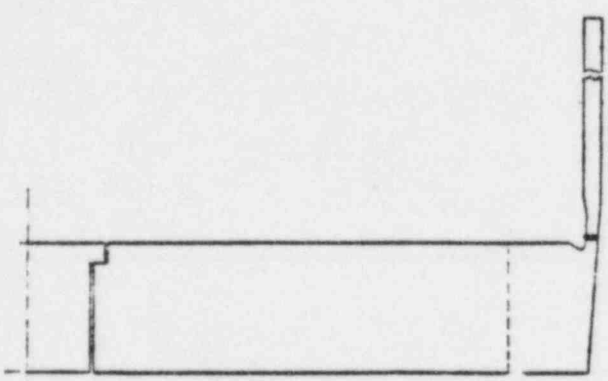

FIGURE 5.2-1 LOWER CORE SUPPORT PLATE

FIGURE 5.2-2 LOWER CORE SUPPORT PLATE MODEL

The maximum stress at the support plate-core barrel welded joint was due to the applied pressure of [ ] psi on the lower support plate [14]. Using the calculated pump-induced pressure of [ ] and assuming 2% damping at resonance, the alternating stress at the weld region is:

$$S_{ALT} = [\quad]$$

$$\leq [\quad]$$

It [illegible] seen that the alternating stress, σ_{ALT}, is small enough to be neglected compared to the allowable of 13,200 psi.

5.3 Guide Tubes and Upper Support Columns

The pump induced vibrational response of the guide tubes and upper support columns due to high frequency forcing functions is also investigated in [10]; and these results have been discussed in Section 4.0.

6.0 SUMMARY AND CONCLUSIONS

The results of the flow-induced vibration assessment program for the 4XL (TGX) plant are summarized as:

Lower Internals

- 4XL (TGX) lower internals vibrational characteristics are similar to those plants with 12 foot core.
- Vibrational behavior of the TGX lower internals can be established by previous plant and scale model tests.
- Vibrational amplitudes and stresses are small.
- Effects of added core length is shown to be insignificant from analytical investigations and tests.
- Trojan-1 core barrel is similar to TGX core barrel and has long operating experience.

Upper Internals

- Very small vibratory amplitudes and stresses.
- Paluel-1 upper internals design is identical to TGX and has successfully passed hot functional test.
- Doel 3 guide tubes and support columns have same dimensions (Design) and have long operating experience.

In conclusion, the vibrational response of 4XL (TGX) plant obtained from the scale model tests and the instrumented plant tests show that the internals vibration levels are low and that the TGX reactor internals design is adequate to assure structural integrity against flow-induced vibrations.

7.0 REFERENCES

1.

2.

3.

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APPENDIX A

The TGX core barrel cantilever beam mode amplitudes predicted from three different tests (i.e., 4XL 1/7-scale model test, 1/24 scale model test of a 4-loop neutron pad core barrel, and the in-plant test of Paluel-1) are presented here.

A.1 4XL 1/7-Scale Model Test

The 4XL 1/7-scale model test results given in Reference [ ] report that the core barrel cantilever beam mode amplitude determined from the frequency band [ ] Hz with center frequency of [ ] Hz is approximately [ ] mils (rms). Referring to [ ] of [ ], the band-limited response is defined by:

[ ] (A.1-1)

where

(A.1-2)

and

[ ]

The value of I is plotted in Figure A.1-1 as a function of frequency ratio f/f_n, and $Q = \frac{0.5}{\xi}$. On the other hand, the full modal rms response at the center frequency f_n is:

[ ] (A.1-3)

Thus, once ξ is known, the value of full modal response can be determined from the band-limited modal response or vice versa.

FIGURE A.1-1 INTEGRAL FACTOR FOR MEAN SQUARE RESPONSE OF SINGLE-DEGREE-OF-FREEDOM SYSTEM TO BAND-LIMITED WHITE NOISE.

Then using Figure A.1-1 and the parameters calculated in [ ], it can be seen that the response over this band width is approximately [ ] of the full modal response. Thus, scaling to plant size, plant temperatures and the plant flow rates we get:

$$\tilde{y}_P = [\quad]$$

$$= [\quad]$$

$\tilde{y}_P$ = [ ] mils (rms) at the operating temp. 560°F.

Note that the subscripts P and m stand for the plant and model, respectively.

A.2 1/24 - Scale Model Test

Figure A.2-1 shows that for a given inlet nozzle velocity, U_n, the amplitude is given by

$$\tilde{y}_m \propto [\quad] \qquad \text{(A.2-1)}$$

The inlet nozzle velocity, U_n, for the TGX flow rates is given by:

$$U_n \text{ (ft/sec)} = \frac{\text{(gpm/loop)} \times 144 \text{ (in}^2\text{/ft}^2\text{)}}{7.48 \text{ (gallons/ft}^3\text{)} \times A_n \times 60 \text{ (sec/min)}}$$

wherein A_n is the maximum nozzle inlet area (in^2):

$$U_n = [\quad]$$

Then, in view of (A.2-1)

$$\tilde{y}_m = [\quad]$$

With the use of scaling laws

$$\tilde{y}_P = [\quad]$$

$$\tilde{y}_P = [\quad]$$

FIGURE A.2-1 INLET NOZZLE VELOCITY, Un (ft/sec) vs. CANTILEVER BEAM MODE AMPLITUDE

A.3 Paluel-1 Plant Test (Hot Functional)

The core barrel amplitude measurements from the Paluel-1 hot functional test are given in Table A.3-1. Note that the Paluel test was carried out without the neutron pads attached to the core barrel. Therefore, the effects of the neutron pads on the Paluel core barrel amplitudes are not included in this test. However, a test program was undertaken at W R&D to study the effects of neutron pads on the 4-loop core barrel amplitudes with regard to the flow induced vibrations. The study shows that the response of the core barrel without the neutron pads is about [ ] of that of the neutron pads core barrel. It should, therefore, be noted that these effects are included in predicting the TGX core barrel response from that of the Paluel in-plant test data.

In Table A.3-1, transducers A_{10} and A_{12} measure the response of the core barrel in the tangential direction, whereas transducers A_9 and A_{11} measure the response in the radial direction (see, e.g., Figure A.3-1). Then the average response of these transducers in the tangential and radial directions is:

y_t = [ ] (rms)

y_r = [ ] (rms)

Scaling to TGX flow rates and accounting for the effects of neutron pads, we get:

$(\tilde{y}_p)_t$ = [ ] mils (rms)

$(\tilde{y}_p)_r$ = [ ] mils (rms)

TABLE A.3-1 PALUEL-1 CORE BARREL BEAM AND SHELL MODES AMPLITUDES

FIGURE A.3-1 TRANSDUCER LOCATIONS ON PALUEL-1 CORE BARREL

APPENDIX B

The TGX core barrel shell mode deformations from the scale model and in-plant tests are deduced in this section.

B.1 1/24-Scale Model Test

The 1/24-scale model shell mode rms accelerations in terms of the inlet nozzle velocity are shown in Figure B.1-1. At the TGX inlet nozzle velocity, U_n = [ ] ft/sec the shell mode accelerations from Figure B.1-1 are given in Table B.1-1.

TABLE B.1-1

SHELL MODE ACCELERATIONS FROM 1/24 SCALE MODEL TEST

f_n	n = 2	n = 2'	n = 3	n = 3'
$f_n/24$				
Acc.* gs (rms)				

The modal rms amplitude at the center frequency f_n is given by [1].

$$\tilde{y} = [\quad] \qquad (B.1\text{-}1)$$

where the peak value y* is obtained from

$$y^* = [\quad] = [\quad] \qquad (B.1\text{-}2)$$

Now from Figure B.1-2 taken from Reference [1] yields:

*Accelerations measured approximately at mid elevation of the core barrel and at TGX flow rates (i.e., U_n = [ ] ft/sec).

FIGURE B.1-1 NARROW BAND rms ACCELERATION AT NATURAL FREQUENCIES OF 1/24th SCALE NEUTRON PAD MODEL INTERNALS. U_n = 29.6 fps at 100% FLOW

FILTER BANDWIDTH BW = [ ] Hz

FIGURE B.1-2 ACCELERATION SPECTRA OF 1/24th SCALE MODEL NEUTRON PAD CORE BARREL.

FILTER BAND WIDTH = [ ] Hz

$$\Delta f_n = [\quad]$$

$$BW = [\quad] \qquad (B.1\text{-}3)$$

Using equations (B.1-1) through (B.1-3) and accounting for the temperature effects we get:

$$\tilde{y}_p = [\quad]$$

or

$$\tilde{y}_p = [\quad] \qquad (B.1\text{-}4)$$

Equation (B.1-4) together with Table (B.1-1) yields the shell mode rms amplitude as given in Table B.1-2, i.e.:

TABLE B.1-2

SHELL MODE RMS AMPLITUDE

f_n	n = 2	n = 2'	n = 3	n = 3'
$f_n/24$				
Amplitude $\tilde{y}_p$ mils (rms)				

The SRSS value values are

n = 2: [ ]

n = 3: [ ]

B.2 1/7-Scale Model Test

Figure B.2-1 shows the 1/7-scale model spectra (transducer number 51) at 100% test flow rate. A summary of n = 2 core barrel shell mode response at various flow rates and in the frequency band of [ ] Hz and [ ] Hz is given in Table 7-3 of Reference [7]. Then following the procedure adopted earlier in Appendix A.1 and the parameters calculated in [10], the shell mode deformations are summarized in Table B.2-1.

TABLE B.2-1

SHELL MODE RESPONSE FROM 1/7-SCALE MODEL TEST

f_n	N = 2	N = 2'	N = 3 = 3'
$f_n/7$			
$\tilde{y}_p$ (Mils) rms			

Then SRSS values are:

n = 2: [

n = 3:]

B.3 Paluel Plant Test (Hot Functional)

The core barrel shell mode amplitude measurements from the Paluel hot functional test are given in Table A.3-1. As mentioned earlier, the Paluel hot functional data was obtained without the neutron pads; and, therefore, the effects of neutron pads are included in predicting the TGX response from that of Paluel.

FIGURE B.2-1 4XL 1/7-SCALE MODEL SPECTRA AT 100% FLOW (TRANSDUCER NUMBER 51)

Shell Mode n = 2: f = [ ]

The SRSS value of transducers A_7 and A_9 yield

$$y^* = [\quad]$$

Shell Mode n = 3; f = 31.5 Hz

$$y^* = [\quad]$$

Now scaling to TGX flow rates and accounting for the effects of neutron pads, we get:

$$\tilde{y}_p = [\quad]$$

which yields

	n = 2	n = 3
f (Hz)	[ ]	[ ]
$\overline{y}_p$ Mils (rms)	[ ]	[ ]

APPENDIX C

The TGX core barrel stresses due to flow-induced vibrations were determined using an axisymmetric finite element model subjected to non-axisymmetric loadings. Figure C.1-1 shows the core barrel geometry and dimensions; and Figure C.1-2 shows the finite element representation using [ ] Note that the increased thickness of the lower core barrel in Figure C.1-1 accounts for the effects of baffle-former assembly.

The non-axisymmetric loadings consisted of applying a maximum of [ ] mils displacements as the bottom end mode (2013) in the manner such that U_x = [ ] and U_z = [ ] Three different support conditions were evaluated and these consisted of supporting the core barrel flange at the vessel ledge by restraining nodes [ ] respectively, in all degrees of freedom. The maximum stress intensity of approximately [ ] psi due to the applied displacement of [ ] mils occurred at the barrel-flange weldment. Then the peak stress at the weldment becomes σpeak = [ ]

FIGURE C.1-1   TGX CORE BARREL DIMENSIONS

FIGURE C.1-2a TGX CORE BARREL FINITE ELEMENT REPRESENTATION

FIGURE C.1-2b TGX CORE BARREL FINITE ELEMENT REPRESENTATION

APPENDIX D

The Paluel-1 hot functional test measurements of the guide tubes and upper support columns are summarized in Table D.1-1.

TABLE D.1-1

PALUEL HOT FUNCTIONAL TEST MEASUREMENTS

Component-Orientation	Total Strain $\mu\varepsilon$ (rms)	1st Beam Mode m = 1 $\mu\varepsilon$ (rms)	2nd Beam Mode m = 2 $\mu\varepsilon$ (rms)
Lower Guide Tube			
0° - 180°			
90° - 270°			
Upper Support Cols.			
0° - 180°			
90° - 270°			
Upper Guide Tube			
0° - 180°			
90° - 270°			

In addition, the static and dynamic calibration test data for the guide tubes and upper support columns is summarized in Table D.1-2.

TABLE D.1-2

PALUEL CALIBRATION TEST DATA

Component - Orientation	Static Calibration	Dynamic Calibration m = 1	Dynamic Calibration m = 2
Lower Guide Tubes			
0° - 180°			
90° - 270°			
Upper Support Columns			
0° - 180°			
90° - 270°			
Upper Guide Tube			
0° - 180°			
90° - 270°			

From the Tables D.1-1 and D.1-2, the guide tube and upper support column component loads in each direction can be evaluated as:

$$\text{Force} = \varepsilon_0 \times (SC)_0 + \varepsilon_1 \times (DC)_1 + \varepsilon_2 \times (DC)_2 \qquad (D.1\text{-}1)$$

wherein

ε_0 = Low Frequency Strains ($\mu\varepsilon$)

ε_1 = 1st Beam Mode Strain ($\mu\varepsilon$)

ε_2 = 2nd Beam Mode Strain ($\mu\varepsilon$)

$(SC)_0$ = Static Calibration Load (lb/$\mu\varepsilon$)

$(SC)_1$ = Dynamic Calibration Load for 1st Mode (lb/$\mu\varepsilon$)

$(SC)_2$ = Dynamic Calibration Load for 2nd Mode (lb/$\mu\varepsilon$)

and the low frequency strains are calculated as

$$\varepsilon_0 = \left\{(\varepsilon_{Tot})^2 - [(\varepsilon_1)^2 + (\varepsilon_2)^2]\right\}^{1/2} \qquad (D.1\text{-}2)$$

Using equations (D.1-1) - (D.1-2) and Tables D.1-1 and D.1-2, the Paluel guide tubes and upper support columns loads are calculated in the 0° - 180° and 90° - 270° planes. The resultant of these loads is then determined by the SRSS method.

The TGX guide tubes and upper support columns load are determined from those of Paluel by scaling to TGX flow rates, i.e.,

$$\text{Force Ratio} = \frac{F_{TGX}}{F_{Paluel}} = \frac{(\rho_o V_o^2)_{TGX}}{(\rho_o V_o^2)_{Paluel}} \qquad \text{(D.1-3)}$$

where ρ_o and V_o represent the outlet water density and velocity, respectively. The outlet flow rate, Q_o, is determined by the relation

$$Q_o = Q_{inlet} \left(\frac{\rho_{inlet}}{\rho_{outlet}} \right) \qquad \text{(D.1-4)}$$

$(Q_o)_{TGX}$ = [ ]

Using equation (D.1-3), we get

Hot, Fuel Power

$$\frac{(F)_{TGX}}{(F_{PAL})} = \frac{(\rho_o V_o^2)_{TGX}}{(\rho_o V_o^2)_{PAL}}$$

= [ ]

= [ ]

$(Force)_{TGX}$ = [ ] $(Force)_{PAL}$.

At Hot, Full Power — At Hot, Zero Power

Hot, Zero Power

= [ ]

= [ ]

$(Force)_{TGX}$ = [ ] $(Force)_{Paluel}$

Hot, Zero Power — Hot, Zero Power